THE IMPACT OF AIRCRAFT DESIGN REFERENCE MISSION ON FUEL EFFICIENCY IN THE AIR TRANSPORTATION SYSTEM

by

Brian Yutko

B. Sc. The Pennsylvania State University, 2008
M. S. Aeronautics & Astronautics, Massachusetts Institute of Technology, 2011

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Author:

Certified by:

R. John Hansman
Professor of Aeronautics & Astronautics, MIT

Certified by:

Cynthia Barnhart
Professor of Civil and Environmental Engineering and Engineering Systems
Associate Dean of Engineering, MIT

Certified by:

Philippe Bonnefoy
Lead of Advanced Analytics/Aviation, Energy and Environment, Booz Allen Hamilton

Certified by:

Mark Drela
Professor of Aeronautics and Astronautics, MIT

Certified by:

Aleksandra Moddzanowska

Accepted by:

Eytan H. Modiano
Associate Professor of Aeronautics & Astronautics, MIT
Chair, Graduate Program Committee
The Impact of Aircraft Design Reference Mission on Fuel Efficiency in the Air Transportation System

Brian Yutko

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ABSTRACT

Existing commercial aircraft are designed for high mission flexibility, which results in decreased fuel efficiency throughout the operational life of an aircraft. The objective of this research is to quantify the impact of this practice and other non-optimal emergent behaviors of the current global air transportation system. The analysis focuses on improvements that can be made using existing technology.

Previous attempts at performing this type of analysis, especially the joint optimization of aircraft design and operations, have been hindered by problem complexity and computational time. In order to overcome these issues and perform the analysis on a global scale, a machine-learning algorithm is used to create a computationally efficient artificial neural network relating aircraft design and off-design mission performance to operational fuel burn and flight time. The data used to train the aircraft performance neural network is generated from an extensive sample of new vehicles optimized for minimum fuel burn on an extremely broad combination of Design Reference Missions (design-payload, -range, and cruise Mach). The resulting comprehensive model of aircraft performance is capable of solving large-scale air transportation network optimization problems.

A set of scenarios is analyzed to both establish the limits of the major contributors to system fuel consumption and determine potential realistic benefits from introducing new aircraft with varying design reference missions. Results indicate that approximately 33% of current system fuel consumption is due to the slow retirement and replacement of aircraft in the operational fleet. Additionally, a significant pool of potential fuel burn savings can be realized by designing aircraft closer to their intended operating regime. Multiple large-scale optimization scenarios are presented, including the optimal choice of new aircraft designs for fixed cruise Mach numbers and the globally optimum aircraft choices given any cruise Mach. It is found that reducing design cruise speed can yield system fuel benefits on the order of 7%. Fuel stops are shown as a potentially promising method to operate long-haul missions closer to the maximum fuel efficiency range of an aircraft, and also as a way to mitigate the impact of designing high-efficiency, short-range aircraft that can no longer fly long haul missions directly.

Thesis Supervisor: R. John Hansman
Title: Professor, Department of Aeronautics and Astronautics
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To my friends, family, and coworkers: None of this was possible with your support.

I'm forever grateful.

"I can live with doubt and uncertainty and not knowing. I think it is much more interesting to live not knowing than to have answers that might be wrong... If we will only allow that, as we progress, we remain unsure, we will leave opportunities for alternatives. We will not become enthusiastic for the fact, the knowledge, the absolute truth of the day, but remain always uncertain... In order to make progress, one must leave the door to the unknown ajar."

–Richard Feynman
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Chapter 1

MOTIVATION AND INTRODUCTION

Growing concerns regarding the implications of greenhouse gas emissions, the increasing volatility of fuel prices, and the potential for increased effective fuel prices have created an impetus to improve future aircraft fuel efficiency. Future reductions in fuel consumption will likely be achieved in large part through the development of fuel efficiency technologies and alternative fuels. However, achieving even more significant improvements, which will be needed as demand continues to increase, may require reconsidering all phases of the aircraft design and operations process [1].

1.1 Motivation: The Fuel Efficiency Challenge

A combination of rising demand, policies intending to reduce the impacts of climate change, and rising fuel prices is increasing the pressure to improve both aircraft and air transportation system fuel efficiency.

1.1.1 Climate Change Policy

Increasing concerns regarding the implications of climate change have created an impetus to reduce greenhouse gas emissions. In 2007, the International Panel on Climate Change (IPCC) released its Fourth Assessment Report declaring, “warming of the climate system is unequivocal,” and that “most of the observed increase in global average temperatures since the mid-20th century is very likely due to observed increase in anthropogenic greenhouse gas concentrations.” [2]-[4] Further increases in anthropogenic greenhouse gas emissions are likely to have impacts on ecosystems, food supply chains, and coastal habitats, included many of the world’s largest cities. In order to avoid significant or catastrophic impacts as a result of climate change, many researchers have suggested stabilizing the atmospheric concentration of CO₂ to 350-450ppm, resulting in a net average global temperature increase of approximately 1-2°C above pre-industrial levels [5].
While commercial aviation contributed approximately 2% of total anthropogenic CO₂ emissions in 2005 [6], as in Figure 1, aviation's relative contribution to climate change is estimated to be higher due in part to the types of emissions produced and the high altitude at which the majority of emissions are produced [7]-[10]. In addition, due to continued increases in demand for air travel, aviation's relative contribution to climate change is expected to continue growing. The identification of CO₂ as a leading contributor to climate change, coupled with concern over the increasing contribution of CO₂ emissions by aviation motivates action to mitigate aviation's CO₂ emissions in the near-term.

![Aviation CO₂ Emissions](image)

**Figure 1: Growth in CO₂ Emissions for all Anthropogenic Activities and from Aviation, Lee, et al. [6]**

To this end, governments and trade organizations have adopted near and far term goals to reduce CO₂ emissions [11]. In 2009, the United States (US) agreed to the Copenhagen Agreement, a non-binding accord that lead to the US declaring a goal of 17% reduction from 2005 levels of national CO₂ emissions by 2020 [12]. Additionally, both The International Civil Aviation Organization (ICAO) and the International Airline Industry Association (IATA) have set aviation specific goals. ICAO has adopted a target of 2% global annual average fuel efficiency improvement through 2050 [13]. IATA has stated a goal of an average fuel efficiency improvement of 1.5% per year to 2020, a cap on emissions after 2020, and a net reduction in aviation emissions of 50% from 2005 levels by 2050 [14].

As a first step towards meeting these goals, the European Union (EU) has implemented an emissions trading system (ETS) for flights originating or terminating within the EU [15]. The EU ETS is a market-based measure that intends to reduce emissions by providing
additional economic incentives for reduction beyond traditional market forces. Firms are allocated permits that correspond to each unit of emissions. Firms can then trade permits with each other, thereby rewarding firms that have reduced emissions and placing an extra economic cost on those intending to emit more than their allocated number of permits. In this sense, total emissions are "capped," efficient firms are rewarded, and firms with increasing emissions face an additional cost.

Additionally, the Committee on Aviation Environmental Protection (CAEP) within ICAO has initiated a process to develop a commercial aircraft CO₂ emissions certification requirement [13] with a goal to develop the CO₂ standard by 2013 [16]. CAEP has reached agreement on a metric system framework in July 2012 [17]. The purpose of the standard is to reduce aviation emissions through the introduction of more fuel-efficient technologies.

The result of these policies and future policies is likely to be an increase in the effective cost of fuel.

1.1.2 FUEL PRICE INCREASES AND PRICE VolATILITY
Fuel price volatility has increased during the past decade. In 2000, jet fuel prices surged to over double 1999 levels. Between July 2004 and July 2008, fuel prices increased 244% before dropping 50% by July 2009 (Figure 2). Into 2011, fuel prices rose sharply again. If the world supply of oil decreases and demand does not slacken, fuel prices may continue their upward trend. Without economical, technologically mature, and safety certified energy substitutes, commercial aviation will continue to rely on petroleum based jet fuel at increased prices. The Energy Information Administration's (EIA) reference case forecasts jet fuel prices to reach $2.97/gallon by 2020 and $3.41/gallon by 2035 (2010 US$) without carbon pricing [18], as shown in Figure 1. This represents a three to four fold increase over early 2000 fuel prices. The low/high oil scenarios depend on more optimistic/pessimistic assumptions for economic access to non-OPEC resources and for OPEC behavior. In the high price scenario, jet fuel is forecasted to climb to $4.35/gallon by 2020 and $5.17/gallon (2010 US$) by 2035 [19].
1.1.3 **Market Outlook**

In spite of the desires to reduce net aviation emissions, passenger demand is likely to increase. The air traffic industry has a long-term growth rate of approximately 5 percent per year. This growth rate has historically been robust, returning quickly to the long-term average even following major macroeconomic downturns. Year over year growth between 2011 and 2012 was 5.3 percent, despite a slowly recovering economy. Boeing forecasts a need for 35,280 new airplanes through 2032, with 41% of this total replacing old aircraft, and the remaining 59% for fleet growth [20].

Reducing net emissions in the face of growing demand requires that the system fuel efficiency, i.e., system productivity divided by system energy consumed increase significantly.

1.2 **Introduction: Commercial Air Transportation as a System-of-Systems**

The increase in effective cost of fuel due to environmental policies and rising crude oil prices in combination with growing demand is placing increased pressure on the air transportation industry to improve fuel efficiency. Future reductions in fuel burn and greenhouse gas emissions from commercial aviation will be, in part, achieved through improvements aircraft technology (i.e. improvements in aerodynamics, propulsive...
efficiency, and structural efficiency). However, achieving even more significant fuel and environmental efficiency improvements may require opening up the design space so as to consider the entire commercial aircraft life cycle and the interactions between multiple systems [1].

An overview of the commercial aircraft life cycle is depicted in Figure 3. Aircraft are designed in a complex, iterative process that is intended to meet the needs of the market. Because the general purpose of air transportation is to move people and goods at a high rate of speed between distant locations, to first order the market needs tend to be capacity, range, and speed. Other requirements are also considered in the iterative design process, such as fuel consumption on flight segments of interest, the ability to takeoff or land at various airports, the ability to fit inside typical airport gates, noise during takeoff, potential cabin layouts, etc. Once the aircraft is designed, it is manufactured and eventually acquired either directly by airlines or by large financial institutions intending to lease the aircraft to airlines [21]. Airlines then allocate the aircraft in their network and operate missions in the air traffic system. Eventually, the aircraft is retired and is sometimes replaced by another aircraft.

![Commercial Aircraft Life Cycle Diagram](image)

**Figure 3: Commercial Aircraft Life Cycle**

There exists a significant amount of literature in each of these areas; however, research efforts typically do not stray far from the central system of interest [22]. For example, operations research seeks to identify the best allocation of a fleet on a set of flight legs without also considering what is the best aircraft to design that set of flight legs [23]. Likewise, aircraft manufacturers traditionally assume fixed aircraft demand and routing (or fixed relative to some future projection) and design the aircraft without considering the optimal allocation or routing for the various new designs [24]. While these systems are typically considered in isolation, increasing pressure for highly fuel-efficient transportation has driven a growing body of research that widens the scope to include interactions that may be leveraged to yield a larger benefit.

In 2010, the Committee on Aviation Environmental Protection (CAEP) within the International Civil Aviation Organization (ICAO) convened a group of Independent Experts (IE) from various Western European countries and the United States in order to explore the fuel efficiency impact of both future technologies and changes in mission specifications. Mission specification changes can include variables such as design- cruise speed, -payload,
and -range; wing span; balanced field length, etc., that can have significant economic and operational impacts across multiple systems [25]. The independent experts found that relaxing span, cruise Mach number, and design-range constraints yield improvements in fuel-efficiency comparable to those that could be obtained with significantly accelerated technology developments. The experts also found that,

"It has become clear that past technology improvements have partly been used to increase performance, primarily design range. Because of this the reductions in fuel burn have been smaller than they might have been... In assessing future reductions in fuel it is important to include the effect of the specified design range... The IEs have been made aware that the majority of flights for both the single-aisle and twin-aisle aircraft are substantially below the maximum payload range of the aircraft. Both manufacturers and airlines have opted for long range since a long-range aircraft can always operate a short flight, but not the other way around. The impact of this on fuel-burn does not appear to have had the attention it deserves."

Thus, increasing the analysis scope could yield even larger benefits than isolated technology introductions. However, this wider scope and potentially larger pool of benefits comes at the cost of problem complexity.

In Systems Engineering, the previously described architecture is generally understood as a system-of-systems (SoS), which is a collection of systems that operate independently but which has considerable benefits when compared simply to the sum of the parts. In a SoS, the entities and the relationship between the entities combine to form an evolutionary and emergent behavior of the whole system [26]. Typically a SoS is large-scale system that contains many heterogeneous entities and often suffers from dimensional complexity where optimizing the performance of one entity may be possible but the feedback and connections between entities results in a computationally infeasible problem [27].

The air transportation system is well suited for this SoS definition. It is recognized that, as with most SoS, no high-level system designer or central planner exists in the air transportation domain. However, it is expected that as pressure to improve fuel-efficiency is increased, entities will seek out cost effective solutions that may involve coordination across multiple system boundaries.

This research seeks to quantify the impact of the non-optimal emergent behaviors of the current air transportation system and the potential benefits that can be realized by improved coordination and optimization across system boundaries.

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1.3 Organization of the Thesis

This research seeks to quantify the impact of the non-optimal emergent behaviors of the current air transportation system and the potential benefits that can be realized by improved coordination and optimization across system boundaries.

The research will focus on improvements that can be made assuming "fixed" technology, i.e., system or aircraft level changes that could be implemented without the requirement to develop new technologies that do not yet exist. These changes are particularly interesting because, given existing market pressure to improve aircraft fuel efficiency, manufacturers will tend to optimize technology for a given design choice; however, the design choice itself is not necessarily optimal from an overall air transportation system fuel consumption standpoint. Also, any potential benefits can potentially be implemented without developing technologies that do not yet exist. To perform this analysis, a novel and computationally efficient method will be developed to deal with increased problem complexity and will be used to calculate the maximum pool of benefits due to multi-disciplinary optimization.

The general approach to the research and the resulting thesis organization is presented in Figure 4 and explained briefly below.

Figure 4: Research Method and Thesis Organization
Chapter 2: Opportunities to improve system fuel efficiency will be developed from first principles. The importance of the Design Reference Mission (DRM) will be established. A review of relevant literature will be presented, and the opportunities to expand and improve on the body of knowledge will be discussed.

Chapter 3: The analysis approach will be explained in detail, including descriptions of the scenarios to be evaluated.

Chapter 4: Real world global operations will be examined to establish a baseline and identify opportunity areas. A model will also be created to fly existing or new aircraft through the current network or in a modified network.

Chapter 5: A wide range aircraft with similar technology and alternative DRMs will be designed and optimized. The resulting large dataset of on-design and off-design performance for mission fuel and mission time will be used as the basis for a more computationally efficient model of aircraft performance.

Chapter 6: The large amount of data generated from the aircraft design process will be synthesized into a comprehensive model of aircraft performance using a machine-learning algorithm. The resulting artificial neural network will capture the physics inherent to the aircraft design process while being computationally efficient enough to resolve the performance of a global transportation network in a reasonable time.

Chapter 7: A few scenarios uniquely enabled by the new aircraft performance model will be evaluated. Analysis will be focused on two major areas: first, the maximum potential system fuel improvements from operating differently or designing new aircraft will be computed in order to bound the benefits space, and second, industry constraints will be introduced to evaluate the potential realistic benefits from changing DRM.

Chapter 8: Results will be discussed, and a few recommendations leading from these results will be presented.
Chapter 2

BACKGROUND AND LITERATURE REVIEW

The increase in effective cost of fuel due to environmental policies and rising crude oil prices, in combination with growing demand is placing increased pressure on the air transportation industry to improve fuel efficiency. In this chapter, opportunities to improve system fuel efficiency will be developed from first principles. A review of relevant literature will be presented, and the opportunities to expand and improve on current research will be presented.

2.1 Measurement of Air Transportation Efficiency

In general, transportation system productivity, regardless of mode, is derived from moving people or cargo between locations at the cost of the energy consumed during transportation. Thus, transportation efficiency, in the form of output divided by input, can be described as the amount of productivity produced from the consumption of one unit of energy, as in Equation (1).

\[ \eta_{\text{transport}} = \frac{\text{productivity}}{\text{energy}} \]  

(1)

Defining productivity for transportation is difficult and depends on the purpose and scope of use of the resulting measurement [28]. For example, the US Corporate Average Fuel Economy (CAFE) regulates the fleet-wide, sales-weighted average fuel economy of new automobiles sold in the United States using an efficiency metric of Miles Per Gallon (mpg). The purpose of the regulation is to reduce negative externalities related to automobile use without instituting politically untenable Pigovian taxes such as a gasoline tax [29]. In order to derive a measure that is relevant to consumers and thus increases the market pressure to improve fuel efficiency, the simple metric is evaluated over a carefully designed duty-cycle that is intended to mimic typical driving behaviors in the US.
The International Civil Aviation Organization (ICAO) is executing a similar effort to establish a vehicle-level fuel efficiency standard for the air transportation industry [30]. The fuel efficiency metric Specific Air Range (SAR) is essentially aircraft miles per gallon, as in the CAFE standard. However, the ICAO aircraft standard differs from the CAFE standard in that the purpose is to measure and regulate the technology on the aircraft regardless of how it is used during typical operations. Because of this difference, it is not necessary for SAR to be measured on a complex duty-cycle that mimics typical operator behaviors [31]. Instead SAR is evaluated at a few instantaneous weight points and averaged together to arrive at a vehicle level metric value. Thus, an aircraft of a similar size and technology will have similar metric values, regardless of how they are eventually operated in the air transportation network.

While the ICAO metric is appropriate for fuel efficiency standards intending the regulate the technology of the aircraft regardless of the way it is operated, it is not be convenient for an evaluation of the impacts in system efficiency resulting from changes in high-level design parameters and typical operations. Therefore, it was necessary to seek out a more appropriate measure of efficiency.

Hileman[32] evaluated potential efficiency metrics for air transportation and found that Payload Fuel Energy Efficiency (PFEE) was an appropriate measure of fleet and aircraft fuel efficiency given the way aircraft are typically operated. PFEE is defined as the total payload carried, multiplied by the mission length, and divided by the fuel energy consumed in order to perform the mission, as in Equation (2). PFEE is able to capture the productivity due to moving passengers, as well as the productivity due to moving cargo as belly freight or in freighter aircraft. Hileman finds that this is especially important from a fleet analysis perspective, as cargo represents roughly 1/3 of revenue payload distance carried by U.S. airlines with 1/5 being carried as belly freight on passenger flights.

As efficiency improves, e.g. carrying more passengers or flying a further distance while using the same fuel energy, or alternatively, carrying the same passengers over the same distance while using less fuel energy, PFEE should increase. It should be noted that PFEE is typically stated in terms of fuel energy as opposed to fuel mass, as this allows for the comparison of alternative fuels to the kerosene based fuels widely used today. In this research PFEE is also used to describe the efficiency metric when fuel energy is converted to fuel mass, assuming a standard fuel specific energy. The reciprocal of PFEE, Payload Fuel Energy Intensity (PFEI), as in (2), is also used where convenient.
Both PFEE and PFEI can refer to aircraft-level or system-level efficiency. Aircraft-level efficiency is the efficiency of the aircraft on a specific payload-range mission, whereas system-level efficiency is aggregated payload, range, and energy.

### 2.2 Opportunities to Improve System Fuel Efficiency

From first principles, total air transportation system fuel efficiency is a function of three high-level parameters, as in Equation (3). The product of these parameters is summed over system output to arrive at system PFEI in kilograms of fuel per kilogram-kilometer of productivity. Influencing system fuel consumption requires influencing one or more of these high-level parameters.

\[
\frac{\text{fuel}_{\text{system}}}{\text{output}_{\text{system}}} = \sum_{\text{output}} \left( \frac{W_{\text{fuel}}}{\text{energy}} \cdot \frac{1}{\eta_{\text{LF}}\eta_{\text{ATC}}\eta_{\text{airline}}} \cdot \frac{\text{energy}}{\text{output}} \right)
\]

The first term, fuel weight divided by unit energy, is the inverse of the specific energy of the fuel used during operations. A fuel with a higher specific energy would result in improved system efficiency. Since the amount of CO\textsubscript{2} emitted scales directly with the mass of fuel consumed, a fuel with a higher specific energy would also result in a decrease in GHG emissions.

The second term consists of airline business constraints and operational efficiencies. These operational factors are composed of (1) a generic load factor measure, (2) inefficiency of the air traffic control system, and (3) inefficiency of the airline operations and network topology.

The third term, energy divided by output, is the aircraft-level PFEI as defined above. The energy required to produce this output can be estimated using the Breguet Range Equation, as in (4).
\[ R = \frac{V}{g} \frac{1}{SFC} L \ln \left( \frac{W_{\text{initial}}}{W_{\text{final}}} \right) \]  

(4)

Where,

\[ W_{\text{initial}} = W_{\text{empty}} + W_{\text{payload}} + W_{\text{reserve}} + W_{\text{fuel}} \]

\[ W_{\text{final}} = W_{\text{empty}} + W_{\text{payload}} + W_{\text{reserve}} \]  

(5)

The Breguet Range Equation, Equation (4), is a fundamental relationship that defines the range an aircraft can cruise given aerodynamic, propulsive, and structural efficiencies on a constant velocity, cruise-climb mission. For simplicity, crew weight and reserves can be considered as part of empty weight for the remainder of the derivation. Thus, Equation (4) can be rearranged into energy/output by first combining Equation (4) and Equation (5),

\[ R = \frac{V}{g} \frac{1}{SFC} L \ln \left( \frac{W_{\text{empty}} + W_{\text{payload}} + W_{\text{fuel}}}{W_{\text{empty}} + W_{\text{payload}}} \right) \]  

(6)

and then, assuming all of the technology parameters are combined in the variable,

\[ X = \frac{L}{D} \eta_p \frac{\Delta h_{\text{fuel}}}{g} = \frac{V}{g} \frac{1}{SFC} L \]  

(7)

finally yields,

\[ \frac{\text{energy}}{\text{output}} = PFEI_{\text{aircraft}} = \left( 1 + \frac{W_{\text{empty}}}{W_{\text{payload}}} \right) \left( \frac{1}{R} \right) \left( e^{R/X} - 1 \right) \]  

(8)

Thus, the third aspect of system level fuel efficiency, i.e. aircraft-level PFEI as in Equation (8), is itself a function of five major factors: (1) aerodynamic efficiency, \( L/D \); (2) overall propulsive efficiency, \( \eta_p \); (3) structural efficiency, \( W_e/W_p \); (4) fuel heat of combustion, \( \Delta h_{\text{fuel}} \); and (5) range, \( R \).
In summary, the levers\(^1\) to improve system-level fuel efficiency are:

1. **Alternative Fuels**, by increasing specific energy content
2. **Operations**
   - Load Factor inefficiencies, by increasing load factor
   - Air Traffic Control inefficiencies, by allowing optimal speeds, altitudes, and flight profiles
   - Airline inefficiencies, by improving fleet mix and network topology
3. **Technology**
   - Aerodynamic efficiency, by increasing L/D
   - Propulsive efficiency, by reducing SFC
   - Structural efficiency, by reducing empty weight per passenger
4. **Range**, by designing for optimal range or operating closer to optimal range

It is of great interest to this research to consider the trend of improvements in system-level fuel efficiency due to improvements in each of these levers. It can be seen from Equation (3) and (8) that, all else equal, improving many of the major levers identified above will always yield monotonically increasing system-fuel efficiency due to fundamental physics. Specifically and all else equal, improving fuel energy content, increasing load factor, flying optimal flight profiles, improving technology, \(X\), or improving structural efficiency, \(W_{\text{empty}}/W_{\text{payload}}\), yields monotonically increasing system-fuel efficiency. However, interestingly system-fuel efficiency is convex in the range dimension, as in Equation (9):

\[
PFEI_{\text{system}} \propto PFEI_{\text{aircraft}} \propto \frac{e^R}{R}
\]

The fact that efficiency is convex for positive values of range implies not only that there is some tradeoff between range and efficiency, but also that a theoretical optimum range exists. This tradeoff will be explored in the next section.

\(^1\) It should be noted that Kar [11] performed a similar first-principles analysis for CO\(_2\) emissions, but assumed improvements in CO\(_2\) emissions from the range variable are due only to reducing mission distance and did not explore the convex behavior between efficiency and range or the implications leading from this.
2.3 The Fundamental Tradeoff between Range Flexibility and Efficiency

Flexibility is considered to be an attribute of an aircraft that increases with increasing capability, such as range. An aircraft designed for long range can be operated over a wider range of missions and is thus more flexible in real-world operations when compared with shorter-range aircraft. However, flexibility is often obtained at the cost of decreased fuel efficiency. To understand this tradeoff, first consider the range dimension.

J.E. Green [33], [34] investigated the relationship between design range and fuel efficiency by transforming the Breguet Range Equation into PFEI, as in Equation (8). Because the Breguet Range Equation assumes cruise-climb range, Green used energy balance to derive a climb fuel augmentation due to the additional energy required to takeoff and arrive at cruise altitude, as indicated by the 1.022 multiplier in Equation (10).

\[
\frac{\text{energy}}{\text{output}} = PFEI_{\text{aircraft}} = \left(1 + \frac{W_{\text{empty}}}{W_{\text{payload}}}ight)\left(\frac{1}{R}\right)\left(1.022e^{R/X} - 1\right)
\]  

(10)

If it is assumed that, to first order, the propulsive, aerodynamic, and structural efficiencies are fixed and that the same fuel will be used, the technology variable, X, becomes a constant. Thus, PFEI becomes only a function of range. Creemers et al. [35] further extended this analysis by augmenting Equation (10) to include taxi and reserve fuel. The result of this analysis is shown in Figure 5.

Green's design range study (and Creemers' augmentations) clearly show two fundamental and unavoidable effects resulting from the choice of design range. First, peak efficiency, as seen in Figure 5, is strongly a function of design range, with a maximum at approximately 3,000-4,000km. Second, aircraft with long design range sacrifice peak efficiency for a more flexible operating envelope. For example, consider the long-range aircraft in Figure 5 with a Design Reference Mission (DRM) range of 14,000km (denoted by DRM-2). This aircraft can fly all of the missions that the shorter range, DRM-1, aircraft can fly, but it operates many of those missions at a decreased efficiency, as indicated on the bottom of Figure 5. However, DRM-2 has a noticeably wider operating envelope, as noted by the difference in maximum operating range. Any mission operated by the DRM-2 aircraft in the regime where the DRM-1 aircraft is more efficient will be done so at the cost of increased fuel burn.
Indeed, many of the missions seen in service are at these low mission ranges where a shorter DRM would lead to fuel burn savings. Previous studies have shown that 99% of missions in the US are flown on distances below maximum range at maximum payload [31].

Figure 6 shows the performance (in terms of PFEI) of two real aircraft from Bonnefoy, et al [30]. On the left, the Boeing 737-800 is shown with best efficiency point indicated by the red circle on an R1 mission. Underneath, May 2006 US Air Carrier global operation frequency by mission range is shown. As can be seen, very few missions are flown near the max efficiency point.

Likewise, the Boeing 777-300ER and corresponding operating frequencies are shown on the right. The best fuel performance mission is indicated by the red circle and occurs at maximum payload near 4,000km, instead of on the R1 mission. This is an interesting and unavoidable result of long-range flight: the fuel for the latter parts of the mission must be carried during the early parts of the mission, resulting in a heavier aircraft which in-turn consumes more fuel, and so on. This vicious cycle, or logarithmic fuel carrying means an aircraft will always have it's highest fuel efficiency (in terms of PFEI) on missions close to 4,000km. Note that this trend holds true even when considering only the basic Breguet Range performance for the long-range design in Figure 5.
The 777-300ER has a bimodal operating pattern reflecting both domestic and international network service. As with the 737-800, most flights would benefit from being flown by an aircraft designed with a shorter range. However, due to the fuel-carrying issue, the best fuel efficiency would still occur near 4,000km. One way to improve the fuel consumption of missions longer than this is to consider moving the same people or goods to and from the same locations differently. This could mean stopping in the middle of a flight to refuel the aircraft such that each leg is more closely operated near the maximum efficiency point. This procedure is known throughout the literature as an Intermediate Stop Operation [36].

The fact that aircraft are operated on missions both shorter and longer than their maximum efficiency range (which is approximately fixed around 4,000km due to fundamental physics) motivates investigating both the redesign of aircraft and operating vehicles closer to their peak efficiency.

While this analysis only considers the tradeoff between range capability and efficiency, the tradeoffs between design-payload, -range, -speed and efficiency are coupled through the fundamentals of aircraft design and operations. These tradeoffs will be explored in the next section.
2.4 The Design Reference Mission

The Design Reference Missions (DRM) is the mission, or set of missions, used as the constraining mission or in an optimization objective function by aircraft manufacturers during design of an aircraft. While fuel burn is not the only design consideration, it is typically minimized on this mission subject to other constraints. At a high level the DRM is defined by, the range the aircraft is required to fly, the payload the aircraft is required to carry over this range, and the speed at which the aircraft must carry the design payload over the design range. The DRM essentially captures the fundamental objective of air transportation: transporting people or cargo over some distance at a high rate of speed.

The relationship between these dimensions is complex. While aircraft range might imply the ability to service a particular segment, this might only be physically possible with, for example, a payload that is reduced from the maximum possible payload. And while that payload and range combination might be serviceable for a speed near the aircraft’s fuel-optimal speed, it might not be possible if it is required to fly faster. In practice, the tradeoffs between the three major dimensions are inextricably linked via the aircraft payload/range diagram, a notional example of which is shown in Figure 7.

A mission is defined by a unique combination of payload, range, and speed and feasible missions fall within the boundary of the payload range curve shown in Figure 7. The boundary is defined by the physical structural and volumetric limitations of the aircraft. While speed does not explicitly appear in the payload/range diagram, it is implicitly captured in every mission. For example, if an aircraft were to carry maximum structural payload while filled with fuel to maximum takeoff weight, it could fly further at maximum-range cruise speed than it could otherwise. For this reason, a payload/range diagram is only valid at a particular speed².

² The payload range diagram is also a function of atmospheric conditions; takeoff, climb, cruise, descent, and landing profiles; power extraction and air conditioning bleed; reserve and mission rules; and other higher order effects.
The DRM is closely linked to the strategic decision by an airline to acquire a particular aircraft type, as this process is informed by estimation of future market demand and market share on particular legs of an airline's network operations [37]. First, range determines which segments, defined by origin and destination airports or multi-airport systems, are potentially serviceable by the aircraft. Second, capacity, or payload, determines how much of the segment can potentially be serviced on a single flight. Third, speed determines how quickly a particular segment can be serviced and has implications for passenger utility and network connectivity.

An airline can use candidate aircraft capabilities (defined by payload/range diagrams) in its strategic acquisition process. The goal of this process is to acquire equipment that will enable the construction of a viable transportation network [38]. The highly complex process considers factors such as competitive market effects and network connectivity. Competition might dictate, for example, more frequent operations of a smaller capacity aircraft in a market, even though a larger capacity aircraft could carry the sum total of passengers using less fuel [39]. The result of this practice can be an increased market share and an increase in induced demand, leading to a higher profitability. Likewise network effects might dictate flying a "loss-leader," or a non-profitable or fuel-inefficient route in order to maintain equipment availability on a different, highly profitable market at a particular time. The result of this practice can be a network that seems incongruous at the flight-leg level, but is maximally profitable on a system level [40].

Figure 7: Notional Payload/Range Diagram
Due to the uncertain nature of future market demand forecasts, competitive market environments, exigent circumstances, and operations, aircraft mission flexibility is become a valued attribute by airlines. Additionally, many of the large financial institutions that lease aircraft to operators value an asset that is diverse enough to be leased again if the original leasing contact ends [41]. In terms of a financial asset, a more flexible aircraft might have a lower return, but it can also have less financial risk.

A manufacturer must balance the competing market demands for a fuel efficient aircraft that will yield low variable operating costs with a market desire for a flexible asset that can be used by many different operators on markets all over the world for a period of time measured in decades [27], [38]. Due to these competing objectives and to the high capital costs and long time scales involved in a successful commercial aircraft-manufacturing program, the resulting aircraft are designed with significant operational flexibility.

2.5 Decomposition of Contributors to System Fuel Consumption

Given the previously described five major levers to improve system fuel efficiency and the rational tradeoffs made in the real air transportation industry between DRM flexibility and efficiency, the contributors to system fuel consumption can be described notionally as in Figure 8. This notional description assumes the serviced demand between all origins and destinations is fixed, i.e., that the same people and goods are transported between the same cities.

- **Technology Lag:** The current worldwide aircraft fleet consists of hundreds of aircraft types designed throughout many decades with varying levels of technology [38]. These aircraft types are continuously retired and replaced based on market forces and cost-benefit analyses by airlines. This lag in average fleet technology contributes to system fuel consumption.

- **Non-Optimal Sizing and Allocation:** There are a finite number of available aircraft types for an operator to utilize on a market of interest. In some cases, the ideal aircraft, in terms of DRM, for a given market may not exist, or conversely, an operator might be forced to utilize an aircraft type on a non-ideal market due to network or competitive considerations. The potentially non-optimal allocation of existing aircraft types into a network, and the choice of DRM of the aircraft types available to operators both contribute to system fuel consumption.
• **Non-Optimal Operations**: Aircraft operated in a real air traffic system are required to follow regulations that improve the safety of the system but might result in non-fuel-optimal flight operations. Additionally, market considerations, such as the value of time versus the value of fuel, might dictate flying the aircraft faster than optimal cruise speed. These effects contribute to system fuel consumption.

• **Non-Optimal Network Topology**: The demand between origin and destination can either be served directly or by routing passengers via onward connecting hubs. The choice of passenger routing can be subject to competitive and market constraints, and thus may be non-optimal. This effect contributes to system fuel consumption.

• **Energy Required for Air Transportation**: Lastly, assuming all of the aforementioned effects are accounted for, there is some unavoidable energy required to transport people and cargo between distant locations through the air at high speeds for a fixed level of technology. This energy can only be affected or reduced through the use of improved technologies or alternative fuels.

This decomposition represents the available pool of benefits to be affected by policies or changes in behavior in each of the areas. Also, because air transportation is a system-of-systems, there are additional benefits to be had from optimizing across multiple categories, such as coupling between sizing and allocation and network topology.

In this sense, DRM is particularly interesting because, given existing market pressure to improve aircraft fuel efficiency, manufacturers will tend to optimize technology for a given design choice; however, the choice itself is not necessarily optimal from an air transportation system fuel consumption standpoint.
2.6 System Analysis of the Major Contributors to Air Transportation Fuel Consumption

Multiple recent studies have attempted to quantify the potential pool of benefits for each of the contributors to system fuel consumption identified in the previous section.

Lovegren [42] and Jensen [43] have evaluated the pool of benefits available due to non-optimal flight operations. They have found that approximately 4% of US system fuel consumption is due to non-optimal operations in terms of cruise speed and cruise altitude.

Azzam [44] evaluated the fuel efficiency of the US air transportation network structure. It was determined that the 2007 US air transportation network exhibits a topology that is close to optimum, and that further topological improvements would only yield a reduction in fuel burn of approximately 1%. However, using a simple regression model to relate aircraft size and performance, Azzam found that changes in aircraft assignment and alternative airline routing strategies could provide 8-10% in system fuel reduction.

Multiple studies have reported potential system-wide benefits due to changing future aircraft capability or operating aircraft closer to peak efficiency. Green [33], [34] determined the fundamental tradeoff between flexibility and efficiency using the Brequet equation. He also evaluated the impact of operating aircraft closer to their design range, and found that an aircraft with a 5,000km design range could save approximately 50% of the fuel required to fly a 15,000km mission if it stopped along the way versus an aircraft designed to fly 15,000km direct. He also indicated that, “the impact on climate of aircraft design parameters such as range, cruise Mach number... needs further study.”

Creemers [35] takes a similar approach to Green and finds that operating a long-range aircraft with fuel stops can save between 5-15% of fuel on a long-haul mission, but that a combination of a shorter design range fuel stops can improve fuel burn on some missions up to 27%.

More recently, Mane et. al. [45] noted the gap between maximum capability and serviced missions, then designed a short-haul, high capacity aircraft to take advantage of more closely matching design and operations.

In addition to fuel savings from redesigning for payload and range, a NASA N+3 study [46] also found significant fuel reduction was possible by designing aircraft with reduced Mach numbers, as this allowed for structural weight savings by reducing wing sweep.
A few studies [27], [47], [48] have attempted to solve the joint aircraft-design and network optimization problem, however they have been limited to extremely small networks for computational tractability, limited the potential design solutions, and gave no indication of the shape of the solution space.

While these studies provide excellent insight into the direction of improvement for both design-range and -speed, none provide a study of the full design-range, -payload, and -speed space including both conventional and non-conventional designs. Furthermore, none of the studies have analyzed this problem on a global scale.

### 2.7 Summary

From first principles, there are four potential levers to improve system fuel efficiency:

- Alternative Fuels
- Operations
- Technology
- Design Reference Mission

Also from first principles, there is a tradeoff between DRM, operations, and fuel efficiency. Given real-world constraints, this tradeoff can contribute significantly to system fuel consumption.

System fuel can be decomposed into a few high-level components, and these components represent the available pools of benefits to be affected by policies or changes in behavior. Many researchers have attempted to quantify these pools, with more recent studies focusing on the impact of DRM and operating missions closer to the optimum performance point of the aircraft. In particular, studies have attempted to quantify the impact of the choice of DRM on fuel consumption and the potential benefits of designing aircraft that are more suited to a particular network, but these studies are severely limited in scope due to computational constraints. A more robust and computationally efficient method is required to determine the bounds of the savings potential from each of the categories.
Chapter 3

APPROACH

3.1 Objective

The objective of this research is to quantify the impact of the non-optimal emergent behaviors of the current global air transportation system and the potential benefits that can be realized by improved coordination and optimization across system boundaries.

The research presented in this thesis will focus on improvements that can be made assuming "fixed" technology, i.e., system or aircraft level changes that could be implemented without the requirement to develop new technologies that do not yet exist. These changes are particularly interesting from a system standpoint because, given existing market pressure to improve aircraft fuel efficiency, manufacturers will tend to optimize technology for a given design choice; however, the choice itself is not necessarily optimal from an air transpiration system fuel consumption standpoint.

To accomplish this goal, a novel and computationally efficient method will be developed to deal with the increased problem complexity and will be used to calculate the maximum pool of benefits due to multi-disciplinary optimization. Aircraft with an extremely broad combination of design-Mach, -payload, and -range will be designed, and the system-wide fuel benefits of selecting various aircraft for entry into real world network service will be quantified.

3.2 Challenges

Existing Aircraft Performance and Baseline Development

Because air transportation is a global industry and the effects of climate change are global in nature, the objective of the analysis is to determine the benefits of changes in behavior on a global scale. In order to do accomplish this, a baseline must be established. A global fuel burn and detailed aircraft-type database does not exist. Instead, a global operations
database created from multiple sources must be matched with a performance tool for existing aircraft and a model must be created to virtually fly the global network and establish the performance and operations baseline. Such a performance tool does not exist in a way that would enable this calculation, so one must be created.

**Designing Future Aircraft and Robust Aircraft Design**

In order to complete the system level analysis, the performance of aircraft types with fixed technology and varying DRM must be calculated. However, the limits of the design reference mission space for a constant level of technology are not known a priori. Thus, a potentially large number of aircraft designs must be created in order to determine the edges of the feasible design space and performance within the space. Further, for each feasible aircraft in the DRM space, the mission performance, i.e., the performance of the aircraft on any mission in the unique, aircraft-specific payload/range diagram is not known a priori. Thus, a similarly large number of missions must be simulated for each feasible aircraft to determine the edges of the payload/range diagram and the performance on feasible missions. These unavoidable issues makes it impossible to use aircraft design tools based heavily on empirical correlations, as a large number of unconventional designs will be designed, and the designs that violate physics should be noted.

**Computational Efficiency**

A global network analysis requires the simulation of millions of flight legs every time the performance of the system must be computed. Additionally, given the objective of this research, it is likely that this process will be repeated thousands or even millions of times as part of a system optimization tool. Other studies have attempted to deal with this problem by greatly simplifying the potential aircraft solution set by pre-designing a handful of potential aircraft, reducing the scope to extremely local or hypothetical networks, or by greatly simplifying the design process itself. This research will seek to maintain a high level of aircraft design and performance fidelity while analyzing the full global network. This will require the creation of a computationally efficient comprehensive model of aircraft performance.

### 3.3 Method

This general approach is described in Figure 9 and will be described in detail below. First, a baseline set of global operations will be established and the performance of existing aircraft on these missions will be computed. Next, a series of aircraft with a fixed level of technology and varying design reference mission will be developed. The data resulting from the design
of these aircraft will be used to create a comprehensive model of aircraft performance using a machine-learning algorithm. The result of this process will be a computationally efficient model that can be used to quantify the impact of the non-optimal emergent behaviors of the current global air transportation system and the potential benefits that can be realized by improved coordination and optimization across system boundaries.

### 3.3.1 Baseline Development

A global operations database will be used to establish the baseline set of operations in terms of passengers, cargo, flight distances, etc. In order to calculate fuel burn for the baseline missions, an existing-aircraft performance model will be created. A performance simulator will be automated to virtually fly an extensive range of missions for each aircraft type, and then the resulting data will be used as the basis for the existing aircraft performance model. This performance model will then be to fly the baseline aircraft through the baseline mission using the network model. The result of this process will be a full description of the baseline, including passengers transported on each mission, range, cargo, fuel burn, flight time, load factors, etc.
3.3.2 Design of Aircraft with Alternative Design Reference Missions

A large set of diverse vehicles will be designed at a fixed technology level and for varying DRMs. The design will be performed with a first-principles, fundamental physics based aircraft performance tool to ensure feasibility and consistency with physics for unconventional aircraft types. The vehicles will be optimized for minimum fuel burn on the DRM, and will thus represent the fuel optimal aircraft designs given the prescribed technology. Each of the feasible aircraft designs will also be flown on a series of missions to establish the performance on, and limits of, the payload/range diagram.

3.3.3 Development of an Aircraft Performance Model for Fast-Time Simulation

Searching between discrete aircraft is not computationally feasible for determining globally optimum system performance in a large network. The aircraft design process can generate hundreds of gigabytes of data; it is a necessity to synthesize this data into an efficient model of aircraft performance so that a global analysis can be performed. A machine-learning algorithm will be used to learn the relationship between the performance (in terms of mission fuel or mission time) of an aircraft on a mission and that aircraft’s DRM, as in Figure 10.

![Figure 10: Purpose of the Comprehensive Model of Aircraft Performance](image)

The model represents the fuel-optimal aircraft for any DRM designed at equivalent levels of technology. It is capable of flying aircraft on feasible off-design missions to determine mission fuel burn and flight time. An important aspect of this technique is that, by virtue of the chosen machine learning technique, the resulting comprehensive model of aircraft performance is continuous. That is, a specific aircraft/mission combination does not have to be designed/flown in the previous section in order to determine the mission fuel burn or time, as the comprehensive model captures the underlying physics-based relationship between the five input variables and the output variable. The resulting model will also be fast enough to meet the demands of resolving global transportation system performance in a reasonable time.
3.3.4 Scenario Evaluation

Scenarios are generated to perform two major analyses: (1) to establish the limits of the major contributors to system fuel consumption and (2) to determine realistic benefits from changing aircraft DRM.

Establishing Limits of Major Contributors to System Fuel

The major contributors to system fuel consumption for a fixed passenger and cargo network were determined from first principles in Section 2.5. The approximate limits of two of these factors were determined from literature review. Specifically, non-optimal speed and altitude operations were expected to contribute approximately 4% to system fuel consumption, and non-optimal network topologies are expected to contribute another 1% to system fuel consumption, as in Figure 11.

The capabilities developed in this thesis will be leveraged in order to determine the approximate effect of technology lag in the fleet and the effects of non-optimal aircraft sizing and allocation.

- **Technology Lag: Fleet Modernization.** The current worldwide aircraft fleet consists of hundreds of aircraft types designed throughout many decades with varying levels of technology. These aircraft types are continuously retired and replaced based on market forces and cost-benefit analyses by airlines. In this scenario, the amount of global system fuel consumption due to the technological lag of the fleet will be quantified.

- **Non-Optimal Sizing and Allocation: Optimally Matching Aircraft Size to Demand.** There are a finite number of available aircraft types for an operator to utilize on a market of interest. The available types are created through an iterative
process between manufacturers and customers, and are influenced by the actions of competitors. In some cases, the ideal aircraft for a given market may not exist, or conversely, an operator might be forced to utilize an aircraft type on a non-ideal market due to network or competitive considerations. In this scenario, the amount of global system fuel consumption due to the chosen allocation of resources will be quantified.

**Determining Realistic Benefits from Changing DRM**

In the previous scenarios, the maximum limits of improvements due to system inefficiencies will be determined by ignoring some fundamental industry constraints. For example, the maximum benefits due to right sizing and proper allocation of aircraft to meet demand will assume an infinite number of aircraft types available to operators on a mission-by-mission basis. In reality, the huge capital constraints and long development and certification time frames required to produce a commercial aircraft mean that only a few can be produced by all global manufacturers over a period measured in decades. For this reason, a series of optimization scenarios are formulated to determine the optimum aircraft selection in terms of DRM.

- **Serial Optimal Aircraft Selection at Fixed Cruise Speed:** In the real market an aircraft manufacturer can only create a small amount of aircraft due to the capital costs and time scales inherent to aircraft programs. In this scenario the question: "which new aircraft would have the most impact on global system fuel burn?" will be answered for a single cruise speed. Results will indicate which aircraft classes, e.g., medium-range narrow body, long-range wide body, etc., would yield the largest impact on fuel consumption, and therefore might indicate which aircraft types should be considered for future production.

- **Impact of Design Cruise Speed Reduction.** The optimal aircraft selection will be repeated for various cruise speeds to determine the impact of design cruise Mach number on the resulting aircraft selections. Changes in flight time will be evaluated to quantify the resulting impact to passengers and operators.

- **Impact of Capacity Restrictions on Optimal Aircraft Choice:** In previous analyses the number of passengers on a flight leg was held constant, and the resulting aircraft was flown if it improved fuel consumption, regardless of the load factor. In reality, operators will attempt maintain high passenger load factors and utilization. Operators have some flexibility in the number of passengers on a flight leg via
pricing and spill controls. The effect of this operator practice on the resulting optimum aircraft and system fuel consumption will be analyses by performing a parametric study of passenger flexibility.

- **Serial Optimal Aircraft Selection at Variable Cruise Speed:** In previous scenarios, the question: “which aircraft would have the most impact on global system fuel burn?” were solved using a prescribed cruise speed. In this scenario, the three-dimensional (design-payload, -range, and -speed) will be solved using a global search optimization algorithm. The resulting aircraft indicate the globally optimum aircraft Design Reference Missions for potential future aircraft. The impact on regions, countries, airports, and aircraft replacement due to flying these new aircraft in the air transportation system will be presented.

- **Benefits of Fuel Stops on Long-Range Missions:** From first principles, the optimum range-efficiency point for any aircraft is located near approximately 4,000km. Because of this characteristic, one approach presented in literature to save fuel burn is to stop part way along long-range missions to refuel. This allows breaking a single, inefficient long-range mission into multiple more efficient short-range missions. The benefits of this procedure will be evaluated for the existing fleet on a global scale.

- **Joint Optimization of Aircraft Selection and Fuel Stops on Long-Range Missions:** In all previous analyses, the network was fixed such that the same passengers and cargo are always transported between the same origins and destinations. In this scenario, optimal aircraft are selected as before, except intermediate fuel stops are also permitted. This allows for evaluating the potential costs or benefits of the real-options trade between aircraft flexibility and efficiency.

The results of this research are expected to inform stakeholders across the air-transportation industry, including manufacturers, airlines, and governments with respect to policies and research investments. The models created to enable this research are expected to be extremely useful for future research studies that require either quickly resolving the performance characteristics of a large-scale network or designing many airplanes in a short period of time. This method will be shown to generalize well, and can easily be adapted to include other relevant parameters (e.g. operational cruise speed, technology parameters, etc.)
Chapter 4

TRENDS IN COMMERCIAL AIRCRAFT OPERATIONS

Historical operations data is used to establish a system baseline. This baseline consists of network definition, flight level fuel burn, frequency statistics, and operations relative to existing aircraft design reference mission. The baseline operations are derived from the Common Operations Database, a list of global flights from April 2006. Aircraft performance on these flights is obtained by using a lookup table extracted from a commercially available performance tool.

4.1 Data Sources and Assumptions

4.1.1 OPERATIONS: COMMON OPERATIONS DATABASE

The Common Operations Database (COD) is a global flight-by-flight operational database. The COD is constructed from Eurocontrol’s (EC) Enhanced Traffic Flight Management System (ETFMS), FAA’s Enhanced Traffic Management System (ETMS), and International Official Airline Guide (IOAG) data. ETFMS and ETMS account for up to ~75% of global commercial operations, while ETMS alone covers ~55%, and the remainder of worldwide operations are covered by IOAG year 2006 schedule [49]. The COD is particularly useful as it contains data payload data, which is not typically reported or included in operational databases.

Each line in the database represents a single aircraft flight and contains the following information:

- Flight Month,
- Flight Day
- Departure Airport Code
- Arrival Airport Code
- Departure Country Code
- Arrival Country Code
Payload is not directly reported on a flight-by-flight basis; therefore, assumptions were used to generate payload in the COD (Table 1). Equations (11) and (12) describe the assumptions used to populate the COD payload data. Passenger payload is computed by multiplying the passenger payload factor by the median number of seats for a given aircraft and the average passenger weight. Cargo payload is computed by multiplying the cargo load factor by the available cargo capacity. Specifically, I or D specifies international or domestic; \( W_p \) is the average passenger weight (91kg); PLF is the passenger load factor; CLF(BEL) is the cargo load factor on passenger flights; and CLF(FRT) is the cargo load factor on freight flights.

\[
P(pax)_{I,D} = PLF_{I,D} \times Seats_{median} \times W_p \times CLF_{BEL:I,D} \times (MSP_{median} - Seats_{median} \times W_p)
\]

\[
P(cargo)_{I,D} = CLF_{I,D} \times MSP_{median}
\]

For a specific aircraft type, \( W_p \), median seats, and median max structural payload are constant.

**Table 1: April 2006 Common Operations Database Load Factors [%]**

<table>
<thead>
<tr>
<th>Region</th>
<th>PLF</th>
<th>PLF</th>
<th>CLF</th>
<th>CLF</th>
<th>CLF</th>
<th>CLF</th>
<th>CLF</th>
<th>CLF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>D</td>
<td>TOT-I</td>
<td>TOT-D</td>
<td>FRT-I</td>
<td>FRT-D</td>
<td>BEL-I</td>
<td>BEL-D</td>
</tr>
<tr>
<td>Asia/Pacific</td>
<td>73.4</td>
<td>72.3</td>
<td>54.5</td>
<td>33.1</td>
<td>66.4</td>
<td>53.8</td>
<td>49.5</td>
<td>33.1</td>
</tr>
<tr>
<td>Europe</td>
<td>77.3</td>
<td>66.9</td>
<td>54.7</td>
<td>29.8</td>
<td>68.5</td>
<td>39.6</td>
<td>47.5</td>
<td>29.1</td>
</tr>
<tr>
<td>North America</td>
<td>80.2</td>
<td>79.3</td>
<td>45.0</td>
<td>29.5</td>
<td>63.9</td>
<td>60.9</td>
<td>31.7</td>
<td>8.4</td>
</tr>
<tr>
<td>Latin America/Caribbean</td>
<td>71.0</td>
<td>65.8</td>
<td>40.8</td>
<td>22.5</td>
<td>66.6</td>
<td>64.6</td>
<td>26.6</td>
<td>17.3</td>
</tr>
<tr>
<td>Africa</td>
<td>65.4</td>
<td>74.8</td>
<td>36.1</td>
<td>29.2</td>
<td>49.8</td>
<td>66.4</td>
<td>35.4</td>
<td>22.7</td>
</tr>
<tr>
<td>Middle East</td>
<td>73.6</td>
<td>74.7</td>
<td>44.7</td>
<td>12.7</td>
<td>56.5</td>
<td>24.1</td>
<td>39.5</td>
<td>12.0</td>
</tr>
</tbody>
</table>
4.1.2 **Performance: Piano-5**

Piano-5 is an integrated tool for analyzing and comparing existing or projected commercial aircraft. It consists of a 389 aircraft database, a flight simulation module, and an aircraft redesign tool. Piano's aircraft database contains existing types as well as projected aircraft developments, and these models are constructed independently on the basis of generally available, non-confidential information and descriptions.

Piano does not support batch operations of the type that would be required to resolve the entire global network of air transportation flights. Instead, a multi-dimensional lookup table is created from the Piano data, and this lookup table is then used to compute performance of the baseline network.

Because the operational database does not contain detailed route data such as flight specific speed and altitude profiles, the baseline performance calculation will assume generic parameters as follows:

**Cruise Speed – Maximum Range Cruise (MRC) speed.** For a given weight, altitude, and atmospheric condition, MRC is the speed that will provide the furthest distance traveled for a given amount of fuel burned and the minimum fuel burned for a given cruise distance [50]. This is also the speed at which Specific Air Range, a common measure of cruise fuel efficiency, is maximized, i.e. 100% SAR. Aircraft are capable of flying faster than MRC, and do so commonly, but flying faster than MRC comes at the cost of increased fuel burn. For example, most jet aircraft offer a 3-5% increase in cruise speed over MRC for a 1% penalty on Specific Air Range, i.e. Long Range Cruise (LRC) speed. During typical operations, cruise speed is determined on a flight-by-flight basis by operators. Airlines weigh their time related costs against the fuel costs on a particular flight leg using a Cost Index, as in Equation (13).

\[
CI = \frac{C_{\text{time}}}{C_{\text{fuel}}}
\]  

(13)

The Cost Index is operator-specific and varies with over time. Because the cost index for each operator-flight-time pair is not known, it is assumed that each flight is operated at MRC. This assumption amounts to a conservative, best-case scenario of fuel burn on the

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3 Dimitri Simos, http://www.piano.aero/
flight due to cruise speed. The impact of this assumption on system fuel consumption is a savings of approximately 2%, per Lovegren [42] and Jensen [43].

**Cruise Altitude – Step Climb.** As a flight progresses and an aircraft becomes lighter due to fuel consumption, the fuel optimal altitude increases. This is a continuous process, i.e., the aircraft loses weight at an approximately constant rate, and thus the cruise altitude should increase at an approximately constant rate. This procedure is known as “cruise climbing,” and is the fuel optimal cruise altitude profile any given flight leg. In typical operations this practice is not possible due to air traffic limitations. The common procedure, instead, is to approximate the smooth cruise-climb profile by step climbing throughout the cruise phase. It is assumed that the each flight is operated with using a step-climb profile, with available flight levels from FL110 to FL530 in increments of 2,000 feet. Current research [43] indicates that operators do not typically fly near-optimal step climb profiles for a variety of reasons, and as a result this assumption amounts to a conservative, near best-case scenario of fuel burn on the flight due to cruise altitude.

**Atmospheric Conditions – International Standard Atmosphere (ISA), no wind.** ISA conditions will be assumed in order to calculate the temperature and pressure at altitude during a flight. Additionally, the flights will be simulated with no wind or other weather conditions. During typical operations airlines are required to deal with the changing atmosphere and weather conditions. These conditions sometimes force non-optimal cruise altitudes or cruise speeds. As such, this assumption results in a conservative, best-case scenario of fuel burn on the flight due to atmospheric conditions and avoiding weather. However, winds can sometimes be beneficial. Since the analysis will be done on a global basis, it is assumed that the effect from prevailing winds on a global basis over a reasonable timeframe results in a net neutral effect on system fuel burn.

**Reserve Fuel – 5% of Mission Fuel-** Calculation of mission fuel requires the definition of reserves, which typically vary by operator and crew. While reserve fuel is not counted as “fuel burned” during the calculation of block fuel, it is important to include due to the extra weight carried during the mission. Reserve fuel is defined by operational requirements (FAR121 or EU-OPS 1.255) [51] and is mandated to cope with deviations between predicted flight plan and actual flight.

Using these assumptions, the payload/range diagrams for each of the aircraft are extracted from the performance database. Each aircraft is then flown on 2,500 missions equally gridded on their payload/range diagrams. Emissions species and vehicle state variables are returned for each of the mission simulations. The resulting data is arranged into a large structure that forms the backend of a lookup table performance calculator. The
The performance calculator can output any of the variables as indicated in Figure 12 by inputting mission payload and range for a given aircraft type.

4.1.3 **Matching Performance and Operations Database**

In order to calculate fuel burn on each flight segment, the aircraft identifiers in the baseline performance database (Piano-5) must be matched with the aircraft identifiers in the operational database (COD). Each of the aircraft in the COD was matched with the closest existing aircraft in the performance database. A full list of the aircraft matches are listed in Appendix B. The flights operated by aircraft in the COD with no available match were removed from the baseline and consisted mainly of small general aviation flights.

The matching procedure presents an unavoidable issue for modelers using most government provided operational databases. Many aircraft types have different weight variants or options, and these are frequently not indicated in the operational database. For example, all Boeing 737-8 aircraft would be included under the B737-8 indicator, even though multiple weight variants of this aircraft type exist. Those different variants have different capabilities (in the form of viable payload/range missions), and thus while a mission might be possible for one variant, it might not be possible for another. Likewise, an aircraft with an option, such as winglets, will have different fuel burn on a given mission from an aircraft without the option.
In order to test the sensitivity of the performance results due to the effect of matching, a set of light, medium, and heavy, aircraft matches are created for the COD aircraft list. For example, if multiple variants are available for a single aircraft type, then the smallest variant would be matched for the small scenario, and the largest variant would be used for the large scenario. If multiple medium variants exist, the most popular version was chosen from a list of publicly available data. If only one variant exists, that variant is used for all three scenarios. The possible missions and system fuel burn are computed using each of the sets of aircraft matches and the results are presented in Table 2. Fuel for the flyable missions is summed to determine the aggregate system level fuel burn.

Table 2: Sensitivity of Fleet-Level Results to Possible Aircraft Match

<table>
<thead>
<tr>
<th></th>
<th>Original Dataset</th>
<th>Light</th>
<th>Medium</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flights [#]</td>
<td>2,001,932</td>
<td>1,832,834</td>
<td>1,823,269</td>
<td>1,869,680</td>
</tr>
<tr>
<td>Fuel [1e10 kg]</td>
<td>n/a</td>
<td>1.0647</td>
<td>1.1025</td>
<td>1.1308</td>
</tr>
</tbody>
</table>

Approximately 9% of the flights in the database have no available aircraft match. A list of the unmatched aircraft and their operational frequency is available in Figure 13. These flights are mostly general aviation and business jets, and thus are not expected to have a large impact on system fuel burn. Additionally, a histogram of payload operations for the unmatched aircraft is shown in. Assuming 215 pounds per passenger and cargo, it can be seen that nearly all of the operations for the unmatched aircraft occur with less 25 passengers. These aircraft types are generally not considered within the scope of this study.

Assuming the medium scenario as the baseline from which to compare, the light scenario differs by 0.5% of flyable flights and 3.4% of system fuel burn. The heavy scenario differs by 2.5% of flyable flights and 2.6% of system fuel burn. Given these results, system fuel calculations should be understood to contain approximately +/-3% of error due to the imprecise but necessary matching process. The medium scenario is used to match the COD with the performance database for all future calculations, as in Table 19 (Appendix B).
Figure 13: Frequency of Operations for all Unmatched Aircraft Types

Figure 14: Payload Histogram for Unmatched Aircraft
4.2 Baseline Operations

4.2.1 Frequency

In order to determine the aircraft mission performance of the current fleet, the April 2006 worldwide traffic data from the COD is flown using the Piano performance calculator. Frequency can be used as an indicator of the potential disruption to operations given a change in a particular market. The baseline operations are plotted in Figure 15. Each line represents a unique origin and destination market (OD). Darker areas of the network map indicate regions of high market density.

![Figure 15: April 2006 COD Origin and Destination Markets](image)

The departure frequency of flights by region is shown in Figure 16. For the purposes of this study, the terms domestic, international, continental, and intercontinental are defined as follows:

- **Domestic**: A flight that originates and terminates in the same country.
- **International**: A flight that originates and terminates in different countries located within the same region.

*Country and Region list can be found in Appendix A.*
• **Continental**: A flight that originates and terminates in *either* the same country or different countries located within the same region. The continental distinction can help when comparing regions with very different political boundaries.

• **Intercontinental**: A flight that originates and terminates in different regions.

North America has the most number of departures, with approximately 90% of those departures being domestic flights, 7% of the departures are international, and the remaining 3% are intercontinental. Cargo flights are approximately 5% of total departures for North America. The European region contains the second most departures with approximately half of North American traffic. Because of Europe's geographic location with respect to other regions and many close member countries, the distribution of flights is very different from that of the North American region. This motivates examining the flights on a payload and range basis. The Asia/Pacific region closely follows the European region in terms of number of flights, with approximately 75% as many departures. The South America/Caribbean, Africa, and Middle East regions have relatively smaller markets, so they will be less influential in system-level studies of future aircraft designs. However, the 2006 dataset underrepresents their current status in the air transportation marketplace as these regions, especially the Middle East and Asian markets, have seen a significant uptick in growth in recent years [52]. A future study might adopt a more recent operations dataset and employ the same techniques identified in this thesis to capture recent growth in these regions.

![Figure 16: April 2006 Flight Frequency by Region and Flight Type](image)
Departure frequency by Airport is shown in Figure 17. Most of the top airports by departure, such as Atlanta (KATL), Chicago O'Hare (KORD), Dallas Fort Worth (KDFW), and Denver (KDEN), serve as major hubs for the North American region, and thus most of their operations are domestic short-range flights. However, a few airports, such as Paris' Charles de Gaulle (LFPG), London's Heathrow (EGLL), Germany's Frankfurt, and United State's Miami International (KMIA), operate a disproportionate number of intercontinental, long-range flights. It is expected that the distribution of benefits due to the introduction of a new aircraft will be different for the major domestic hubs versus airports that serve predominately as intercontinental connections.

The most popular aircraft in the world in April 2006 was the Airbus A320-200 with approximately 155,000 departures (Figure 18). The A320-2 seats approximately 150 passengers in a typical 2-class configuration and has an R1 range of approximately 6,000km. This aircraft is typical of the single-aisle, narrow body market, which dominates the list of most frequently used aircraft. Wide body aircraft, which typically fly long-range intercontinental routes with high payloads, are not represented in the list of most frequent departures until the Boeing 767-300ER (14th) and the Boeing 747-400 (18th).
Payload (kg) and range (km) histograms for the global missions are plotting in Figure 19 and Figure 20. The payload distribution is multi-modal, with a mean value of 10,806kg and a standard deviation of 8,167kg. Ignoring belly freight and at 91kg per person with bags, this results in an average of approximately 118 passengers. The actual number of average passengers is slightly lower when considering the weight of additional cargo, but this number further indicates the prevalence of the single aisle market.

The range histogram is slightly bimodal, with peaks near 600km and 6,500km, indicating the continental and intercontinental markets. The mean flight range in the dataset is 1,450km with a standard deviation of 1,447km.
Figure 19: April 2006 Mission Payload Frequency by Region [COD]

Figure 20: April 2006 Mission Range Frequency by Region [COD]

A three dimensional histogram of the payload/range space is shown in Figure 21. There is a general correlation between payload and range, with short-range missions carrying low payload, and vice versa. Again, a large majority of the flights are operated in the short-range, domestic market place with low mission payload, with relatively few aircraft operated in the long-range, high payload, intercontinental market.
It is crucial to establish where these missions are being operated with respect to the aircraft design characteristics. In Figure 22, a comparison of operations and design data is plotted for select aircraft with high frequency within classes (Regional Jets, Narrow Body, Wide Body). The $R_1$ payload, or Maximum Structural Payload (MSP), is taken directly from the Piano database. The Design Payload, $P_D$, is calculated using listed Piano data for number of design passengers and design weight per passenger, as in Equation (14).

$$P_D = P_{D,Pax} \times W_p$$ (14)

The design payload and MSP values are shown as bars in Figure 22. Each aircraft has operations differentiated by continental, intercontinental, and all flights. The distribution of flights in each of these categories is depicted by the box plots, where the circle indicates the average payload, the edges of the box indicate one standard deviation from the mean, the whiskers indicate the 95th and 5th percentiles, and the “+” indicates the minimum and maximum values. It can be seen that, for all of the representative aircraft indicated on this plot, the mean payload values are very close to design payload. Some aircraft, such as the long range Boeing 777-200ER, were even operated on average with payload above the
design payload. This is to be expected as operators try to maximize the utilization of their assets, and with load factors near 80% (Table 1).

In general, the distribution of payload for each aircraft is narrow, but increases with increasing aircraft size. There is also no discernable trend when comparing payload distributions for an individual aircraft across different mission types.

This trend applies generally across the fleet, as seen in Figure 23, where aircraft are sorted by MSP. Some aircraft, especially freighters, show averages well above design payload, but this is simply due to the method used for calculating $P_d$. Passenger aircraft with a relevant number of operations tend to have averages somewhere near or slightly above design payload, indicating that operators are attempting to maximize the payload utilization of the asset.

Figure 22: April 2006 Operating Payload and Aircraft-Specific Payload Limitations for Frequently used Aircraft in Various Classes [COD & Piano]
A similar design and operations comparison is shown for the range dimension in Figure 24 and Figure 25. Here, the R1, R2, and R3 ranges are taken directly from Piano, while the design range is established by computing the range at which a mission carrying design payload is constrained by the payload/range curve. Again the distribution of flights in each category is depicted by a box plot, where the circle indicates the average payload, the edges of the box indicate one standard deviation from the mean, the whiskers indicate the 95th and 5th percentiles, and the "+" indicates the minimum and maximum values. Every aircraft in Figure 24 has a mean operations range that is well below design range. Nearly all aircraft are operated well over 95% of the time below the calculated design range. This stands in stark contrast to the payload dimension, where operators attempting to maximize utilization drive mean values towards the design capability.

Fleet trends are shown in Figure 25. Across the fleet, the average and usually 95th percentile flight distance is well below the design capability of the aircraft. Also, as R1 range is increased, the aircraft are operated on an ever-wider distribution of mission ranges, indicating that large, long-range aircraft are somewhat frequently operated on short-range missions. Due to the size of the aircraft, it is likely that they missions are being operated at a

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See Figure 7 for payload/range diagram terminology.
significant loss of fuel efficiency when compared with an aircraft designed specifically for that mission.
4.2.2 **FUEL BURN**

Fuel burn for each mission in the operations database is calculated in order to develop a baseline from which to compare future results. The fuel burn for each mission is determined by using a bi-cubic interpolation algorithm to interpolate between entries in the performance database lookup table.

Flights originating from the North America region are responsible for the most fuel burn, as in Figure 26, although the predominance of intercontinental flights in Europe and long-range continental flights in Asia/Pacific bring those regions closer to North America fuel burn than frequency statistics would indicate. This implies improvements in long-range aircraft might yield disproportionate benefits in these regions, compared with a North American market that is dominated by high frequency on short to medium range flights.

![Figure 26: Fuel Burn by Region and Flight Type [COD]](image)

The aggregate fuel burn for each airport is shown in Figure 27. Here, intercontinental flights play a prominent role even though they are under represented when compared with continental flights in the frequency statistics. London's Heathrow Airport (EGLL), which is listed at 12\textsuperscript{th} in terms of number of departures, is highest in terms of fuel burn due to the large amount of long-range intercontinental traffic. Many of the other airports listed as high contributors to fuel burn are relatively low on the frequency charts. The predominance of intercontinental flights at these airports contributes significantly to the aggregate airport-level fuel burn.
Fuel burn for each aircraft type is plotted in Figure 28. The aircraft are ordered from highest frequency to lowest to give an indication of how important some of the low frequency aircraft are from a fuel burn perspective. In April 2006, the Boeing 747-400 was the largest contributor to system fuel burn, while ranking 18th in number of flight operations. To illustrate the importance of size on fuel burn, the B747-400 burned 1.9 times as much fuel as the A320-200 even though the A320-200 flew nearly 7 times as many missions. While narrow body aircraft flying many short-range flights dominates frequency, system fuel burn is distributed fairly evenly between small and large aircraft.
The combined frequency and fuel burn histograms for payload and range are shown in Figure 29 and Figure 30, respectively. It can be seen that, while only a relatively small amount of flights are operated high-payload or long-range flights, these flights contribute significantly to the total system-wide fuel burn. As with flight frequency, there is a general correlation between long-range and high-payload flights (Figure 31).

It is clear from this data that there are two potential ways to improve system fuel consumption through coordinated design and operations. The first is to design aircraft closer to where they are typically operated, especially in the range dimension. The other is to operate aircraft closer to their maximum efficiency point, even if they’re designed for longer-ranges. For example, the intercontinental flights in Figure 30 and Figure 31 could essentially be transformed into short-range flights resembling domestic operations by introducing a fuel stop along the mission. The impact of both of these options will be explored in greater detail in this thesis.
Figure 29: April 2006 Frequency and Fuel Burn by Region as a Function of Mission Payload [COD]

Figure 30: April 2006 Frequency and Fuel Burn by Region as a Function of Mission Range [COD]
4.3 Summary

A global operations database was used to establish typical operator patterns. It was found that while operators utilize aircraft close to their payload capacity limits, they are frequently operated well below their design range.

An aircraft performance tool was used to compute the fuel burn for baseline aircraft in the global network. Narrow body aircraft tend to contribute the most fuel burn as they are operated the most frequently, but a disproportionately large amount of fuel burn is consumed by wide body aircraft on long range missions. This implies that there are two potential ways to improve system fuel consumption through coordinated design and operations. The first is to design aircraft closer to where they are typically operated, especially in the range dimension. The other is to operate aircraft closer to their maximum efficiency point, even if they’re designed for longer-ranges. The latter is especially appealing as impacting a small amount of long-range missions might yield large savings.

The established baseline network will be used in a later stage to quantify the benefits of introducing new aircraft into the fleet.
Chapter 5

DESIGN OF AIRCRAFT WITH ALTERNATIVE DESIGN

REFERENCE MISSIONS

In order to define a potential design space (design-payload, -range, and -speed) at a constant technology level for maximum fuel efficiency aircraft, a large amount of new aircraft types must be created. The Transport Aircraft System OPTimization (TASOPT) tool, developed by Professor Mark Drela, MIT, is used to design these new vehicles. TASOPT [46], [53] consists of a series of low-order physical models that employ fundamental thermodynamic, aerodynamic, and structural theory for all primary calculations. While many aircraft design programs are semi-empirical models that use historical correlations or traditional wetted-area drag prediction methods, TASOPT relies instead on low-order models that can be used for unprecedented designs. This design philosophy is especially important for this study, as highly unconventional designs are considered within the potential solution space.

5.1 Background and Theory

Aircraft are typically designed by optimizing some metric(s) of interest subject to a large number of constraints. The metric of interest and the constraints are also known as requirements. The set of requirements for a given aircraft are unique and tend to be driven mostly by market demand and external forces, such as emissions or noise standards. For example, an aircraft might be designed for minimum fuel burn on a specific market over some flight time, while enabling stretch missions to further markets and takeoffs and landings on runways of a defined length. The design process can be broken into multiple phases [54], [55], each of them closer to the final manufactured aircraft.
The first phase, Planning, is an iterative process that consists of market surveys, customer requests, and initial design and trade studies, the result of which defines the mission specifications or requirements for use in later phases.

**Conceptual design** uses these requirements to develop an aircraft configuration and layout along with preliminary sizing.

During Preliminary Design, the aircraft is iterated while focusing on major structural features, stability, and control. It is in this stage that wind tunnel models are usually created and tested to verify computational analyses. Typically final economic analysis is completed using the computed performance characteristics and estimates of program lifecycle costs.

The last stage, Detail Design, involves the design of all parts until the final manufacturing drawings are created.

This work will focus on the conceptual design phase. A series of requirements will be developed, a configuration will be specified, and preliminary sizing will occur by optimization of an objective metric on the DRM.

The metric of interest to this research is fuel efficiency, or fuel burn over a given design mission. Fuel efficiency is a function of many competing drivers and aircraft systems; as such, development of fuel-efficient designs must necessarily encompass all the disciplines involved, starting at the conceptual design stage [56]. To manage these many competing drivers, traditional conceptual design approaches such as those employed by, e.g., Roskam [54], Torenbeek [57], and Raymer [55], utilize historical correlations in an iterative process to develop a design that minimizes the metric of interest. These approaches are inappropriate for comprehensive exploration the design space because historical correlations are not robust to extensive deviations from the original correlation dataset.

More recent approaches, such as those by Knapp, Wakayama, and Kroo attempt to dispose of some of these historical correlations and focus on optimization of major parts of the aircraft, but still rely on relatively simple drag and engine models. The recent development of a design tool based almost entirely on first-principles enables the exploration of the design space with a high degree of certainty that the results are consistent with physics and not a result of an inappropriately extrapolated historical correlation.

### 5.2 Transport Aircraft System OPTimization (TASOPT)

Recently, the Transport Aircraft System Optimization (TASOPT) tool was developed by Professor Mark Drela at MIT using first-principles methods for primary weight,
aerodynamic, and engine performance predictions [58]. TASOPT's multi-disciplinary optimization does not rely on historical primary weight correlations, wetted-area drag prediction methods, or engine lookup tables or correlations [56]. This design philosophy is especially important for this study, as highly unconventional designs are considered within the potential solution space.

TASOPT is structured as in Figure 33 [53]. The design closure procedure begins with specifying design inputs (listed as both design parameters and design variable in Figure 33), which are technology specifications, system requirements, mission requirements, etc. These inputs all serve as inputs to the underlying low-order physics models that are used to compute tail and wing dimensions, loads and structural gauges, aerodynamic performance, engine size and performance, and mission performance. This procedure is iterative, and iterating on weight until the specified weight tolerance is met closes the design. The result of this process is an aircraft design that is consistent with physics given the input variables. A high-level description of the major models are provided below, with all information derived from Drela [53].

- **Airframe structure and weight:** The primary structural elements are modeled as simplified geometric shapes, and the gauges and loads are computed directly. The fuselage is assumed to be a pressure vessel with ellipsoidal end caps, which are subject to bending and torsion loads. The wing is assumed to have a double piecewise linear taper planform at a specified sweep angle, and is subjected to a double piecewise linear aerodynamic lift distribution with tip and fuselage-carryover lift modifications. The wing structural box, spar caps, and shear webs are sized to achieve specified allowable stresses at the chosen critical loading condition. Engine weight and fuel weight are computed in the loop to provide relieving loads. The calculated gauges then give the wing's primary structural weight, and the internal box volume gives the maximum fuel capacity. Tail structures are calculated in a similar manner to the wing.

- **Aerodynamic performance:** Aerodynamic lift is generally calculated via compressible viscous/inviscid Computational Fluid Dynamics (CFD), while drag is formulated as a power balance derived by Drela [59]. A parameterized transonic airfoil family spanning a range of thicknesses represents the wing airfoil performance. The airfoil performance is determined by 2D viscous/inviscid CFD calculation[60] for a range of lift coefficients and Mach numbers. The overall model gives reliable transonic lift and drag performance predictions of the entire wing in cruise, and also in high climb and high descent. This approach for representing the
airfoil performance in effect represents a “rubber airfoil”, whose thickness can be optimized by trading profile drag versus structural merit, together with the effects of all the other airframe, engine, and operating parameters. Fuselage drag is also obtained from compressible viscous/inviscid CFD. The dissipation on the exterior of the engine nacelle is estimated using the nacelle’s exterior velocity distribution from the flight and fan-face Mach numbers. This approach makes the predicted nacelle drag strongly dependent on the flight speed and the engine power setting as is the case in reality, and thus provides realistic nacelle drag estimates over the entire flight regime. Overall aircraft induced drag is predicted by a Trefftz-Plane analysis.

- **Engine performance:** TASOPT uses a component-based turbofan model. It is based on the approach of Kerrebrock [61], with added models for turbine cooling flow and cooling loss predictions. The engine model has a design mode, which is used to size the engines for cruise, and also an off-design mode used to determine performance at takeoff, climb, and descent.

- **Stability:** Each of the components designed in the aircraft structure and weight models has an associated mass centroid, so a weight-moment buildup can be completed. Likewise, the span wise lift integration for the wing and horizontal tail is performed in parallel with pitching moment integration, including airfoil profile moment contributions. The pitching moment of the fuselage is also computed. The overall weight and aerodynamic moment is then used to impose pitch trim and pitch stability requirements. This procedure ensures that any aircraft produced by TASOPT is both pitch-trimmable and stable to within the specified margins.

- **Mission profile:** At each iteration step, the trajectory (Figure 32) is integrated to determine the weight, altitude, and thrust profiles over the DRM. The cruise portion is assumed to be at the ideal cruise-climb angle so as to maintain the specified cruise Mach number and overall lift coefficient. A takeoff performance model is also used to evaluate the balanced field length (BFL) in order to ensure the BFL constraint is not violated. The integration is repeated with varying initial takeoff fuel until the exact specified range is obtained, thus giving the required mission fuel. The end result is a defined aircraft and engine combination that achieves the specified payload and range mission. Off-design missions are calculated with the airframe fixed.
The resulting aircraft is not, however, optimized for fuel burn on the specified design reference mission. In order to optimize the aircraft for minimum fuel burn, inputs with non-monotonic influence on the objective function ("design variables") are moved to an outer optimization loop, while inputs with a monotonic influence are left as design parameters, as in Figure 33. For example, the effect of material allowable stress on mission fuel burn will always be strictly monotonic negative, since the stronger material will always result in a lighter aircraft (all else equal) and less fuel energy required. However, Aspect Ratio (AR), for example, has a non-monotonic impact on mission fuel burn since a small AR will result in excessive induced drag, and a large AR will result in excessive wing weight. Thus the aircraft can be optimized for minimum mission fuel burn by varying AR.

![Figure 32: TASOPT Mission Profile](image)

The mission profile shows the different phases of an aircraft's flight: takeoff, climb, cruise, and descent. The mission profile is characterized by specific points such as $h_b$, $h_c$, $h_d$, and $h_e$, which represent different altitudes during the mission.

![Figure 33: TASOPT Design Structure, from Drela [53]](image)

The design structure diagram illustrates the optimization process. Design inputs include parameters such as Range, $N_{max}$, $C_{Mfuse}$, Payload, $f_{stress}$, $I_{BFmax}$, Mach, and $T_{metal}$. Design outputs include parameters such as Sweep, CL, AR, $FPR$, BPR, and $T_{41}$. Design closure includes parameters such as Surface spans, areas, Loads, Shears, Moments, Structural gauges, Volumes and Weights, Drag, Engine size+weight, Trajectory, Fuel Weight, Total Weight converged?, and Fuel burn minimized?.
The optimizer modifies the design variables and then invokes the design-closure procedure as described above. This process is repeated for descent steps towards the minimum fuel burn configuration while maintaining constraints (e.g. field length, span, etc.). The list of design variables used for optimization is included in Table 3. The optimization variables impact aerodynamic, structural, and engine efficiency. The resulting aircraft represents the globally fuel optimum design for the specified DRM.

Table 3: Variables Optimized During TASOPT Design Process

<table>
<thead>
<tr>
<th>Description</th>
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<tbody>
<tr>
<td>$C_{\text{Lcr}}$</td>
<td>cruise lift coefficient</td>
</tr>
<tr>
<td>$AR$</td>
<td>overall aspect ratio</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>wing sweep angle</td>
</tr>
<tr>
<td>$(t/c)_0$</td>
<td>airfoil thickness at wing root</td>
</tr>
<tr>
<td>$(t/c)_S$</td>
<td>airfoil thickness at planform break</td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>inner panel taper ratio</td>
</tr>
<tr>
<td>$\lambda_t$</td>
<td>outer panel taper ratio</td>
</tr>
<tr>
<td>$r_{cl_s}$</td>
<td>local section $c_l$ at planform break</td>
</tr>
<tr>
<td>$r_{cl_t}$</td>
<td>local section $c_l$ at tip</td>
</tr>
<tr>
<td>$OPR_D$</td>
<td>design overall pressure ratio</td>
</tr>
<tr>
<td>$FPR_D$</td>
<td>design fan pressure ratio</td>
</tr>
<tr>
<td>$BPR_D$</td>
<td>design bypass ratio</td>
</tr>
<tr>
<td>$h_{CR}$</td>
<td>start-of cruise altitude</td>
</tr>
<tr>
<td>$T_{t4CR}$</td>
<td>cruise turbine inlet temperature</td>
</tr>
<tr>
<td>$T_{t4TO}$</td>
<td>takeoff turbine inlet temperature</td>
</tr>
</tbody>
</table>

### 5.3 Design Specifications and Assumptions

In order to define a potential design space (design-payload, -range, and -speed) at a constant technology, a large amount of new aircraft types must be created. The technology level (e.g. allowable engine metal temperature, aluminum vs. composite, etc.) is fixed in order to strictly identify the performance sensitivity to design capabilities.

A baseline technology level was established based on the Boeing 777-300ER, and can be considered approximately 2003 vintage. Work done by Drela[62] established the TASOPT design parameters, such as allowable engine metal temperatures, material properties, engine efficiencies, etc., such that the sizing routine in TASOPT will provide an aircraft whose performance and dimensions closely match that of the 777-300ER. This technology baseline was chosen as it is the most recent available technology baseline available for the
TASOPT design program. Given these fixed parameters, the DRM is then modified and the aircraft is optimized for minimum fuel burn on the DRM.

**Objective:**
Minimize mission fuel burn on the design mission specified by design-payload, -range, and -Mach.

**Subject To:**
Balance Field Length $\leq$ 10,000 feet
Mission Fuel Volume $\leq$ Max Useable Fuel Volume

The analysis further assumes:

- Tube and wing configuration
- Aluminum structure
- Two engines located on the wings
- Kerosene fuel ($C_{14}H_{30}$), 817g/L
- 215lbs per passenger (including baggage)
- Sea level takeoff and landing
- ISA atmosphere, no wind

In order to account for the changes in fuselage size required by designing the aircraft for a variable amount of passengers, the baseline fuselage is photo scaled such that the area per passenger remains constant. In reality a manufacturer would adjust the number of seat rows (fuselage length) or seats abreast / aisles (fuselage width) in order to accommodate a certain number of seats of a specified class. However, this method would lead to step changes in the resulting performance surface that are a simply a function of the internal configuration design choice as opposed to a behavior driven by fundamental physics. Because of this, the photo-scaling assumption is used, and as a consequence it is possible for the internal configuration to contain a non-integer number of seats. It is not expected that this assumption will have a significant impact on the resulting system-wide analysis, as a small change in one of the fuselage dimensions, and likewise a small change in performance, would lead to an integer number of seats.

In order to test the impact of the fuselage assumption, the 777-300ER baseline aircraft is resized to match the Boeing 737-800 design-mission. The baseline aircraft top views are shown on the left of Figure 34. The figure on the left shows the original 777-300ER, the Boeing 737 and the fuselage-scaled 777-300ER (777_030000180). The fuselage scaled 777-300ER is an aircraft that uses the fixed 777 technology values as described above and is
redesigned for 3,000nmi and 180 passengers to match the 737 design mission. As can be seen in this plot, the fuselage of the new vehicle is slightly longer (due to the stretch in the baseline 777-300ER) but matches exactly the width. The redesigned vehicle has slightly more wing sweep, but this difference is resolved when the new vehicle is designed for the same Mach number as the baseline 737 (Mach 0.8), as in Figure 34 right.

![Figure 34: Baseline 777, 737, and Redesigned Top View (left) and Including Cruise Mach Similarity (right)](image)

A comparison of the resulting aircraft shows that the redesigned aircraft (Optimi) from the established technology baseline closely matches the performance of an optimized 737-800 for the same design reference mission. MTOW differs by +1.3%, empty weight differs by +3.4%, L/D differs by +3.1%, and TSFC varies by 3.7%. In total, fuel burn on the design mission differs by -4.0%. This is generally consistent with what one would expect, as the 737-800 is of slightly older technology vintage from the established technology baseline (777-300ER).

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Optim1</td>
<td>3000</td>
<td>180</td>
<td>0.8</td>
<td>159,000</td>
<td>87,700</td>
<td>16.4</td>
<td>0.52</td>
<td>34,000</td>
</tr>
<tr>
<td>737-8</td>
<td>3000</td>
<td>180</td>
<td>0.8</td>
<td>157,000</td>
<td>84,800</td>
<td>15.9</td>
<td>0.54</td>
<td>35,000</td>
</tr>
</tbody>
</table>

Next, a large set of diverse vehicles is designed at the established fixed technology level by varying DRM. Because the limits of the DRM space at this technology level are not known a
priori, a wide variety of vehicles must be designed in order to accurately define the edges of the feasible design space. The design parameter space limitations in Table 5 were chosen with this in mind, and are reasonable estimates of the potential edges of the feasible design space.

A full factorial combination of the parameter space (30,000 potential aircraft designs) is optimized for minimum fuel burn on the design mission. Optimization occurs by varying the design variables listed in Table 3, specifically: wing parameters such as cruise lift coefficient, aspect ratio, sweep, thickness to cord ratios, and taper ratios; engine design parameters such as overall pressure ratio, fan pressure ratio, and bypass ratio; and mission parameters such as start of cruise altitude, cruise turbine inlet temperature, and takeoff turbine inlet temperature.

Table 5: Design Parameter Space

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>25</td>
<td>200</td>
<td>0.68</td>
</tr>
<tr>
<td>Maximum</td>
<td>1,500</td>
<td>10,000</td>
<td>0.86</td>
</tr>
<tr>
<td>Step</td>
<td>25</td>
<td>200</td>
<td>0.02</td>
</tr>
</tbody>
</table>

For each feasible aircraft in the DRM space, the mission performance, i.e., the performance of the aircraft on any mission in the unique, aircraft-specific payload/range diagram is not known a priori. Thus, a large number of missions must be simulated for each feasible aircraft to determine the edges of the payload/range diagram and the performance on feasible missions. Once each aircraft is designed, it is flown on an equally spaced 50x50 grid of flights in the mission space with payload limits of [0, Design Payload] and range limits of [0.04*Design Range, 2*Design Range]. These two spaces are notionally shown in Figure 35.
5.4 Computation and Filtering

A python script is used to automate the generation of the 30,000 input files according to the above tables. An example input file script is show in Appendix C. The input files are distributed to the head node of a computing cluster, and batches of input files are dynamically distributed to computing nodes as each batch of aircraft designs is finished. The resulting computation time is approximately 1.5 weeks on a cluster containing 150 computing cores.

The aircraft are designed subject to the input file constraints, such as balanced field length. However, the mission simulation is not subject to any constraints, and since viable missions are not known a priori, the output files (as in Figure 36) must be scanned and filtered to ensure mission feasibility. Figure 36 shows an example of an output file mission summary. Each row indicates a phase of flight (e.g. takeoff, cutback, climb, cruise, decent) as indicated by the mission profile diagram in Figure 32. The columns contain variables of interest, such as current range, altitude, time, speed, weight, fuel flow, L/D, and TSFC, and glide slope.
The following criteria are used to ensure mission feasibility:

- Takeoff weight must be less than or equal to MTOW
- Aircraft weight must be monotonically decreasing
- Mission range and time must be monotonically increasing
- For all time steps, fuel onboard the aircraft must be less than maximum fuel tank volume

Calculation of the payload/range diagram boundary is done by interpolation. Figure 37 shows a notional illustration of the interpolation procedure used to calculate the payload/range diagram boundary. For every mission simulated in the above process (denoted by a red ‘x’ on Figure 37), the takeoff weight and fuel volume is known. The takeoff weight and fuel volume data for a given payload are transformed into the %MTOW and %Fuel Volume space, as on the right of Figure 37. Lines L1 – L3 indicate three example mission payloads in both the payload/range space and the transformed spaces. For a given mission payload, the mission range at which the takeoff weight equals MTOW defines the takeoff weight limited boundary. Likewise, for a given mission payload, the range at which the mission fuel plus reserves equals the maximum fuel volume defines the fuel volume limited boundary. Both of these boundaries are calculated for every mission payload. At a given mission payload, the boundary with the lowest range is the constraining boundary for defining the edges of the payload/range diagram. A notable exception is the R2 mission, where the takeoff weight is equal to MTOW and also the mission fuel plus reserves are equal to maximum fuel volume.

As can be seen by the solid lines on the notional payload/range diagram in Figure 37, mission payloads larger than R2 payload are constrained maximum takeoff weight, while
mission payloads smaller than R₂ payload are constrained by maximum fuel volume. The R₂ mission is constrained by both MTOW and maximum fuel volume, by definition.

Figure 37: Notional Illustration of Payload/Range Boundary Calculation

Figure 38 shows the transformed mission payload curves for all 50 payload-missions simulated for an example TASOPT aircraft design. The left side of Figure 38 shows the takeoff weight curves for a fixed mission payload, which decreases in the direction from upper-left to lower-right. Three mission payloads are highlighted in this plot to emphasize the number of data points used as the basis for a curve fit. Each point on a given line is a different mission range at the fixed mission payload, and each of the curves is fit using a 2nd degree polynomial. The right side of Figure 38 shows the fuel volume space. It is computed using the same method and assumptions as the takeoff weight space.
Each curve can be interpolated or extrapolated at a fixed mission payload to find either the range at which takeoff weight reaches the MTOW limit, or the range at which the fuel volume reaches the volumetric limit of the fuel tanks. An example of this procedure is shown in Figure 39. For this aircraft, the fuel tank limit crosses the MTOW limit at a range of approximately 10% longer than the design range and 85% of design payload. The intersection of these two curves indicates the R_2 mission on the payload/range diagram. The boundary of the payload/range diagram is defined by the left-most curve. Missions to the left of the curves are feasible; missions to the right of the curves are infeasible as they violate one or more of the constraints.
This procedure is used to define the R₂ mission and payload/range boundaries for all of the newly designed aircraft. It should be noted that, the last portion of the payload/range diagram, the maximum structural payload boundary, is not computed by TASOPT. This is because TASOPT designs the structure to be sufficiently strong at the design point and does not determine the point of failure for components away from this design point. Since weight in the fuselage impacts the structure differently from weight in the wings, an additional analysis would have to be completed to incrementally add payload weight and reduce wing weight until the first component failed. This payload would then define the maximum structural payload. However, the maximum structural payload boundary is not necessary for this research, therefore it is not computed.

5.5 Simulation Results: Aircraft Performance in the Design Space

A total of 16,202 feasible designs were completed from the initial set of 30,000. Each aircraft represents the fuel optimal solution for a given DRM at the 777-300ER era fixed technology level. The result for a single Design Mach number is shown in Figure 40, with each 'x' representing a valid aircraft design. Interestingly, the design space shows a PFEE
optimum at a design range close to 4,000 km, as predicted by the Breguet analysis in Section 2.3. The optimum design payload is between approximately 100 and 200 passengers with an estimated PFEE improvement of approximately 30% as compared to a typical wide body design mission (M0.84, 12000 km, 450 pax). These efficiency improvements are due entirely to changing design payload and range, as the level of technology, manufacturing efficiency, etc. was held constant.

*Figure 40: Fuel Efficiency Design Surface for Design Cruise Mach = 0.84*

The full sensitivity of fuel efficiency performance to design-Mach, -payload, and -range can been seen in Figure 41. Note that all Mach variants have an optimum performance point near the same design payload and range. However, as the aircraft design cruise speed is reduced, the performance continues to improve across the entire payload range space. This is due to multiple effects, including the reduced sweep of the wing as the aircraft leaves the transonic regime, thus leading to less demanding structural requirements in the wing and an overall lighter aircraft empty weight. Also, slowing down operationally allows the aircraft to fly with a better than proportional reduction in vicious drag. However, speed reduction leads to a decrease in the feasible design space, as the smaller engine is more often restricted by constraints such as the balanced field length takeoff constraint at high payloads.
It is interesting to note that, for all Mach numbers, the fuel efficiency surface is generally convex (with some local minima for low Mach numbers) in both the design passenger and design range dimensions. In order to determine the underlying physics that drive the convexity in both of these dimensions, a few metrics of interest will be evaluated.

First, one measure of structural efficiency, empty weight per design passenger, is shown in Figure 42. Structural efficiency is maximized for design passengers of between 100 and 200 for a wide number of design ranges. It should be noted that these structural efficiency improvements are realized without the improving the underlying material technology (e.g. allowable material stress), and thus the observed trend is due entirely to the physics of air transport. This can be understood by considering the ‘fixed’ and ‘marginal’ costs related to commercial aircraft design. At an extremely low design passenger value, the fixed costs of the aircraft structure (in terms of weight) are distributed across very few passengers. As the number of passengers increase, the aircraft doesn’t necessarily change drastically, as a similar wing and engine combination are likely to be used with a slightly different fuselage. This virtuous process repeats until the optimum, after which the marginal changes in passenger load lead to larger changes to the engine and wing, which are required in order to fly the additional weight.
As can be seen from the 2 dimensional cross-sections in Figure 43, structural efficiency at the design point is convex (with few outliers) in only the design-payload dimension. However, the fuel efficiency surface (Figure 40) is convex in both dimensions, implying there must be another underlying effect that causes convex behavior in the design-range dimension.
Green [34] and others [35] have theorized that an optimal design range exists due to the fundamental physics behind typical aircraft operations, namely energy required to climb to altitude and carrying fuel for the end of the flight during the earlier stages of a flight. In order to examine these effects using empirical data, three metrics of interest are plotted across the design space. First, cruise fuel per mile (Figure 44) indicates high efficiency for short design ranges and monotonically decreasing efficiency for longer design ranges.

![Figure 44: Cruise Fuel per Mile Across Design Space for Design Cruise Mach = 0.84](image)

However, short-range design missions tend to be heavily dominated by climb fuel, as in Figure 45. For aircraft with a design-range near 1,000km, approximately 50% of the fuel burned on the design mission is consumed during the climb phase, and the other 50% is consumed during the cruise phase. Alternatively, a 10,000km design-range aircraft consumes close to 100% of mission fuel during cruise operations. The decreasing efficiency for long-range aircraft is an interesting and unavoidable result of long-range flight: the fuel for the latter parts of the mission must be carried during the early parts of the mission, resulting in a heavier aircraft which in-turn consumes more fuel, and so on.
A convenient way to combine the effects of fuel carrying and climb-energy is to create a new metric, mission fuel per mission range. This commonly used metric for automobiles essentially yields the average miles per gallon of an aircraft flight. It can be seen that, below a design-range of approximately 4,000km, flights become increasingly dominated by the fuel-inefficient climb phase. Above 4,000km, the fuel-carrying issue inherent of long-range flights increasingly dominates fuel efficiency. The combined result of these effects explains the location of the PFEE optimum in the range dimension.
5.6 Simulation Results: Aircraft Performance in the Mission Space

For each feasible aircraft in the DRM space, the mission performance, i.e., the performance of the aircraft on any mission in the unique, aircraft-specific payload/range diagram calculated. This enables the calculation of mission fuel burn given a specific aircraft type, which will be used later to fly specific aircraft types through the global network on missions of varying length and payload.

It is interesting to note the comparison between the analytical predictions from the Breguet Range Equation (and Creemer's [35] corrections) in Section 2.3 and the empirical data computed by TASOPT. Figure 47 shows PFEE across varying mission ranges for a typical narrow body sized aircraft similar to the most common aircraft by flight frequency (B737 and A320) in the operational data. Multiple aircraft are designed with a capacity of 180 passengers and varying design ranges, indicated by red squares. Each of the aircraft are then flown on off-design missions with 180 passengers, and the mission fuel burn computed for each mission is then used to construct fuel efficiency (PFEE). It can be seen that maximum fuel efficiency range is typically between 4,000km and 5,000km, as predicted.
analytically. Aircraft with design range less than approximately 4,000 km have a maximum fuel efficiency mission at the design point, while aircraft with design ranges longer than 4,000 km have a maximum fuel efficiency mission away from the design point, near 4,000-5,000 km. The tradeoff between flexibility and efficiency, as described in Section 2.3, can clearly be seen in this plot, as medium-design range aircraft have higher maximum fuel efficiency, but obtain this efficiency at the expense of a restricted operations space, in terms of reduced range. This effect implies potential system wide benefits from (1) designing shorter-range aircraft with higher maximum efficiency and (2) flying aircraft closer to their maximum fuel efficiency range using fuel stops. These effects will be explored in the later scenario analysis.

![Figure 47: PFEE Across Varying Mission Ranges for Aircraft with Design Payload = 180pax, Design Mach = 0.84, and Design Range Listed on Plot](image)

A sensitivity analysis was completed in order to evaluate the impact of various aircraft DRM on the fuel burn required to fly a given mission. The most frequent mission in the baseline operations dataset is approximately 120 passengers and 800 km. Figure 48 shows the mission fuel burn for aircraft with a capacity of 120 passengers, varying design range (indicated by the x-axis), and varying design cruise Mach (indicated by the different lines). Mission fuel burn is normalized to the fuel burn for an aircraft with design payload of 120 passengers, design range of 800 km, and design cruise Mach of 0.86. It can be seen that maintaining design payload and range while reducing cruise Mach to 0.70 can yield approximately 15% real fuel burn savings (in kg). A similar trend applies across all design ranges, implying potential system-wide benefits from reducing design cruise Mach.
5.7 Summary

The Transport Aircraft System OPTimization (TASOPT) tool was used to design and optimize a large set of new aircraft with fixed 2003 era technology and a wide diversity of design-payload, -range, and -speed. Each of the aircraft represents the fuel-optimal aircraft designs for the given DRM at the fixed technology level. For each aircraft designed within the feasible space, a payload/range diagram was computed, and off-design missions were flown to simulate off-design performance.

Across the space of feasible designs, the best fuel efficiency on a design mission occurs for a vehicle with a design payload of approximately 150 passengers and a design range of approximately 4,000km, which aligns with analytical predictions from the Breguet Range Equation. Performance data also indicates fuel efficiency improves as design speed decreases. Additionally, off-design mission performance data indicates best mission efficiency near 4,000-5,000km, which is consistent with analytical predictions. This effect implies potential system wide benefits from (1) designing shorter-range aircraft with higher maximum efficiency and (2) flying aircraft closer to maximum fuel efficiency range, potentially using fuel stops. These effects will be explored in the later scenario analysis.

Next, this large dataset of on-design and off-design performance for mission fuel and mission time will be used to create a more computationally efficient model of aircraft performance.
Each of the aircraft in the previous section is designed for minimum fuel on the design reference mission and then flown on a series of off-design missions. The result of this process is an extensive amount of data (approximately 160GB) that is computationally infeasible for use in large-scale network optimization problems. Other studies have simplified either the design space or limited the network size in order to make the problem computationally tractable. In this chapter, a comprehensive model of aircraft performance capable of solving large-scale network optimization problems will be developed. The data generated in the last chapter will be distilled into an Artificial Neural Network (ANN) using a machine-learning algorithm. The model will be validated against known performance data to ensure accurate representation of the physics underlying aircraft design and operations.

6.1 Background and Theory

Searching between discrete aircraft is not computationally feasible for determining globally optimum system performance in a large network. The aircraft design process generated 160GB of data; it is a necessity to synthesize this data into an efficient model of aircraft performance so that a global analysis can be performed.

The general approach is to create a tool that can design aircraft and fly them on any feasible mission, as in Figure 49. The model should represent the fuel-optimal aircraft for any DRM designed at equivalent levels of technology. It should be capable of flying aircraft on feasible off-design missions to determine mission fuel burn and flight time. It should also be continuous; that is, a specific aircraft/mission combination does not have to be designed/flown in the previous section in order to determine the mission fuel burn or time, as the comprehensive model captures the underlying physics-based relationship between the five input variables and the output variable. The resulting model should be fast enough to meet the demands of resolving global transportation system performance in a reasonable time.
Figure 49: High-Level Overview of Aircraft Performance Model for Fast-Time Simulation

One potential solution to this type of problem is the use of Artificial Neural Networks (ANN). ANN are functional imitations of simplified biological networks, and are especially useful because, like biological neural networks, they are capable of learning. An ANN typically consists of nodes (neurons) connected by weights (synapses) to other nodes in a network format. As in biological networks, the nodes of an ANN perform a very simple operation, however, the cooperative and highly connected network of simple operations can result in incredibly complex and intelligent information processing [63]. ANN are particularly adept at learning complex relationships in datasets when no prior functional relationship is known by the user, even if the relationships are highly nonlinear and many-dimensional [64].

There are many different types of ANN, however, each ANN has the following attributes.

- **Neuron**: Also known as nodes in network terminology. Neurons are processing units that are connected in a network and send data to one other. The information processed in a single neuron is very simple. Typically neurons are organized in layers, and the layers are connected to form the full network.

- **Synapse**: A connection between neurons is known as a synapse. Each connection has a numerical strength known as synaptic weight, or simply, weight. Synapses are used to manipulate data calculations that occur at each neuron. The ANN is capable of learning because of the ability to modify synaptic weights.

- **Learning Algorithm**: The ANN learns by modifying the weights between neurons using a structured algorithm. In general, an input is passed to a neuron that then performs a calculation using both the input data and the weights from the connection. If the output of this process is not the desired output (based on the known output from the training dataset), then the weights are changed to compensate for the error and improve the network's ability to predict output given input. The learning algorithm is the set of rules that govern how the changes are made [64].
The weights are adjusted using the learning algorithm until a defined performance measure, typically the error following each iteration of learning, converges to within some tolerance. Mean-squared error is a commonly used performance measure for functional approximation problems similar to the approach presented in Figure 49. Functional approximation problems are typically referred to as Supervised Learning problems, as the inputs and outputs are known and the ANN is trained specifically to infer the relationship between them using a user-defined training algorithm. Optimization of the network performance by minimizing mean-squared error using a gradient descent method results in one of the most commonly used training algorithms, Backpropagation of Error [65], which will be explained in detail in the next section.

The process of creating an ANN starts by first generating three datasets.

- **Training:** Dataset containing the inputs and outputs (targets) that will be used during the learning phase. The inputs are processed through the network, and the resulting calculated outputs are checked against the targets to determine the error of the current state of the ANN. If the ANN has not converged, the weights will be updated using the learning algorithm and the process will be continued until convergence.

- **Testing:** It is possible to over-fit data, especially since the regression is not known *a priori*, by definition. Therefore, a second dataset is created entirely from data foreign to the training dataset. Following all training iterations, the cost function is computed for the testing dataset inputs and targets. If the cost function value for the testing dataset starts to increase, it indicates potential over-fitting and the learning process will halt.

- **Validation:** After training is complete, it is important to ensure that the ANN generalizes. Therefore, a third dataset is created entirely from data foreign to either the testing dataset or the training dataset. The purpose of the validation data is to test the errors of the final ANN within the intended bounds of calculation to ensure the resulting regression generalizes to data not seen during the training phase.

These principles will be applied to the aircraft performance dataset in order to create a continuous, validated, and comprehensive model of aircraft performance for the use in fast-time simulation of the air transportation system.
6.2 Application to Aircraft Performance Data and ANN Training

The aircraft design data is used to create a Multilayer Perceptron Network, a specific type of Feed Forward Artificial Neural Network (ANN). The ANN learns the complex relationship between the design parameters, the off-design or mission parameters, and the resulting fuel burn using a supervised learning process. The ANN is comprised of four layers: one input, two hidden, and one output. Each layer has a number of nodes, and the nodes in each layer are connected to the nodes in the next layer. A notional example of two of the layers is provided in Figure 50. Each of the nodes has an associated sigmoid processing function that takes the sum product of outputs and weights from previous layers and computes a new output.

![Figure 50: Notional ANN; Two Layers Forward Connected by Weights, with Two Input Nodes and a Sigmoid Processing Function](image)

Each of the nodes in the layers has an associated nonlinear activation function of sigmoid form given by Equation (15). The activation function determines the signal to send to the next nodes. In other words, the output of each node is the hyperbolic tangent of the weighted sum of the synapse inputs to the node.

\[
\phi(v_i) = \tanh(v_i), \phi \in [-1,1]
\]
The ANN is trained to learn the relationship of the data by adjusting the weights connecting the nodes such that the ANN output values match their intended targets. The training process follows six stages, as follows.

1. Randomly initialize the ANN
2. Forward propagate the input to obtain an initial output
3. Backward propagate the target value through each node and store the bias value
4. Use the bias value to calculate the error gradient of each weight
5. Subtract a ratio of the gradient form the weight (learning rate)
6. Repeat until convergence

Assuming a training dataset of known inputs, $X$, known outputs, $Y^*$, and calculated outputs, $Y$, this process can be depicted by Figure 51.

![Figure 51: ANN Training Procedure](image)

Calculating the error gradient of each weight in step four is done by chain rule using known derivatives, as in Equations (16) and (17). Once the gradient of the error for a given weight, $dE/dv_i$, is known, the weight is moved in the opposite direction of increasing error. The amount that each weight is moved is known as the learning rate. A high learning rate sacrifices accuracy for speed.

$$\frac{\partial E}{\partial v_i} = \frac{dE}{dY} \frac{dY}{dz} \frac{\partial z}{\partial v_i}$$  \hspace{1cm} (16)

Where,

$$\frac{dE}{dY} = \frac{d}{dY} \left( \frac{1}{2} (Y^* - Y)^2 \right) = Y - Y^*$$

$$\frac{dY}{dz} = \frac{d(tanh(z))}{dz} = sech^2(z)$$  \hspace{1cm} (17)

$$\frac{\partial z}{\partial v_i} = \frac{d(x_1v_1 + x_2v_2 + \cdots)}{dv_i} = v_i$$
Thus, the training problem can be formulated as an optimization problem where the objective is to minimize the mean squared error, as in Equation (18), subject to the process described above.

\[
\min(\varepsilon(n)) = \min\left(\frac{1}{N} \sum_{j=1}^{N} (Y^* - Y)\right)
\]  

(18)

There exists a series of methods capable of solving this class of optimization problem [66]. The Levenberg-Marquardt backpropagation method was chosen as it was designed specifically for ANN of the size and type presented in this chapter [65]. The problem gradient can be computed as,

\[
g = J^T e
\]

(19)

Where \( J \) is the Jacobian matrix containing derivatives of the errors with respect to weights, as calculated above, and \( e \) is a vector of network errors [65]. The Levenberg-Marquardt algorithm is essentially a hybrid optimization approach as it uses a parameter, \( \mu \), to adjust the speed of the optimization process by switching between gradient descent and Newton's method. Newton's method tends to be faster near a minimum, and gradient descent is faster away from a minimum, so the purpose is to use both of these methods when appropriate.

The five dimensional input space and associated outputs are methodically split into training, testing, and validation data. The training dataset is used to learn the relationship between inputs and outputs. The testing dataset is held separately from the training dataset and is used to prevent over-fitting of the input data. Finally, the validation dataset is held in isolation from the training process so the ANN can be checked to determine how well it predicts real performance values. In order to prevent over-fitting of particular regions of the five dimensional space, the input data is pseudo randomly sampled at constant density in the design-payload, design-range space and the mission-payload, mission-range space as in Figure 52. The data is sampled at a rate of 20% in the design space and 20% in the mission space. The design-payload, design-range space and the mission-payload, mission-range spaces are gridded and each grid is sampled at a constant density. For grids that contain an edge of the performance space, slight preference is given to the edge values so that the edge of the space is more likely to be well defined.
Figure 52: ANN Training Constant-Density Pseudorandom Sample Selection

Of the 20% design and mission space sample, 15% are used for testing during the training phase. The remaining 80% of the data is used for validation. An ANN with 5 input nodes, 20 nodes in the second layer, 15 nodes in the third layer, and 1 output node (fuel burn) was trained using the above procedure.

The training process is summarized in Figure 53. It should be noted that that all dimensions were scaled to [0,1] to prevent issues related to poorly conditioned problems. The specified gradient convergence tolerance of 1e-6 was not reached before the maximum epoch limit of 3,000 iterations was reached. The epoch limit was chosen after test-training smaller portions of the dataset to determine reasonable performance values for the trained network, and was a balance between training time and marginal increase in performance. The training procedure is time intensive, as the epoch limit was reached in 71 hours while parallelized across 4 computing cores. The extremely small value and trend of the Levenberg-Marquardt parameter indicates the algorithm was using Newton’s method likely near an error minimum. The final mean squared error was on the order of 1e-5.
6.3 Validation of the Resulting ANN

The ANN is validated against a subset of the TASOPT data that is not used during the learning phase in order to quantify accuracy across the design and mission space. This procedure ensures generalization within the boundaries of the input data. It does not prove accurate generalization via extrapolation, thus all future design and missions are constrained to the validated space. A histogram of errors is shown in Figure 54. The ANN has a mean error of 0.31\% across 20,146,002 validation samples.
A closer evaluation of the mean errors across the binned design-payload and mission-range space (Figure 55), it is evident that the average error increases for the extremely short mission ranges and low payload aircraft designs.
One explanation for this effect is that the ANN does not have a sufficient plasticity to learn the relationship between the data, and thus the number of nodes must be increased and the network should be re-trained. However, it is unlikely that continually re-training the network until errors are low in all dimensions will have a material effect on the resulting system wide analysis since the areas of high error are extremely localized and rare. Also, aircraft in these size ranges (25 passengers, 400km design range) are both outsize of the scope of this analysis and would not significantly impact total system fuel consumption. Validation statistics are shown in Table 6 for the full dataset and for the bin with the highest errors.

Table 6: Fuel Burn Neural Network Validation Statistics

<table>
<thead>
<tr>
<th>Full Validation Dataset</th>
<th>&lt;=25 PAX &lt; 5% MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Samples</td>
<td>20,146,002</td>
</tr>
<tr>
<td>Mean Error</td>
<td>0.307%</td>
</tr>
<tr>
<td>Standard Deviation Error</td>
<td>0.404%</td>
</tr>
<tr>
<td>5th Percentile Error</td>
<td>0.014%</td>
</tr>
<tr>
<td>95th Percentile Error</td>
<td>1.052%</td>
</tr>
<tr>
<td>Max Error</td>
<td>15.51%</td>
</tr>
<tr>
<td>Number of Samples</td>
<td>4,102</td>
</tr>
<tr>
<td>Mean Error</td>
<td>2.515%</td>
</tr>
<tr>
<td>Standard Deviation Error</td>
<td>1.989%</td>
</tr>
<tr>
<td>5th Percentile Error</td>
<td>0.181%</td>
</tr>
<tr>
<td>95th Percentile Error</td>
<td>6.025%</td>
</tr>
<tr>
<td>Max Error</td>
<td>15.51%</td>
</tr>
</tbody>
</table>

Most of the high errors are attributed to aircraft with design payloads of 25 passengers and missions ranges less than or equal to 5% of design range, as indicated in Table 6. However, the sample size in this area is extremely small compared to the rest of the dataset, with only 4,102 samples.

One way to consider the impact of errors across the five-dimensional space on the results of a system level study is to consider the errors that will be commonly seen during typical analyses. In order to evaluate this impact, the mean error, standard deviation, and 5th/95th percentile errors were computed for all five dimensions for the full validation dataset (20,146,002 samples) and also for the entries in the validation dataset bounded the minimum and maximum values observed in real operations (1,565,832 samples). The results of this analysis are shown in Figure 56. In general, very small design payloads (<50pax) and short mission ranges (<5% Design Range) tend to see the largest upticks in
error. However, across the full validation dataset the average, standard deviation, and 95th percentile errors are generally well below 2% for all dimensions. Because the error is approximately evenly distributed about the origin (Figure 54) and the errors are generally below 2% (Figure 56), the ANN is appropriate for use in larger system level studies.

![Error distribution plots](image)

Figure 56: Fuel Burn ANN Validation Across Five Input Dimensions for Entire Validation Dataset (20,146,002 Samples, LEFT) and Validation Data within the Bounds of Observed Missions (RIGHT)

### 6.4 Flight Time Neural Network and Validation

The process described above was also followed in order to create a comprehensive model of aircraft flight time. Validation was completed with the same 20,146,002 validation samples, and the resulting error distribution is plotted in Figure 57. The errors are approximately evenly distributed about the origin with a mean of 0.08% and a standard deviation of 0.18%.
6.5 Computational Performance

In order to determine if the model meets the goal of resolving a worldwide operations network, a sensitivity study of the time to compute any number of aircraft designs or missions was competed. A plot of the computational performance (Figure 58) shows that designing 1 million aircraft, or computing a network of 1 million flights can be done in approximately 1 second. For reference, the baseline network developed in Chapter 4 contains 1.7 million passenger flights, so the comprehensive model of aircraft performance could resolve the fuel burn for this network in slightly longer than one second. This is sufficiently fast to allow for continuous, rather than discrete searching of the performance space, and also enables studying a computationally demanding worldwide air transportation network with a diversity of mission ranges and payloads.
6.6 Summary

In this chapter, a new method was presented to develop a comprehensive model of aircraft performance that is uniquely capable of solving large-scale network optimization problems. The model represents the performance of fuel-optimal aircraft designed with 2003 era technology and is capable of flying these aircraft on feasible off-design missions to determine mission fuel burn and flight time. Validation against a large dataset of known-performance data was completed and the results indicate that the fuel burn model is able to predict aircraft performance with a normally distributed error, mean error of 0.31%, and a standard deviation of 0.40%. The computational performance of the model is exceptional, as approximately 1 million aircraft can be designed, or alternatively, 1 aircraft can be flown on 1 million off-design missions in approximately 1 second.

As a next step, the comprehensive model of aircraft performance will be used as part of a larger system-level study to understand the impact of design reference mission on fuel efficiency in the air transportation system.
Chapter 7

AIR TRANSPORTATION SYSTEM SIMULATION

The objective of this study is to understand the impact of design and operator choices on fuel consumption in the global air transportation system. To perform this analysis, a baseline was established by using a performance model for existing aircraft and worldwide fuel burn for year 2006 operational data was computed (Chapter 4). Then, a set of diverse new vehicles was designed at a constant technology level (Chapter 5) and this data was used to create a computationally efficient response surface (Chapter 6). The response surface represents the fuel-optimal aircraft design for a given design-payload, -range, and -speed, and contains associated off-design performance for any aircraft.

In this section, the unique capabilities of the aircraft performance response surface are leveraged to evaluate various system fuel scenarios of interest.

7.1 Scenario Descriptions

Two major scenario sets were evaluated in order to determine the impact of design and operator choices on fuel consumption in the global air transportation system. The first set bounds the maximum theoretical potential system fuel improvements from both changing DRM and updating the technology of the operational fleet, while the second set imposes a series of constraints to determine the effects under real world constraints.

7.1.1 SCENARIO SET 1: BOUNDING POTENTIAL SYSTEM FUEL IMPROVEMENTS

First, the approximate effect of technology lag in the fleet and the effects of non-optimal aircraft sizing and allocation will be evaluated in order to bound the system fuel improvements available from non-technology advancements or alternative fuels.

- Technology Lag: Fleet Modernization. The current worldwide aircraft fleet consists of hundreds of aircraft types designed throughout many decades with varying levels of technology. These aircraft types are continuously retired and
replaced based on market forces and cost-benefit analyses by airlines. In this scenario, the amount of global system fuel consumption due to the technological lag of the fleet is quantified.

- **Non-Optimal Sizing and Allocation: Optimally Matching Aircraft Size to Demand.** There are a finite number of available aircraft types for an operator to utilize on a market of interest. The available types are created through an iterative process between manufacturers and customers, and are influenced by the actions of competitors. In some cases, the ideal aircraft for a given market may not exist, or conversely, an operator might be forced to utilize an aircraft type on a non-ideal market due to network or competitive considerations. In this scenario, the amount of global system fuel consumption due to the chosen allocation of resources is quantified.

### 7.1.2 Scenario Set 2: Determining Realistic Benefits from Changing DRM

In the previous scenarios, the maximum limits of improvements due to system inefficiencies are determined by ignoring some fundamental industry constraints. For example, the maximum benefits due to right sizing and proper allocation of aircraft to meet demand assumes an infinite number of aircraft types available to operators on a mission-by-mission basis. In reality, the huge capital constraints and long development and certification time frames required to produce a commercial aircraft mean that only a few can be produced by all global manufacturers over a period measured in decades. For this reason, a series of optimization scenarios are formulated to determine the optimum aircraft selection in terms of DRM.

- **Serial Optimal Aircraft Selection at Fixed Cruise Speed:** In the real market an aircraft manufacturer can only create a small amount of aircraft due to the capital costs and time scales inherent to aircraft programs. In this scenario the question: "which new aircraft would have the most impact on global system fuel burn?" is answered for a single cruise speed. Results will indicate which aircraft classes, e.g., medium-range narrow body, long-range wide body, etc., would yield the largest impact on fuel consumption, and therefore might indicate which aircraft types should be considered for future production.

- **Impact of Design Cruise Speed Reduction.** The optimal aircraft selection is repeated for various cruise speeds to determine the impact of design cruise Mach
number on the resulting aircraft selections. Changes in flight time are evaluated to quantify the resulting impact to passengers and operators.

- **Impact of Capacity Restrictions on Optimal Aircraft Choice:** In previous analyses the number of passengers on a flight leg was held constant, and the resulting aircraft was flown if it improved fuel consumption, regardless of the load factor. In reality, operators will attempt maintain high passenger load factors and utilization. Operators have some flexibility in the number of passengers on a flight leg via pricing and spill controls. The effect of this operator practice on the resulting optimum aircraft and system fuel consumption is analyzed by performing a parametric study of passenger flexibility.

- **Serial Optimal Aircraft Selection at Variable Cruise Speed:** In previous scenarios, the question: "which aircraft would have the most impact on global system fuel burn?" was solved using a prescribed cruise speed. In this scenario, the three-dimensional (design-payload, -range, and -speed) optimization problem is solved using a global search optimization algorithm. The resulting aircraft indicate the globally optimum aircraft Design Reference Missions for potential future aircraft. The impact on regions, countries, airports, and aircraft replacement due to flying these new aircraft in the air transportation system is presented.

- **Benefits of Fuel Stops on Long-Range Missions:** From first principles, the optimum range-efficiency point for any aircraft is located near approximately 4,000-5,000km. Because of this characteristic, one approach presented in literature to save fuel burn is to stop part way along long-range missions to refuel. This allows breaking a single, inefficient long-range mission into multiple more efficient short-range missions. The benefits of this procedure are evaluated for the existing fleet on a global scale.

- **Joint Optimization of Aircraft Selection and Fuel Stops on Long-Range Missions:** In all previous analyses, the network was fixed such that the same passengers and cargo are always transported between the same origins and destinations. In this scenario, optimal aircraft are selected as before, except intermediate fuel stops are also permitted. The solution of this joint optimization problem allows for evaluating the potential costs or benefits of the real-options trade between aircraft flexibility and efficiency.
7.2 **Scenario Set 1: Bounding Potential System Fuel Improvements**

7.2.1 **Fleet Modernization**

The current worldwide aircraft fleet consists of hundreds of aircraft types designed throughout many decades with varying levels of technology. These aircraft types are continuously retired and replaced based on market forces and cost-benefit analyses by airlines. In this scenario, the amount of global system fuel consumption due to the technological lag of the fleet is quantified.

There are 117 aircraft types in the final matched operations and performance database spanning many decades of improvements in design and technology. This number underestimates the actual number of unique variants in operation, as in many cases these matched-types do not include minor technological upgrades or stretch/shrink variants. Jiang recently performed a comprehensive study of all commercial jets – 31,032 units in total – that were built and delivered by western manufacturers since the start of the jet age [38]. While the question of how to define the terms “airplane economic life,” “airplane useful life,” and “airplane service life” are still an open question in the aircraft market analysis domain, Jiang generally found that aircraft tend to leave service within an average of 20-30 years from the time of delivery (Figure 59). Currently, the predominant forces driving the continuous retirement and replacement of the fleet are market based, such as cost-benefit analyses by airlines, rather than policy based.

![Figure 59: Aircraft Survival as a Percentage of Total Deliveries [38]](image_url)

This industry practice implies a technological lag in the fleet that may have a significant impact on system fuel consumption. The effect of this practice will be quantified for two
reasons: first, to discover the potential pool of benefits from accelerated fleet retirement and replacement, and second, to place into context the impact of upgrading the average fleet technology on future studies of varying Design Reference Mission.

The study is formulated as in Equation (20), where $f_{sys}$ is the system fuel consumption, $M$ is the global set of missions, $N$ is the set of aircraft in the fleet, $f^m_n$ is the fuel burn on mission $m$ by aircraft $n$, and $x$ is a decision variable that is 1 if mission $m$ appears in the set of missions, $S$, for the aircraft type $n$, and 0 otherwise. This general formulation applies to both the baseline case and the updated-technology fleet. The system fuel for the equal technology fleet is computed by updating the set of aircraft, $N$.

$$f_{sys} = \sum_m \sum_n f^m_n x^m_n$$

(20)

$$x^m_n = 1 \text{ if } m \in S_n$$

$$x^m_n = 0 \text{ if } m \notin S_n$$

The process is carried out as in Figure 60. Baseline aircraft types and flights for those individual aircraft types are extracted from the Common Operations Database. For each aircraft type, a new vehicle is designed with the same design-payload, -range, and -speed at a fixed technology level, approximately associated with 2003 era 777-300ER technology. Each of these new aircraft is then flown on the set of missions identified with the baseline aircraft. Global system fuel is aggregated and compared against the baseline fuel burn.
This analysis indicates a 33.78% fuel savings due to modernizing the fleet to 2003 era technology while maintaining equivalent design-payload, -range, and -speed, and sustaining the same transportation system structure, i.e., transporting the exact same passengers and cargo between the same origins and destinations. The remaining system fuel burn is due to what can generally be considered allocation of resources; i.e., manufacturers’ design reference mission decisions and operators’ utilization techniques; and the cost of air transportation, i.e., the energy required to transport people and cargo between distant locations through the air at high speeds. In the next section, the effect of resource allocation on system fuel consumption will be quantified.
7.2.2 **Optimally Matching Aircraft Size to Demand**

There are a finite number of available aircraft types for an operator to utilize on a market of interest. The available types are designed and manufactured through an iterative process between manufacturers and customers, and are influenced by the actions of competitors. In some cases, the ideal aircraft for a given market may not exist, or conversely, an operator might have an incentive to utilize a given aircraft type on a non-ideal market due to network or competitive considerations.

The allocation of these resources in terms of both manufacturer choice of design reference mission and operator choice of fleet utilization for a given transportation system mobility (transporting the exact same passengers and cargo between the same origins and destinations) can potentially have a large impact on system fuel consumption. Quantifying this impact using traditional methods (in-line aircraft design or high-dimensional optimization) is computationally infeasible for a global network. The creation of a constant-technology aircraft performance response surface in this research enables the solution to this problem in a reasonable time.

The study is formulated as in Equation (21), where $f_{sys}$ is the system fuel consumption, $M$ is the global set of missions, $N$ is the set of aircraft in the fleet or potential fleet, $f_{nm}$ is the fuel burn on mission $m$ by aircraft $n$, and $x$ is a decision variable that determines if aircraft $n$ is flown on mission $m$. The decision variable, $x$, is 1 if aircraft $n$ is associated with the minimum entry in the set of fuel burn, $F_m$, on mission $m$, by all aircraft $N$, and 0 otherwise. This general formulation applies to both the baseline case and the updated-technology fleet. The system fuel for the equal technology fleet is computed by updating the set of aircraft, $N$.

\[
    f_{sys} = \sum_{m}^{M} \sum_{n}^{N} f_{nm} x_{nm}^m
\]

\[
    x_{nm}^m = 1 \text{ if } f_{nm} = \min(F_m)
\]

\[
    x_{nm}^m = 0 \text{ if } f_{nm} \neq \min(F_m)
\]

The process is carried out as in Figure 62 and consists of two-major computation loops; one loops over all missions, and the other loops over all potential aircraft options on a given mission. First, a list of baseline operations is extracted from the Common Operations Database. For each mission, the payload, range, and number of passengers are stored for
use in mission simulation and mission feasibility checks. Next, a user input list of aircraft candidates is generated. The aircraft-options loop starts by computing the payload/range diagram for a given aircraft, \( n \). Then, three filters are applied to determine if the mission is potentially serviced by aircraft \( n \):

1. **Mission Feasibility:** mission \( m \) operated by aircraft \( n \) is determined to be feasible if mission \( m \) appears inside the payload/range diagram of aircraft \( n \).
2. **Passenger Feasibility:** transporting the listed number of passengers for mission \( m \) is determined to be feasible if aircraft \( n \) has greater than or equal to the required number of seats.
3. **Relative Mission Range Feasibility:** mission \( m \) is prevented from being operated by aircraft \( n \) if mission \( m \) is less than 5% of the design range of aircraft \( n \). This limit is established to prevent utilizing the response surface in an area with potentially high calculation errors. In practice, very few aircraft are operated at these ranges.

It is a requirement for an aircraft to pass all three filters. If any one of the criteria is not met, aircraft \( n \) is not flown on mission \( m \). Aircraft that pass the filters are flown on mission \( m \) over the listed mission range while carrying the listed passengers and cargo. Mission fuel burn is computed using the aircraft performance response surface created in Chapter 6. The fuel burn for all aircraft in the set \( N \) are stored for a single mission, \( m \), and then this process is repeated for all missions in the set \( M \). Finally, the best aircraft for every mission in \( M \) is determined by finding the minimum fuel burn solution for every mission in the set.

The set of candidate aircraft generated for this scenario is as follows:

- **Design Payload:** 50 – 1000 passengers, in steps of 10 passengers.
- **Design Range:** 500 – 18,500km, in steps of 50km.
- **Design Cruise Speed:** 0.68 – 0.86Ma, in steps of 0.02Ma.

The candidate list of aircraft was generated with the goal of being an exhaustive list of options within the Design Reference Mission space. These 346,560 potential aircraft candidates (before filtering for design feasibility) would be flown over 1,762,789 missions, yielding \( 6.109 \times 10^{11} \) potential mission fuel burn calculations. Feasible aircraft designs were established by checking each design-payload, -range, and -speed combination against the design limits as determined by TASOPT design study in Chapter 5. Of the initial set, 222,069 feasible aircraft designs were to be flown over 1,762,789 missions, resulting in approximately \( 3.915 \times 10^{11} \) potential mission fuel burn calculations. The process runtime was approximately 48 hours while parallelized over 4 computing cores.
The results of this study indicate a reduction in system fuel consumption by 57.58% when compared against the baseline, as in Figure 63. Of this 57.78%, approximately 59% of savings are due to upgrading the fleet to a constant 2003 era technology and the remaining 41% is due to flying the aircraft with the best Design Reference Mission on each individual mission.

Viewed from the context of potential levers to reduce global fuel consumption, 33.78% of system fuel burn can be influenced by accelerated retirement and replacement of the fleet with vehicles employing technology that already exists. The specific Design Reference Mission chosen for new aircraft types, and airline’s decisions regarding operating patterns, can influence another 23.8% of total system fuel consumption. Finally, approximately 5% can be affected by improved operations and network topology, leaving a remaining 37.42% of global fuel consumption that can only be affected by technology or alternative fuel
advancements. Any fuel consumption remaining after the introduction of new technologies or alternative fuels represents the energy required to transport people and cargo between distant locations through the air at high speeds.

![Figure 63: System Fuel Accounting](image)

7.3 Scenario Set 2: Determining Realistic Benefits from Changing DRM

7.3.1 Serial Optimal Aircraft Selection at a Fixed Cruise Speed

As a practical matter, an aircraft manufacturer can only create a limited amount of aircraft due to the capital costs and time scales inherent to aircraft programs. Thus, while 33.78% of system fuel consumption can be improved from updating the fleet to equal levels of technology and a maximum of 57.58% of system fuel consumption can be saved by flying the updated, right-sized aircraft on every flight, real savings will come in the form of a combination of these two effects by retiring and replacing old aircraft with a newly designed aircraft.

In this scenario the question: “which new aircraft would have the most impact on global system fuel burn?” will be answered for a single cruise speed. A fixed cruise speed is initially used to isolate the effects due to the choice of payload and range. Results will indicate which aircraft classes, e.g., medium-range narrow body, long-range wide body, etc., would yield the largest impact on fuel consumption, and therefore might indicate which aircraft types should be considered for future production.

This analysis builds on the previously established frameworks and includes a metaheuristic search algorithm to identify the aircraft with the most impact on system level fuel burn. As with previous analyses, this optimization problem is enabled by the creation of the
response surface model and is not computationally possible using previous network analysis and aircraft design techniques. Others have attempted to answer this question by evaluating a small set of pre-designed vehicles that were hypothesized to have a large impact on system fuel [47]. These methods do not ensure global optimality, nor do they give an indication of the shape of the system fuel consumption surface with respect to the design parameters.

The selection method follows the flow chart in Figure 64 and builds upon the Pareto analysis in the previous section. Baseline operations are extracted from the Common Operations Database, a payload/range diagram is generated for the new aircraft design, and filters are applied as in the Pareto analysis. At this stage, the mission is flown by the new vehicle using the aircraft performance response surface and also by the baseline vehicle using the Piano performance model. The decision of which vehicle to fly on the mission is made by a single criteria: if the fuel burn by the new vehicle is strictly less than that of the baseline vehicle, the new aircraft replaces the baseline vehicle. This process is repeated for all missions and the results, including fuel burn and aircraft type on each mission, are stored for further analysis.
The process described in Figure 64 is valid for a single new aircraft candidate. This process is repeated for aircraft with a wide range of design-payload and -range values as in Figure 65. The user inputs a list of new aircraft candidates by specifying design-payload and -range. Then, system fuel consumption is computed according to Figure 64. The system fuel consumption resulting from the introduction of each of the aircraft candidates is stored, and after all candidates are run through the system simulation, the aircraft candidate that results in the minimum system fuel is selected as an optimum aircraft type. Next, the baseline operations are updated to include the new aircraft type, and the process is repeated to solve for as many optimum aircraft types as specified by the user.

This process is referred to as the "serial" solution to the optimum aircraft problem since each aircraft is selected in succession. The serial analysis answers the question: "which aircraft would make the most impact on system fuel consumption? Then, if this aircraft were chosen, what is the next aircraft that would have the most impact on system fuel consumption?" And so on.
The set of candidate aircraft generated for this scenario is as follows:

- **Design Payload**: 50 – 1000 passengers, in steps of 25 passengers.
- **Design Range**: 400 – 18,600km, in steps of 400km.
- **Design Cruise Speed**: 0.68 – 0.86Ma, in steps of 0.02Ma.

The candidate list of aircraft was generated with the goal of being an exhaustive list of options within the Design Reference Mission space. After accounting for feasible designs by checking specific design-payload, -range, and -speed combinations against the design space limitations in Chapter 5, the list of candidate aircraft totals 28,134. The system fuel performance for each of these candidates is computed as above, and a total of five aircraft types are chosen. The resulting computation is completed in approximately 10 hours while parallelized across 4 computation cores.

The results for a fixed Mach number (0.84) are shown in Figure 66 - Figure 69. Serial Aircraft #1 is a narrow body aircraft with a design-range of 6,000km and design-payload of 150 passengers and reduces system fuel burn by 16%. Interestingly, there exists a wide range of vehicles in the 100-200 design-passenger region that have a significant impact on system fuel burn, even with fairly long design ranges. Additionally, it is evident from Figure 66 that multiple local optima exist in the system fuel surface.

If the narrow body aircraft is selected and the process is repeated to find Serial Aircraft #2, the algorithm finds a large, long-range narrow-body 757-type aircraft with a design-range of 14,400km and 250 passengers. Serial Aircraft #2 saves a cumulative 27.6% system fuel burn, or 11% additional savings from Serial Aircraft #1. It is interesting to note in the resulting surface that the selection of Serial Aircraft #1 essentially absorbs all of the benefits in the 100-200-passenger region in Figure 66. Thus, it makes little difference on a system fuel level if another aircraft of similar capability is introduced, assuming Serial Aircraft #1 is widely adopted on operated on the basis of best fuel burn.
Serial Aircraft #3 is a wide body aircraft with design-range of 13,200km and 400 design-passengers. Serial Aircraft #4 is a regional jet type aircraft with a design-range of 4,800km and a design-payload of 100 passengers.

Figure 66: System Level Fuel Burn Savings at Design Mach = 0.84 Across Design Space for Aircraft #1

Figure 67: System Level Fuel Burn Savings at Design Mach = 0.84 Across Design Space for Aircraft #2
A summary of results is included in Table 7.
Table 7: Summary of Results for Serial Optimal Aircraft Selection at Mach 0.84

<table>
<thead>
<tr>
<th>Design Payload</th>
<th>Design Range</th>
<th>Design Mach</th>
<th>FB Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>[pax]</td>
<td>[km]</td>
<td>[M]</td>
<td></td>
</tr>
<tr>
<td>Aircraft #1</td>
<td>150</td>
<td>6,000</td>
<td>0.84</td>
</tr>
<tr>
<td>Aircraft #2</td>
<td>250</td>
<td>14,400</td>
<td>0.84</td>
</tr>
<tr>
<td>Aircraft #3</td>
<td>400</td>
<td>13,200</td>
<td>0.84</td>
</tr>
<tr>
<td>Aircraft #4</td>
<td>100</td>
<td>4,800</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The cumulative benefits as a function of serial aircraft number are plotted in Figure 70. It can be seen that the first four aircraft selections make the most impact on system fuel burn, and the benefits appear to approach an asymptote after this. The asymptote for this curve is defined by the Pareto analysis for a fixed Mach number, and will be presented in the next section.

![Figure 70: Cumulative System Fuel Savings for Aircraft Selected in Series](image)

It should be noted that this analysis was performed on a flight-by-flight basis. A consequence of this assumption is that optimal aircraft size is driven in large part by existing operational tendencies. For example, it would be difficult to find an Airbus A380 in the optimal solution set using this method as the highest passenger load on an individual flight in the 2006 dataset is well below the maximum seating capacity of an A380. This method gives a reasonable estimate of the potential system savings possible by substituting aircraft with new DRM into a minimally-changed competitive transportation system in terms of airline market share, flight frequency, etc. A similar analysis could be performed on the aggregate level, allowing, for example, consolidation of passengers on particular
markets into larger aircraft flying at a reduced frequency. While this framework is more likely to find extra large wide body aircraft like the A380, it requires many additional analyses and assumptions in order to determine a competitive equilibrium via estimates of revenue, market share, profitability, etc.

7.3.2 IMPACT OF DESIGN CRUISE SPEED REDUCTION

Reductions in aircraft design cruise speed can yield significant improvements in aircraft fuel efficiency, as determined in Section 5.5. To quantify the extent of these fuel consumption benefits at the system level, the optimal aircraft selection process described in Section 7.3 is repeated for various fixed cruise speeds. Additionally, the Pareto process described in Section 7.2.2 is repeated for fixed Mach numbers of 0.72M and 0.84M. The resulting computation time was approximately 170 hours parallelized across 4 computing cores.

Results are shown in Figure 71 and Figure 72. Reducing Mach number from 0.84M to 0.72M yields an additional 2.5% of system fuel burn savings for the first aircraft, and an additional 5% fuel burn savings for the second aircraft. These differences are likely related to the fact that the first aircraft is a medium-range narrow body aircraft being operated on short to medium range flights, whereas the second optimal aircraft is typically a long-range wide body aircraft being operated on much longer flights. On short-range flights, the reduction in speed has a small impact over the course of a flight. However, long-range flights, of which there are few yet they contribute significantly to system fuel consumption (Chapter 4), are more influenced by reductions in cruise speed and improvements in aircraft weight efficiency. It appears from these results that the optimum fixed cruise speed is Mach 0.72, which leads to a 6.6% improvement in system fuel when compared with Mach 0.84 for three or more aircraft types.

---

6 The resulting system fuel surfaces and optimal aircraft are presented in Figure 96-Figure 105 in Appendix D.
There exists a growing body of literature regarding the potential costs and benefits from reductions in design cruise speed. Fan and Bonnefoy [67] evaluated the impact on airlines and passengers of flight time increases from cruise speed reductions for existing aircraft and found that overall cost savings are possible. Fan and Bonnefoy find that changes in
flight time due to reductions in cruise speed can be partially mitigated through schedule re-optimization, but that trade-offs among cost savings, risk of delay, and impact to passengers needs further study. As part of this research effort, changes in flight time due to reductions in design speed can be calculated and thus may assist in a future system-level study of the detailed cost-benefit tradeoffs of reductions in aircraft cruise speed.

Changes in flight time for each of the Mach scenarios are presented in Figure 44. After the fifth aircraft selection for each Mach number, the flight times for the replaced aircraft are calculated using the flight time performance model. The flight times for the baseline aircraft are also calculated using the baseline aircraft performance calculator. Then, missions are combined into 150km bins and the difference between the new flight times (using the flight time ANN) and the baseline flight times (using the baseline aircraft performance calculator) are calculated.

It is interesting to note that, while M0.72 results in the largest system fuel benefits, it also increases average flight times for missions longer than approximately 2,000km. For example, a transcontinental US flight would result in an increase of 20-30 minutes of flight time on a mission with an average flight time of approximately 5 hours. A typical transpacific flight averages 11 hours and would see an increase of approximately 50 minutes.

![Figure 73: Average Changes in Calculated Operational Flight Time by Mission Range for Optimum Aircraft Selected with Varying Mach Numbers](image-url)
7.3.3 Impact of Load Factors and Passenger Flexibility

In previous analyses the number of passengers on a flight leg was held constant, and the resulting aircraft was flown if it improved fuel consumption, regardless of the load factor. In reality, operators will attempt maintain sufficiently high passenger load factors and utilization, which is accomplished by controlling the number of passengers on a flight leg via pricing and spill controls. Thus, operators have some flexibility in the number of passengers on a particular flight leg.

In order to understand the effect of typical operator practices on the resulting optimum aircraft and system level fuel consumption benefits, the baseline load factor will be maintained for new aircraft, and the number of passengers on a given route will change based on the passenger flexibility factor. This parametric analysis will give insight into the impact of the aircraft replacement assumption, i.e., that a new aircraft replaces an old aircraft if it consumes less fuel on a particular flight leg, regardless of size.

As an example of the distribution of flown load factors, five serially optimal aircraft at a fixed cruise speed of 0.72M will be used, as computed in Section 7.3, and are presented in Table 8. Following the general trend previously described, the first aircraft is a single-aisle narrow body aircraft similar to an A320; the second is a wide-body, long-range aircraft similar to a B777; the third is a twin-aisle long-range aircraft similar to a B757; the fourth is a regional jet, similar to an Embraer E190; and lastly the fifth is another twin-aisle aircraft. Most of the system fuel consumption benefits are yielded in the first three aircraft types.

As previously described, the optimal aircraft selection is done assuming the new aircraft transports the exact same passengers and cargo listed in the baseline mission. This constant payload scenario results in varying load factors. A histogram of load factors for each of the five aircraft is shown in Figure 74. It can be seen that, while the baseline load factors are typically near 80% (Table 1: April 2006 Common Operations Database Load Factors [%] in 7.3.3
Section 4.1.1), the constant-payload scenario results in some flights with load factors less than 50%. Most of the very low load factors are due to regional jet operations.

In order to understand the impact of this assumption on resulting system fuel burn and optimal aircraft selection, a constant load factor will be maintained and the number of passengers on a flight will be varied. The distribution of passengers on a market OD pair in the baseline case is used as an indicator of how much the number of passengers on a particular flight leg might be varied. In Figure 75 the distribution of passengers is plotted for the 80 most frequent markets in the April 2006 Common Operations Database and sorted by number of operations from right to left. The circle indicates the average number of passengers on the market, the box indicates the standard deviation, the whiskers indicate the 95th and 5th percentile values, and the ‘+’ indicates the minimum and maximum values. For example, the most frequent market in the world in April 2006, YMML - YSSY (Melbourne to Sydney, Australia) had an average of 120 passengers per flight, with a standard deviation of 70 passengers per flight.
The process for selecting optimum aircraft is the same as that presented for the constant payload scenario, except in this case an additional filter is applied to maintain constant load factor. The filter is constructed by first multiplying the capacity of the new aircraft by the baseline load factor as in (22). This yields the number of passengers that must be transported by the new aircraft, \( P_{pax, new} \). Demand limits are calculated by multiplying the number of passengers on the baseline flight, \( P_{pax} \), by the passenger flexibility factor, \( f_{pax} \). If the number of passengers to be transported by the new aircraft, \( P_{pax, new} \), is within the bounds of demand on the flight leg, the aircraft passes the filter and is eligible to be flown on the mission using the same criteria as before. The new aircraft carrying \( P_{pax, new} \) will be substituted for the baseline aircraft if it burns less fuel than the baseline aircraft on the mission.

\[
\begin{align*}
    P_{pax, new} &= (Seats)(PLF) \\
    D_{pax, low} &= P_{pax}(1 - f_{pax}) \\
    D_{pax, high} &= P_{pax}(1 + f_{pax})
\end{align*}
\tag{22}
\]

The results for two fixed Mach number cases are shown in Figure 76. In the constant payload scenario, the Mach 0.72 aircraft save 46.17% of system fuel consumption after introducing five aircraft types, and the Mach 0.84 aircraft save 40.82%. If the number of passengers is allowed to vary between +/- one standard deviation of the number of
passengers on each flight route (as in Figure 75), then the system fuel savings are reduced to 28.41% and 24.84%, respectively. If the number of passengers on each route are allowed to vary even more widely, in this case between the minimum and maximum number of passengers on a given flight route, then the system fuel savings become 32.71% and 28.59%.

![Figure 76: System Fuel Burn Savings For Fixed Mach 0.84 and Mach 0.72 for Two Passenger Flexibility Scenarios](image)

These results indicate that operator practices, especially the desire to operate at high load factors, can have an impact on the resulting system fuel consumption and thus the constant payload assumption is a best-case scenario for reductions in system fuel consumption. Conversely, they also indicate that significant savings are possible by changing operator practices and assigning aircraft to markets on a best fuel consumption basis.

The passenger flexibility factor was allowed to vary between 0 and 200 percent in order to get an understanding of the resulting system fuel as a function of flexibility in passenger demand. The results for vehicles with a fixed cruise Mach of 0.72 are shown in Figure 77. It can be seen that system fuel consumption quickly approaches the constant payload values as passenger flexibility is varied from 0% to 20%. It can also be seen that the optimal aircraft selection (design-payload and -range) quickly approaches the constant payload solution. Each new optimal aircraft selection is depicted by circles, with gray circles indicating minor changes from the previous solution (<50pax, <1000km) and black circles indicating major changes from the previous solution (>=50pax, >=1000km).
7.3.4 **GLOBALLY OPTIMUM AIRCRAFT SELECTION**

In previous scenarios, the question: "which aircraft would have the most impact on global system fuel burn?" was solved using a prescribed cruise speed. In this scenario, the best Design Reference Mission (design-payload, -range, and -speed) will be found using a global search optimization algorithm. The resulting aircraft indicate the globally optimum aircraft Design Reference Missions for potential future aircraft. The impact on regions, countries, airports, and aircraft replacement due to flying these new aircraft in the air transportation system will be presented.

**BACKGROUND AND OPTIMIZATION THEORY**

Previous aircraft selections, henceforth referred to as "2D" solutions, benefited from the fact that the search space only contained aircraft size. Thus, a series of trial aircraft could be flown and then visually chosen from the resulting objective function surface. The 3D problem, i.e., choosing the optimal design-payload, -range, and -speed greatly increases the size of the problem. For example, using the previous trial-aircraft method, the solution to the 3D problem would require an order of magnitude more computation time.

Instead, a more sophisticated approach will be used to solve the 3D problem. First, a series of trial points in the three-dimensional design space will be generated randomly. Then, a set of the trial points is further down selected for function evaluation. The test point with the minimum objective function value from the set of test points is used as the starting point.
Then gradient-based optimization is run from the starting point, and the distance from the initial starting point to the local minimum defines the radius of the basis of attraction. The basis of attraction is a spherical zone centered on the initial point. Then, another point is randomly called, and gradient-based optimization is run for this point if it is not already in an existing basis of attraction. This process is repeated until either all trial-points are evaluated using gradient-based optimization or until there are no points left outside a basis of attraction [68] [69].

PROBLEM DEFINITION
The goal of this problem is to minimize system fuel burn by choosing individual aircraft with specified values of design-payload, -range, and -speed. The problem is formulated as in (23), where the objective is to minimize the system fuel as a result of introducing an aircraft optimized for minimum fuel burn on the given design-payload, -range, and -speed tuple. If the aircraft does not meet the passenger or design range constraints for a given mission, the baseline aircraft will be flown as before. Likewise, if the listed mission is not a valid mission given the new aircraft’s payload/range diagram, the baseline aircraft will be flown as before.

\[
\min \left( \sum_{m} f_m(D_p, D_R, D_M) \right) \\
\text{s.t.:} \\
m_{pax} \leq D_M, \text{ else } f_m = f_b \\
m_R \geq 0.05D_R, \text{ else } f_m = f_b
\]  

(23)

RESULTS
The optimization problem was solved five consecutive times, as described in the serial approach to finding optimum aircraft. The results indicate a similar trend in design payload and range as with in the fixed cruise speed scenario. The aircraft with the largest impact on fleet fuel burn is a 156 seat, 6,448km design range narrow body aircraft with a design cruise Mach of 0.681M and results in 20.51% savings in system fuel consumption. The second aircraft is slightly larger than a Boeing 757, has a design cruise Mach of 0.72, and results in an additional 12.53% of system fuel savings. Aircraft #3 is a wide-body, long-range aircraft with 385 seats, a design range of 14,234km, a design cruise speed of 0.752M, and results in an additional 8.38% of system fuel savings. The next two aircraft are both short range regional jets, one with 107 seats and a design range of 4,658km (similar to an Embraer
E190) yielding 4.27% of system fuel savings, and the other with 50 seats and a design range of 2,227km (similar to the CRJ100/200) yielding 1.72% system fuel savings.

Table 9: Globally Optimum Aircraft Selection Results

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft #1</td>
<td>156</td>
<td>6,448</td>
<td>0.681</td>
<td>20.51</td>
</tr>
<tr>
<td>Aircraft #2</td>
<td>265</td>
<td>12,724</td>
<td>0.718</td>
<td>33.04</td>
</tr>
<tr>
<td>Aircraft #3</td>
<td>385</td>
<td>14,234</td>
<td>0.752</td>
<td>41.42</td>
</tr>
<tr>
<td>Aircraft #4</td>
<td>107</td>
<td>4,658</td>
<td>0.689</td>
<td>45.69</td>
</tr>
<tr>
<td>Aircraft #5</td>
<td>52</td>
<td>2,227</td>
<td>0.680</td>
<td>47.41</td>
</tr>
</tbody>
</table>

Baseline aircraft fleet replacements are shown in Figure 78 and are sorted by maximum structural payload from lowest to highest. New aircraft generally replace existing aircraft of similar size and operations type. However, the very short range aircraft, #4, replaces many narrow body aircraft on common short range missions.

Figure 78: Replacements of Existing Fleet, Sorted by Maximum Structural Payload (Lowest Left to Right)

Fuel burn by the new and un-replaced vehicles across mission payload and range is shown in Figure 79 and Figure 80. It can be seen that payload operations are segregated by aircraft type, indicating that aircraft are utilized according to their design payload capability.
However, optimal aircraft are utilized on a wide variety of mission ranges, indicating that with only a few aircraft-type choices and constant system mobility, optimal operations from the perspective of minimum system fuel require a diversity of aircraft operations. It is also interesting to note that, while the two long-range aircraft types replace relatively few aircraft, they make a large impact on system fuel burn as long-range missions are responsible for a disproportionate amount of system fuel burn.

Figure 79: Fuel Burn Binned by Mission Payload
It should be noted again that this analysis was performed on a flight-by-flight basis. A consequence of this assumption is that optimal aircraft size is driven in large part by existing operational tendencies. For example, it would be difficult to find an Airbus A380 in the optimal solution set using this method as the highest passenger load on an individual flight in the 2006 dataset is well below the maximum seating capacity of an A380. This method gives a reasonable estimate of the potential system savings possible by substituting aircraft with new DRM into a minimally-changed competitive transportation system in terms of airline market share, flight frequency, etc. A similar analysis could be performed on the aggregate level, allowing, for example, consolidation of passengers on particular markets into larger aircraft flying at a reduced frequency. While this framework is more likely to find extra large wide body aircraft like the A380, it requires many additional analyses and assumptions in order to determine a competitive equilibrium via estimates of revenue, market share, profitability, etc.

7.3.5 **Intermediate Fuel Stops for Baseline Aircraft**

Operations data indicates that a large amount of fuel is burned by relatively few long-range flights. Additionally, it has been suggested in the literature that one method of adjusting operations in order to reduce system fuel burn is to institute a fuel stop in the middle of long-range flights. The fuel stop allows each leg of the flight to be flown closer to the aircraft's maximum efficiency range. The basic concept of operations for this procedure is
shown in Figure 81. Instead of a single, direct long-range flight, the mission would be broken into a multi-segment flight.

There are three penalties that result from stopping midway through a flight to refuel. The first is the extra energy required due to the extra takeoff and landing. The second is the extra energy required to fly further than great circle distance, as a viable refueling airport might not be along the great circle route between origin and destination. And finally, a viable airport might not exist near the midpoint of the flight, meaning the flight can’t be broken into equal legs with distances close to the aircraft’s maximum efficiency range.

Mathematically the penalties from diversion and unequal division of the flight (eccentricity) can be described as in Equation (24). A diversion factor of 1.0 indicates a great circle route, the shortest possible distance between origin and destination. Diversion factor differences larger than 1.0 indicate longer ranges such that \((f_d - 1.0) \times 100\) is equal to the percentage increase in flight distance due to the mid flight fuel stop. An eccentricity factor of 0.5 indicates a flight that has a fuel stop midway through the mission and large values indicate nonequivalent flight legs.

\[
\begin{align*}
    f_d &= \frac{OS + SD}{OD} \\
    f_e &= \frac{\max(OS, SD)}{OSD}, f_e \in [0.5, 1.0)
\end{align*}
\] (24)

The most fuel optimum values of \(f_d\) and \(f_e\) are 1.0 and 0.5 respectively, indicating a great circle mission with a fuel stop exactly in the center. Based on the fact that all aircraft have a best fuel efficiency range somewhere around 4,000km with a decline in efficiency beyond this distance, there should be some mission range at which it is more beneficial to stop and pay the LTO, \(f_d\), and \(f_e\) fuel penalty. To test this theory, Piano aircraft are flown on a series of
direct and intermediate stop operations using $f_d=1.0$ and $f_e=0.5$ with a fixed 50% of the listed maximum structural payload (MSP). On the left side of Figure 82, it can be seen that a 737-700ER starts to realize benefits from the fuel stop around 5,000 km. The maximum benefit of approximately 7% is obtained at the longest possible mission range for the aircraft at the flown payload. On the right side of Figure 82 the entire Piano 5 fleet is plotted using the above method. For all aircraft with a maximum range of longer than approximately 4,000km, there exists a range at which a fuel stop yields a mission fuel savings. The mission range at which the fuel for the intermediate stop operation equals the direct flight fuel varies between approximately 4,000km and 8,000km across the fleet, with longer-distance aircraft needing longer missions lengths in order to yield a benefit. The maximum flight level benefits are approximately 12%, indicating a significant potential pool of benefits.

![Figure 82: 737-700ER (left) and Fleet-Wide (right) Intermediate Stop Operation Fuel Consumption Sensitivity to Mission Range](image)

A method was developed to assess the maximum system-level fuel burn benefits from intermediate stop operations as shown in Figure 83. The April 2006 COD is filtered for minimum mission distances greater than 4,000km, as this was indicated in Figure 82 to be the minimum range at which flight-level benefits are possible. The resulting operations are flown using the performance calculator for both a direct flight and an intermediate stop with $f_d=1.0$ and $f_e=0.5$. Note that this intermediate stop does not consider the existence of airports at the stopping point; the diversion and eccentricity values are chosen simply to obtain the maximum potential system benefit.

Finally, a minimum improvement filter is applied to determine if the intermediate stop operation or direct flight is flown. The minimum improvement parameter is introduced to
parametrically simulate the extra costs an airline would incur, such as additional landing fees, staffing costs, maintenance due to additional LTO cycles, etc., which act as a disincentive to using a fuel stop. Because these costs are largely unknown, a set of parametric scenarios is analyzed to show the resulting trend in system benefits and flights affected. The 0% scenario indicates no additional airline costs, while higher values indicate increasing airline costs due to the fuel stop.

The results of this analysis are shown in Figure 84. The maximum potential system fuel savings is 3.2% and assumes no additional airline costs. In this scenario, approximately 75% of missions over 4,000km use a fuel stop. The number of missions impacted and the total system fuel burn savings decrease as airline fuel stop-related costs increase.
As mentioned, this method assumes aircraft can land in the optimal stopping location even if an airport does not exist at this point. A more sophisticated method is required if considering real airports. In Figure 85, the minimum mission distance and COD operations are used to filter missions as before. Additionally, a global airport database and a minimum runway length of 10,000ft is used to filter the potential fuel stop airports. The airports used as either an origin or destination, or airports with a 10,000ft runway that don't appear in the operational database comprise the unique airport list in the network model. A distance calculator is used to create a fully connected graph of distance between all of the airports, and this information is passed to the network simulation block (shown in detail in Figure 86). The network simulation uses the performance calculator to fly the direct mission and the selected intermediate stop candidate missions. In order to create a computationally tractable problem, intermediate stop candidate airports are ranked by computing $f_d$ and $f_e$ from origin to destination via the fuel stop airport. This is done quickly by manipulating the fully connected graph that was pre-computed in Figure 85. The airport candidates are ranked by increasing $f_d$ (and secondarily by increasing $f_e$). The user specifies a number of candidates to input to the performance calculator, and then the mission-type decision is made by considering the same airline cost-scenarios as before.
The results of this analysis are shown in Figure 87. Implementing a requirement to land at actual airports decreases the maximum possible benefits from 3.2% to approximately 2.5%. Interestingly, the curves converge at an airline cost scenario of approximately 6%, where 1.5% system fuel savings can be obtained by flying 10% of missions of 4,000km using an intermediate stop operation at a real airport.
Figure 87: Intermediate Stop Operations System Fuel Savings

It should be noted that the savings could be even small when other airport constraints are considered. For example, this analysis assumes the best airport candidate is used as the fuel stop, regardless of infrastructure or political limitations.

7.3.6 Joint Optimization of Aircraft Selection and Intermediate Stops

The tradeoff between flexibility and efficiency presented in Section 2.3 implies a real options trade between long-range capability and fuel efficiency over the life of the aircraft [70]. By designing shorter-range aircraft, the aircraft-level efficiency tends to increase, however, the aircraft is no longer able directly serve long-range missions. In this section, Intermediate Stop Operations (ISO) will be considered as a potential solution to serving long-range missions with short-range aircraft. This analysis will effectively capture the real options trade between capability and efficiency.

The models developed throughout this thesis are leveraged to solve the joint optimization problem, as in Figure 88. For each aircraft candidate, the network is resolved without considering ISO, as in Section 7.3.1. Then, the ISO algorithm developed in Section 7.3.5 is employed to calculate the optimal network changes and system fuel benefits from flying the candidate aircraft on simulated fuel stops at real airports. This process is completed for all aircraft candidates, and then the minimum fuel solution is chosen. Finally, the process is repeated for the number of serial aircraft desired. The 5-aircraft solution to this problem had a runtime of approximately 90 hours while parallelized across 8 computing cores.
A table of results for five serially selected, optimal aircraft is presented in Table 10. It can be seen that by including the ability to restructure the network with fuel stops, the optimal aircraft design range decreases significantly for the longer-range aircraft. For example, the long range wide body aircraft design range for Mach 0.84 decreases by 39%, from 13,200km to 8,000km. The resulting system level fuel consumption benefits increase by 2.9% for the Mach 0.84 case, and by 2.8% for the Mach 0.72 case.

Table 10: Summary of Joint Optimization Results

<table>
<thead>
<tr>
<th>Fixed-Network Optimization</th>
<th>Joint Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Payload [pax]</strong></td>
<td><strong>Design Payload [pax]</strong></td>
</tr>
<tr>
<td><strong>Design Range [km]</strong></td>
<td><strong>Design Range [km]</strong></td>
</tr>
<tr>
<td><strong>Mach 0.84, 0% ISO Mission Threshold</strong></td>
<td><strong>Mach 0.72, 0% ISO Mission Threshold</strong></td>
</tr>
<tr>
<td>150</td>
<td>6000</td>
</tr>
<tr>
<td>250</td>
<td>14400</td>
</tr>
<tr>
<td>400</td>
<td>13200</td>
</tr>
<tr>
<td>100</td>
<td>4800</td>
</tr>
<tr>
<td>200</td>
<td>11200</td>
</tr>
</tbody>
</table>

Savings f/ Baseline: **40.82%**

Savings f/ Baseline: **43.73%**

Interestingly, the system fuel benefits of approximately 2.9% are robust to flight-level aircraft cost sensitivities. As in the previous section, the analysis was repeated for different flight-level improvement thresholds. The minimum improvement parameter is introduced to parametrically simulate the extra costs an airline would incur, such as additional landing fees, staffing costs, maintenance due to additional LTO cycles, etc., which act as a disincentive to using a fuel stop. A summary of these results is presented in Figure 89.
be seen that including a flight-level improvement threshold of 5% reduces the additional potential system fuel benefits from 2.9% to 2.81%. Increasing the threshold to only allow ISO flights with 10% improvements on the individual flight leg still results in 2.76% fuel savings. This figure also includes a breakdown of savings from ISO flights and also from savings due to flying the shorter-range aircraft on direct missions (versus flying a long-range aircraft on the same direct missions). It can be seen that, of the approximately 2.8-2.9% in additional total system fuel savings, approximately 66% is due to savings on ISO flights, and the remaining 33% is due to flying a more appropriately sized aircraft on short range, direct missions.

![Figure 89: Summary of Joint Optimization Results Across Varying Mach Number and ISO Improvement Threshold Filters](image)

This effect can be seen more closely when evaluating Figure 90. The joint optimization process yields additional benefits from using ISO (red), but also yields additional benefits from flying short-range aircraft on missions with the highest frequency, which tend to be short to medium range.
The most promising ISO routes are shown in Figure 91 for the 0% flight-leg benefit filter. The top 1000 routes are highlighted in red, and generally consist of the longest-range flights, including most trans-Atlantic and trans-Pacific flights from the US, and nearly all intercontinental flights from the Asia-Pacific region. The top ISO airports are also plotted in Figure 92. It is interesting to note that 9 major "ISO hubs," or fuel stop airports with greater than 1,000 flight operations in the month of April 2006 naturally evolve from the ISO algorithm. These ISO hubs are approximately equally spaced across the Earth, and tend to be in advantageous locations for intercontinental flights.
A list of the top airports by number of stops is included in Table 11. As with previous ISO analyses, the available airports were limited to only those with a listed runway of at least 10,000 feet. The individual airport infrastructure (terminals, fuel availability, etc.) was not evaluated. Thus this table serves as a list of airports that are in geographically advantageous locations for fuel stops, and in future high fuel-price scenarios, might be ideally situated for further infrastructure development. Interestingly, the largest refueling hub (by a factor of 5)
is Gander International airport located in Newfoundland, Canada. In 2010, Sun Country airlines announced it would be using Gander International as a fuel stop between Minneapolis and London with medium-range Boeing 737 aircraft [71].

<table>
<thead>
<tr>
<th>Airport Code</th>
<th>Airport Name</th>
<th>Country</th>
<th>Region</th>
<th># Stops</th>
<th>Longest Runway (m)</th>
<th>Runway type</th>
</tr>
</thead>
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<tr>
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<tr>
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<td>Nizhnevartovsk Airport</td>
<td>Russia</td>
<td>Asia</td>
<td>1075</td>
<td>3200</td>
<td>Asphalt</td>
</tr>
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<td>Eareckson Air Station</td>
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<td>N.A.</td>
<td>1857</td>
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<td>Asphalt</td>
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<td>Akutan Airport</td>
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<td>N.A.</td>
<td>1779</td>
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<td>Azores, Portugal</td>
<td>Eur.</td>
<td>1520</td>
<td>3314</td>
<td>Asphalt</td>
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<td>Eur.</td>
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<td>Asphalt</td>
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<td>Russia</td>
<td>Asia</td>
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<td>3140</td>
<td>Concrete</td>
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</tbody>
</table>

### 7.4 Summary

In previous chapters, aircraft were optimized for minimum fuel burn across a wide variety of design-payload, -range, and -speed, for fixed 2003 era technology, and then an aircraft performance model was created to relate off-design mission performance to an aircraft Design Reference Mission. This model was then used to solve scenarios related to introducing new aircraft into the air transportation system.

An updated accounting of system fuel consumption is shown in Figure 93. It was determined that the slow rate of retirement in the operational fleet lead to a technology lag that accounts for 33.78% of system fuel consumption. Further, it was found that by ideally sizing an aircraft to fly every mission, another 23.8% of system fuel burn could be affected. Fuel optimal aircraft were selected for a variety of Mach numbers using a serial-selection technique, and it was determined that Mach 0.72 lead to the greatest potential system fuel improvements. However, aircraft with a cruise Mach number of 0.72 were determined to increase transcontinental US flight times by 20-30 minutes, and transpacific flight times by approximately 1 hour. A globally optimum (any Mach) aircraft selection technique was developed, and the five selected aircraft lead to a 47.41% savings in system fuel consumption.
The selected aircraft tend to follow typical narrow-body, wide-body, regional jet patterns for design-payload and range. This is likely due to two reasons: (1) the transportation network was maintained at the flight leg level (i.e. the same passengers were transported between the same origins and destinations on every flight) so some underlying operational patterns perpetuate, and (2) by only allowing the introduction of a few aircraft types, minimizing system fuel requires the resulting aircraft to be versatile, as in real operations.

Fuel stops were considered as a potential way to change the network and take advantage of appropriately sized aircraft. Fuel stops represent a solution to the real options trade between aircraft design flexibility and efficiency. It was determined that an additional 3% of system fuel savings can be achieved with the introduction of fuel stops. Approximately 66% of these savings are due to the fuel stops themselves, while the remaining 33% is due to flying more appropriately sized aircraft on short and medium range missions. Fuel stops can yield significant savings, e.g. 10-15%, on ideally situated routes.

Many of the analyses in this chapter required significant computation time (measured in days) while parallelized across many cores. However, this time was still considered reasonable given any alternatives. The tools created in the early parts of this thesis enabled calculations that would not have been possible otherwise.
Chapter 8

CONCLUSIONS

This objective of this research was to quantify the impact of the non-optimal emergent behaviors of the current global air transportation system and the potential benefits that can be realized by improved coordination and optimization across system boundaries. The research focuses on improvements that can be made assuming "fixed" technology, i.e., system or aircraft level changes that could be implemented without the development of new technologies that do not yet exist.

8.1 Major Thesis Components

There are four major components to this research effort:

The first major component is the development of an existing aircraft performance model, the evaluation of baseline operations, and establishing a network model used to fly aircraft on direct or indirect missions. Because air transportation is a global industry and the effects of climate change are global in nature, the objective of the analysis is to determine the benefits of changes in behavior on a global scale. In order to do accomplish this, a baseline was established. A global fuel burn and detailed aircraft-type database was created by matching a global operations database with a performance tool for existing aircraft. A model was created to virtually fly the global network and establish the performance and operations baseline.

The second major component of the thesis is the design of thousands of aircraft with similar levels of technology and varying design reference missions. Because, the limits of the design reference mission space for a constant level of technology were not known a priori, a large number of aircraft designs were created in order to determine the edges of the feasible design space and performance within the space. Further, for each feasible aircraft in the DRM space, the mission performance, i.e., the performance of the aircraft on any mission in the unique, aircraft-specific payload/range diagram was not known a priori. Thus, a
similarly large number of missions were simulated for each feasible aircraft to determine the edges of the payload/range diagram and the performance on feasible missions.

The third major component is the development a comprehensive model of aircraft performance that is uniquely capable of solving large-scale network optimization problems. This was required because a global network analysis involves the simulation of millions of flight legs every time the performance of the system must be computed. The aircraft performance data for on-design and off-design missions were used along with a machine-learning algorithm to train an artificial neural network. The computational performance of the model is exceptional, as approximately 1 million aircraft can be designed, or alternatively, 1 aircraft can be flown on 1 million off-design missions in approximately 1 second.

The fourth and final major component of the thesis is a scenario analysis of the global air transportation network using the previously developed tools. The scenarios involve bounding the maximum theoretically possible benefits and determining a few 'realistic' ways to capture these benefits.

8.2 Summary of Results

8.2.1 Baseline
A global operations database and aircraft performance model was used to establish typical operator patterns. It was found that while operators utilize aircraft close to their payload capacity limits, they are frequently operated well below their design range.

An aircraft performance tool was used to compute the fuel burn for baseline aircraft in the global network. Narrow body aircraft tend to contribute the most fuel burn as they are operated the most frequently, but a disproportionately large amount of fuel burn is consumed by wide body aircraft on long range missions. This implies that an operational technique aimed at mitigating fuel burn on long-range flights would be appealing as it would affect a small number of flights yet have a large impact on fuel consumption. It was also found that the distribution of benefits from reductions in fuel burn might disproportionately benefit airports, countries, and regions with a large amount of long-range flights.

8.2.2 Design of Aircraft with Alternative DRM
The Transport Aircraft System OPTimization (TASOPT) tool was used to design and optimize a large set of new aircraft with fixed 2003 era technology and a wide diversity of
design-payload, -range, and -speed. Each of the aircraft represents the fuel-optimal aircraft designs for the given DRM at the fixed technology level. For each aircraft designed within the feasible space, a payload/range diagram was computed, and off-design missions were flown to simulate off-design performance.

Across the space of feasible designs, the best fuel efficiency on a design mission occurs for a vehicle with a design payload of approximately 150 passengers and a design range of approximately 4,000km (Figure 94), which aligns with analytical predictions from the Breguet Range Equation. Performance data also indicates fuel efficiency improves as design speed decreases. Additionally, off-design mission performance data indicates best mission efficiency near 4,000-5,000km, which is consistent with analytical predictions. This effect implies potential system wide benefits from (1) designing shorter-range aircraft with higher maximum efficiency and (2) flying aircraft closer to maximum fuel efficiency range, potentially using fuel stops.

8.2.3 Development of an Aircraft Performance Model for Fast-Time Simulation

A new method was presented to develop a comprehensive model of aircraft performance that is uniquely capable of solving large-scale network optimization problems. The model represents the performance of fuel-optimal aircraft designed with 2003 era technology and
is capable of flying these aircraft on feasible off-design missions to determine mission fuel burn and flight time. The aircraft performance data for on-design and off-design missions were used along with a machine-learning algorithm to train an artificial neural network. Validation against a large dataset of known-performance data was completed and the results indicate that the fuel burn model is able to predict aircraft performance with a normally distributed error, mean error of 0.31%, and a standard deviation of 0.40%. The computational performance of the model is exceptional, as approximately 1 million aircraft can be designed, or alternatively, 1 aircraft can be flown on 1 million off-design missions in approximately 1 second.

8.2.4 AIR TRANSPORTATION SYSTEM SIMULATION

The previously developed models were used to solve scenarios related to introducing new aircraft into the air transportation system. Scenarios are grouped into two major analyses: (1) establishing the limits of the major contributors to system fuel consumption and (2) determining realistic benefits from changing aircraft DRM.

An updated accounting of system fuel consumption is shown in Figure 95. It was determined that the slow rate of retirement in the operational fleet leads to a technology lag that accounts for 33.78% of system fuel consumption. Further, it was found that by ideally sizing an aircraft to fly every mission, another 23.8% of system fuel burn could be affected. Fuel optimal aircraft were selected for a variety of Mach numbers using a serial-selection technique, and it was determined that Mach 0.72 lead to the greatest potential system fuel improvements. However, aircraft with a cruise Mach number of 0.72 were determined to increase transcontinental US flight times by 20-30 minutes, and transpacific flight times by approximately 1 hour. A globally optimum (any Mach) aircraft selection technique was developed, and the five selected aircraft lead to a 47.41% savings in system fuel consumption. The selected aircraft tend to follow typical narrow-body, wide-body, regional jet patterns for design-payload and -range.
Figure 95: Updated System Fuel Consumption

Fuel stops were considered as a potential way to change the network and take advantage of appropriately sized aircraft. Fuel stops represent a solution to the real options trade between aircraft design flexibility and efficiency. It was determined that an additional 3% of system fuel savings can be achieved with the introduction of fuel stops, with the resulting optimum aircraft having significantly shorter design-ranges. Approximately 66% of these savings are due to the fuel stops themselves, while the remaining 33% is due to flying more appropriately sized aircraft on short and medium range missions. Fuel stops can yield significant savings, e.g. 10-15%, on ideally situated routes.

A summary of the major results and assumptions is included in Table 12 for reference.
Table 12: Summary table of Major Results and Assumptions

<table>
<thead>
<tr>
<th>Name</th>
<th>Major Scenario/Dataset Assumptions</th>
<th>Result / Savings</th>
<th>Against</th>
</tr>
</thead>
</table>
| Current Aircraft Performance | • Piano aircraft performance tool  
• Maximum Range Cruise speed  
• Step-climb cruise profile  
• 5% reserve fuel carried on flight | 389 Aircraft Types | - |
| New Aircraft Performance | • TASOPT aircraft design and optimization tool 
• Fixed B777-300ER era technology 
• Vehicles optimized for minimum fuel on DRM 
• Fixed cruise speed (design speed) 
• Cruise-climb cruise profile 
• 5% reserve fuel carried on flight 
• Response surface relates DRM and mission to mission FB | 16,202 Aircraft; 3.0x10^7 missions; 1 response surface | - |
| Baseline | • April 2006 global passenger flights (COD)  
• Missions flown by Piano aircraft | 1.049x10^8 kg system fuel | - |
| Intermediate Stop Operations | • April 2006 global passenger flights (COD)  
• Missions flown by Piano aircraft | | - |
| Fleet Modernization | • Baseline vehicles are upgraded to 2003 era technology  
• Baseline missions are flown with upgrade vehicles | 33.78% Baseline | - |
| Optimally Sizing Aircraft to Demand | • Optimal new aircraft is found for each baseline mission | 57.58% Baseline | - |
| Optimal Selection of Aircraft at Fixed Mach Number (0.84M) | | | Cumulative Savings From Baseline |
| | New aircraft are introduced into fleet  
• Replace baseline aircraft on mission-fuel basis  
• Aircraft resulting in min system fuel burn is selected  
• Process is repeated to find additional new aircraft | 150/6000/0.84 16%  
250/14400/0.84 20%  
400/13200/0.84 35%  
100/4100/0.84 38%  
210/8700/0.84 41% | |
| Optimal Selection of Aircraft at Fixed Mach Number (0.72M) | | | Cumulative Savings From Baseline |
| | New aircraft are introduced into fleet  
• Replace baseline aircraft on mission-fuel basis  
• Aircraft resulting in min system fuel burn is selected  
• Process is repeated to find additional new aircraft | 156/5472/0.72 19%  
250/12000/0.72 32%  
200/10800/0.72 46% | |
| Globally Optimum Aircraft Selection | | | Cumulative Savings From Baseline |
| | New aircraft are introduced into fleet  
• Replace baseline aircraft on mission-fuel basis  
• Network changes via fuel stops are permitted  
• Aircraft allowed to stop at real airports w/ runway >=10kft | 150/6000/0.72 16%  
400/12000/0.72 44%  
250/9600/0.72 47%  
52/2272/0.68 57% | |
| Joint Optimization of Aircraft Including Fuel Stops (0.72M) | | | Cumulative Savings From Baseline |
| | New aircraft are introduced into fleet  
• Replace baseline aircraft on mission-fuel basis  
• Network changes via fuel stops are permitted  
• Aircraft allowed to stop at real airports w/ runway >=10kft | 150/6000/0.72 16%  
400/12000/0.72 44%  
250/9600/0.72 47% | |

8.3 Discussion of Results and Future Work

8.3.1 Models Developed in the Thesis

Large-scale air transportation system analyses have historically been limited by computational time, especially when considering the joint optimization of aircraft and networks/operations. The method presented in this research, i.e. generation of a wide range of performance data, and then training an artificial neural network using an established machine-learning algorithm solves many of the traditional computational issues. This method for creating a comprehensive model of aircraft performance is promising for a wide range of analyses.

An additional benefit of the artificial neural network method is that it is not required to know any of the underlying non-linear, usually high-dimensional relationships a priori. Assuming an appropriate testing and validation procedure is carried out, any number of additional dimensions could be added to the neural network, e.g., operational speed, material properties, engine efficiencies, fuselage scaling methods, etc. However, adding dimensions will require a more carefully designed sampling of the resulting experiment space, as the process of designing aircraft is time consuming. In high-dimensional spaces, the Curse of Dimensionality can become increasingly relevant as the volume of space rapidly increases and the samples become increasingly sparse. An artificial neural network trained on even a significantly larger dimension of data should still yield computational performance close to that presented in this thesis.

It should be noted that this type analysis is only made possible with the very recent creation of first-principles based aircraft conceptual design tools, such as TASOPT. Because TASOPT is based on low-order physics models (e.g. inline CFD for aero, individual structural member stress and weight modeling, etc.) rather than correlation based, it gives confidence that the resulting designs are consistent with physics. Thus, if this data is used to train a validated artificial neural network with sufficiently low validation errors, that model will in turn be consistent with the underlying physics.

8.3.2 Scenarios Evaluated in the Thesis

It is interesting to consider the relative system fuel savings between various fuel mitigation techniques. For example, improvements in altitude and speed operations can each yield approximately 2% improvement in system fuel burn, and improvements in network topology can yield approximately 1% improvement in system fuel burn. Meanwhile, updating the average technology in the fleet, without changing design-payload, -range, or -
speed, can yield improvements of 33% by updating to 2003 era technology. Given aircraft useful life measured in decades, it is likely that this 33% “bubble” of inefficiency will continually persist in the air transportation industry. With this in mind, policies targeted at phase-outs of old aircraft can have a significant impact on system fuel burn.

There also exists a significant pool of benefits available from “right-sizing” aircraft for each mission. However, the reality of the air transportation industry, including unavoidable capital limitations, prevents a large number of right-sized aircraft types from being manufactured and operated as in the ideal scenario. When individual optimal aircraft are selected based on their design reference mission, the selected aircraft tend to follow typical narrow-body, wide-body, regional-jet sizes. This reflects two phenomena: (1) the transportation network was maintained at the flight leg level so some underlying operational patterns perpetuate, and (2) more importantly, by only allowing the introduction of a few aircraft types, minimizing system fuel requires the resulting aircraft to be operationally versatile, as in real operations.

One way to consider breaking traditional operational patterns is by reducing the flexibility of aircraft types in an effort to increase aircraft-level efficiency. In order to service long-range demand, short and medium range aircraft would then use a fuel stop. If, for example, all existing long-range aircraft were replaced with shorter design-range aircraft and the same missions were serviced, either directly or with fuel stops, this would result in approximately 15% savings of total system fuel consumption. These savings are partly due to replacing old aircraft with updated technology, partly due to savings on ISO flights, and partly due to savings from a shorter-design range aircraft with higher efficiency flying direct routes. This 15% represents approximately a decade of expensive technology development according to the ICAO CAEP Report of the Independent Experts on Fuel Burn Reduction and Technology Goals [25].

Future high fuel price scenarios might drive the increasing use of more fuel stops on long haul flights. Airports that are ideally geographically positioned on major routes between cities could see an increased incentive to develop infrastructure. This effect can be economically promising for local areas surrounding major fuel stop hubs. However, a future study should consider the costs associated with fuel stops, including landing fees, impacts on passenger utility, network connectivity, crew costs, etc.

A future analysis might also leverage the flexibility vs. efficiency framing to evaluate the impact of reducing flight frequency on segments of interest by consolidating passenger demand onto larger, shorter-range aircraft. This analysis would require an updated operations dataset that includes schedule time, as well as a model to evaluate the changes in
demand as a result of decreased frequency and the impact on captured market share. However, the artificial neural network model of aircraft performance created in this thesis is uniquely capable of solving this problem on a very large scale, including as part of a large-scale, computationally intensive optimization problem.

Reductions in design speed appear particularly promising, as system fuel burn reductions on the order of 7% are possible simply from slowing down. However, a reduction in speed to Mach 0.72 would result in an additional 20-30 minutes on a 5 hour cross continental US flight. The cost implications and schedule risk for airlines and passenger utility should be considered in greater detail. Given the similarities between cruise-speed reductions and fuel stops, an analysis of the costs implications of one of these operational techniques should leverage the results from the other. It is expected that high fuel price scenarios would increase the incentive to developed reduced speed aircraft, in which case the system might evolve to reduce costs by optimally utilize the aircraft on updated networks and schedules.
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and Local NLP Solvers: A Multistart Framework for Global Optimization,”


[70] B. Miller and J. P. Clarke, “Strategic Guidance in the Development of New
Aircraft Programs: A Practical Real Options Approach,” *Engineering

## Appendix A

### Common Operations Database Country and Abbr. List

#### Table 13: Countries and Abbreviations Included in the Common Operations Database (REGION - Africa)

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#### Table 14: Countries and Abbreviations Included in Common Operations Database (REGION - Asia/Pacific)

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Table 15: Countries and Abbreviations Included in the Common Operations Database (REGION – Europe)

Table 16: Countries and Abbreviations Included in the Common Operations Database (REGION – Latin America / Caribbean)
### Table 17: Countries and Abbreviations Included in the Common Operations Database (REGION – Middle East)

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### Table 18: Countries and Abbreviations Included in the Common Operations Database (REGION – North America)

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## Appendix B  Operations Database and Performance Database Matching Results

Table 19: Mapping Aircraft Listed in Operations Database with Performance Database

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*Note: - indicates no available aircraft match.*
Appendix C

Example TASOPT Input File

# configuration name
777-300ER (optimized)

# case description (2 lines)
Baseline technology
Aluminum, turbulent wing

# execution control flags and limits
F ! Litprint print every weight iteration?
100 ! iterwmax max number of weight iterations for design mission
100 ! iterfmax max number of fuel iterations for off-design missions

T ! Lopt optimize variables?
F ! Loprint print every optimization iteration?
1500 ! istepmax max number of optimization-descent steps
100 ! istepout number of opt. steps between solution re-output
0.01 ! Wftol fuel-weight tolerance for optimum [N]

T ! LBFcon constrain IBF < IBFmax during optimization?
T ! LWfmaxcon constrain Wfuel < Wfmax during optimization?
F ! Lbmaxcon constrain b < bmax during optimization?
T ! Lgtoccon constrain g-toc > gtocmin during optimization?

T ! Loutwrite write output to xxx_iNN_jMM.out files?
F ! Lfblwrite write fuse BL to xxx_iNN_jMM.out files?
F ! Ltrpwrite write Trefftz to xxx_iNN_jMM.out files?
F ! Lsavwrite write optimized vars to xxx.sav restart file?
F ! Laswwrite write output to xxx.asw Aswing-input file?

# Keywords of parameters which can be sequenced in "i" or "j" loops,
# declared as array cpars, in index.inc
# A parameter cannot be chosen here if it's also selected as
# an optimized variable farther below
#
# Mach = cruise Mach
# Nmax = max in-flight load factor
# sigfac = max-stress multiplier
# AR = overall aspect ratio
# sweep = wing sweep
# etas = strut-attach eta location
# Tt4CR = cruise Tt4
# Tt4TO = takeoff Tt4
# OPR = overall pressure ratio
# FPR = fan pressure ratio
# lBFmax = balanced field length
# bmax = max span for span constraint

#-----------------------------
#- "i" parameter sequence values (overrides value given later in file),
# AR ! 8 9 10 11 12

#- corresponding MATLAB-plotting label and line colors
"AR = (blue) 8, 9, 10, 11, 12 (magenta)
"bcgrm"

#-----------------------------
#- "j" parameter j sequence values (overrides value given later in file)
Mach ! 0.80 0.78 0.76 0.75 0.74 0.73 0.72 0.71 0.70

#- corresponding MATLAB-plotting x-axis label
"Mach"

#-----------------------------
#- Variables to be optimized (if Lopt=T), and their initial perturbations
#- Keywords are declared as array cparo , in index.inc
#- A zero or missing perturbation value disables the optimization of that variable
CL  0.001  ! cruise CL
AR  0.05   ! overall aspect ratio
sweep 0.025  ! wing sweep angle
hboxo 0.00025  ! airfoil t/c at etao (wing root)
hboxs 0.00025  ! airfoil t/c at etas (planform break)
lambdas 0.0005  ! inner panel taper ratio
lambdat 0.0005  ! outer panel taper ratio
rcs 0.001  ! local cl scale at etas (planform break)
rct 0.001  ! local cl scale at 1 (tip)
FPR 0.005  ! fan pressure ratio
BPR 0.025  ! baypass ratio
alt 10.0   ! start-of cruise altitude
Tt4CR 0.5   ! cruise Tt4
Tt4TO 0.25  ! takeoff Tt4
OPR 0.05   ! overall pressure ratio (pilc assumed fixed)

#-----------------------------
#- fleet mission specification
#- (first one is the weight-sizing design mission)

1.0 0 0 0 0  ! [... input truncated for reproduction]
           ! (these also set the number of missions evaluated)

#- parameters for each mission
#- (all same values used if only one value is given)
6000 240 480 720 !Range [... input truncated for reproduction]
350 0 0 0 0 !Payload [... input truncated for reproduction]
215.0 * 4.45 !Wpx(*) PAX weight (including baggage)
0.0 * 0.3048 !altTO takeoff/landing altitude [m]
288.0 !TOTO ambient takeoff/landing temp [K]

#- Design cruise-start altitude (with max fuel, max payload)
32000.0 * 0.3048 !altCR cruise-start altitude [m]

#- Takeoff and initial climb parameters
2.8 !clpmax wing max cl_perp = Clmax/cos(sweep)^2

0.500 !cdefan CDA_fan /A_fan of dead engine in engine-out climb
0.015 !Cddefan CDA_fan/S during climb
0.10 !Cdspoiler CDA_spoiler/S during climb
0.025 !muroll rolling-resistance coefficient
0.35 !mubrake braking-resistance coefficient

35.0 * 0.3048 !hobst obstacle height

10000.0 * 0.3048 !LBFmax specified max takeoff length for takeoff constraint
0.015 !gtocmin specified min top-of-climb gradient
90.0 !dBSLmax max dBA for sideline
75.0 !dBSLmax max dBA for cutback

40.0 !thetaCB cutback sight angle
3.0 !gammaCB prescribed cutback climb angle

-2.0 !gammaDE1 prescribed descent angle at top of descent
-3.0 !gammaDEN prescribed descent angle at bottom of descent

#- sizing-load parameters
3.0 !Nlift max vertical load factor for wing bending loads
6.0 !Nland max vertical load factor for fuse bending loads
280.0 * 0.514 !Vne never-exceed IAS, for tail loads

8000.0 * 0.3048 !cabin pressure altitude

#- cruise aero parameters
0.476 !CL
0.72 !Mach

#- basic wing parameters
32.50 !sweep wing sweep angle
8.55 !AR overall wing aspect ratio

176.38 * 0.3048 !bmax max span for span constraint (if selected)
0.78 ! lambdas inner panel taper ratio cs/co ( = 1.0 for single taper)
0.175 ! lambdat outer panel taper ratio ct/co

! 0   ! iwplan (cantilever wing, bare)
   1   ! iwplan (cantilever, engine mounted at eta=etas)
   2   ! iwplan (strut braced, strut attach at eta=etas)

! 0   ! ifwcen (no fuel in center wing box)
   1   ! ifwcen (fuel in center wing box)

0.90 ! rWfmax usability factor of max fuel volume

-0.3 ! fLo fuselage lift carryover loss factor
-0.05 ! fLt tip lift rolloff factor

135.82 * 0.0254 ! zs strut vertical base (used only if iwplan=2)
105.83 * 0.0254 ! yo wing centerbox halfspan
0.32 ! etas panel break eta location (strut-attach if iwplan=2)

1.0 ! rVstrut strut local/freestream velocity ratio

#-----------------------------
# tail download parameter at max load case (download looks like added weight)
-0.5 ! CLh / CLmax

#-----------------------------
# wing spanwise cl and cm distributions over mission
# ( rclo = clo/clo = 1.0 by definition, so it’s not specified )

#- takeoff, initial climb
1.1 ! rcls break/root cl ratio = cls/clo
0.6 ! rclt tip/root cl ratio = clt/clo
-0.30 ! cmpo root cm
-0.30 ! cmps break cm
-0.05 ! cmpt tip cm

#- clean climb, cruise, descent, also for wing structure sizing
0.980 ! rcls
1.050 ! rclt
-0.10 ! cmpo
-0.10 ! cmps
-0.10 ! cmpt

#- landing, forward-CG tail sizing case
1.0 ! rcls
0.5 ! rclt
-0.40 ! cmpo
-0.40 ! cmps
-0.05 ! cmpt

#-----------------------------
# wing and tail structural box parameters
0.50 !wbox  box width/c
0.1455 !hboxo box height/c (airfoil t/c) at root
0.1400 !hboxs box height/c (airfoil t/c) at break and tip
0.75 !rh web-height/hbox ratio
0.40 !xaxis spar box axis x/c location
0.15 !hstrut strut t/c (used only if iwplan=2)

# weight fractions of flight surfaces and secondary wing components,
# as fractions of wing box (sum = fwadd)
0.200 !fflap
0.100 !fslat
0.040 !faile
0.100 !flete
0.150 !fribs
0.020 !fspoi
0.030 !fwatt

# horizontal and vertical tail parameters
!1 !iHTsize set Sh via Vh
2 !iHTsize set Sh via Clhkick at max-forward CG during landing
1.2 !Vh HT volume coefficient (only used if iHTsize=1)
-1.00 !Clhkick HT Clh at forward CG trim (only used if iHTsize=2)

1 !iVTsize set Sv via Vv
!2 !iVTsize set Sv via Clvyaw on engine-out
0.06 !Vv VT volume coefficient (only used if iVTsize=1)
1.0 !Clvyaw VT Clh at engine-out trim (only used if iVTsize=2)

!0 !ixwmove fix wing position
!1 !ixwmove move wing to get Clh=Clhspec in cruise
2 !ixwmove move wing to get min static margin = SMmin
-0.02 !Clhspec HT Clh in cruise (used only if ixwmove=1)
0.15 !SMmin min SM with aft CG (used only if ixwmove=2)

1.04 !dClh/dCL lift-curve slope factor for NP calculation
0.60 !deps/da downwash factor at tail

10.70 !dCln/dCL nacelle lift-slope ratio for NP calculation
3.8 !dCln/da nacelle lift-curve slope for NP calculation

4.8 !ARh HT aspect ratio
2.35 !ARv VT aspect ratio
0.32 !lambdah HT taper ratio
0.25 !lambdav VT taper ratio
33.0 !sweeph HT sweep
28.0 !sweepv VT sweep

4.41 * 0.3048 !yoh HT support y location
0.0 ! yov VT support z location

0.1 ! fCDhten  CDhtail contribution factor for center part  0 < y < yoh

1.5 ! CLhmax  HT max +/- CL at Vmn, for HT structural sizing
2.0 ! CLvmax  VT max +/- CL at Vmn, for VT structural sizing

0.30 ! fhadd  HT added-weight fraction (e.g. ribs,LE,elevator, attach)
0.40 ! fadd   VT added-weight fraction (e.g. ribs,LE,rudder, attach)

0.50 ! wboxh  HT box width/chord
0.50 ! wboxv  VT box width/chord
0.14 ! hboxh  HT box height/chord (airfoil t/c)
0.14 ! hboxv  VT box height/chord (airfoil t/c)
0.75 ! rhh   HT web-height/hbox ratio
0.75 ! rhv   VT web-height/hbox ratio

1 ! nvtail  number of vertical tails

#--------------------------------------------------------
#  cabin and fuselage geometry parameters

107.59 * 0.0254 ! Rfuse
0.0 * 0.0254 ! dRfuse
0.0 * 0.0254 ! wbd
7.06 * 0.0254 ! hfloor

1.65 ! anose  nose radius = Rfuse*(1 - xi^anose)^(1/anose)
2.0 ! btail  tail radius = Rfuse*(1 - xi^btail)

7.06 * 0.3048 ! xnose nose tip location
216.07 * 0.3048 ! xend tail tip location
35.28 * 0.3048 ! xblend1 start of cylindrical section
150.81 * 0.3048 ! xblend2 end of cylindrical section
33.51 * 0.3048 ! xshell1 front of pressure shell (center of nose ellipse)
179.91 * 0.3048 ! xshell2 end of pressure shell (center of end bulkhead)
207.25 * 0.3048 ! xconen end of tailcone primary structure
100.54 * 0.3048 ! xwbox wing centroid location
198.43 * 0.3048 ! xhtail HT centroid location
186.97 * 0.3048 ! xvtail VT centroid location

-5.29 * 0.3048 ! zwing wing box z location ! for Trefftz plane
12.35 * 0.3048 ! zhtail HT box z location ! definition

1 ! iengloc  engine location (1 = wing, 2 = fuselage)

89.96 * 0.3048 ! xeng engine x location
28.22 * 0.3048 ! yeng critical-engine y location
2 ! neng  number of engines

0.3 ! lambdac  tailcone taper ratio

0.34 ! fstring  Wstringer/Wskin
0.24 \ fframe \ Wframe \ /Wskin
0.20 \ fadd \ Wfadd \ /Wskin

3000.0 * 4.45 \ !Wfix(.) \ added \ fixed \ weight \ (pilots,cockpit)
8.82 * 0.3048 \ xfix \ location \ of \ Wfixs \ c.g.

145.0 \ !W\'window \ Wwindow/length \ [N/m] \ @
40.0 \ !W\"insul \ Winsul/area \ [N/m^2] \ @
60.0 \ !W\"floor \ Wfloor/area \ [N/m^2] \ @ \ (floor \ planking, \ not \ beams)

0.4 \ !rMh \ HT-load \ fuselage \ bending \ moment \ inertial \ relief \ factor
0.7 \ !rMv \ VT-load \ fuselage \ bending \ moment \ inertial \ relief \ factor

0 \ !ifclose \ (taper \ fuselage \ to \ a \ point)
1 \ !ifclose \ (taper \ fuselage \ to \ an \ edge)

6104.83 * 0.0283 \ !CMVf1 \ fuselage \ moment \ volume \ derivative \ \frac{d(Mfuse/q)}{dCL}
0.185 \ !CLMI1 \ \frac{d^{2}M}{dCL^{2}} \ \frac{dCL}{dCL}

0.019 \ !fduo \ fuselage \ velocity \ overspeed \ at \ wing \ root
0.014 \ !fdu \ fuselage \ velocity \ overspeed \ at \ wing \ break
0.004 \ !fdu \ fuselage \ velocity \ overspeed \ at \ wing \ tip

#---------------------------------------------
#- power \ systems \ and \ landing \ gear \ locations \ and \ weight \ fractions
#---------------------------------------------

110.24 * 0.3048 \ !xhpesys \ hyd/pneu/ele \ system \ location
24.69 * 0.3048 \ !xlgm \ nose \ LG \ location
2.65 * 0.3048 \ !dxlgmain \ main \ LG \ offset \ behind \ wing \ lift \ centroid

0.010 \ !fhp \ Whpesys/WMTO
0.010 \ !flg \ Wlgm/nose/WMTO
0.040 \ !flg \ Wlgmain/WMTO

#---------------------------------------------
#- \ other \ added-weight \ fractions
#---------------------------------------------

204.6 * 0.3048 \ !xapu \ APU \ location
0.035 \ !fapu \ Wapu/Wpay \ APU \ weight \ fraction

0.10 \ !fseat \ Wseat/Wpay \ seat \ weight \ fraction
0.35 \ !fpadd \ Wpadd/Wpay \ other \ payload-proportional \ fraction

0.10 \ !feadd \ Wadd/Wbare \ engine \ accessories, \ fuel \ system \ fraction @
0.05 \ !fpylon \ Wpylon/We+a+n \ engine \ pylon \ weight \ fraction @
0.05 \ !freserve \ Wreserve/Wburn

#---------------------------------------------
#- \ allowable \ stresses \ at \ sizing \ cases
1.0 \ !sigfac \ convenient \ multiplier \ on \ all \ the \ stress \ values \ below

15000.0 / 0.000145 \ !sigskin \ fuselage \ pressurization \ skin \ stress
30000.0 / 0.000145 !sigbend fuselage bending skin+stringer stress
30000.0 / 0.000145 !sigcap wing, tail bending caps
20000.0 / 0.000145 !tauweb wing, tail shear webs
30000.0 / 0.000145 !sigstrut strut

#- fuselage shell modulus ratio, for bending material sizing
1.0 !rEshell Ebend/Eskin ratio

#- moduli, for strut-induced buckling load estimation
10.0e6 / 0.000145 !Ecap wing spar cap
10.0e6 / 0.000145 !Estrut strut

#- structural material densities
2700.0 !rhoskin fuselage skin
2700.0 !rhobend fuselage bending stringers
2700.0 !rhocap wing, tail bending caps
2700.0 !rho web wing, tail shear webs
2700.0 !rhostrut strut

#- database for wing profile cd in transonic cruise, high climb
!B.air !B-series airfoils
!C.air !C-series airfoils
!Cl.air !C-series airfoils with laminar bottom

0.0085 !cdfw wing profile cd for low speed (takeoff, initial climb)
0.0035 !cdpw
20.0e6 !Reref w

0.0060 !cdft tail profile cd
0.0035 !cdpt
10.0e6 !Rer eft

0.0085 !cdfs strut profile cd (not used if there's no strut)
0.0035 !cdps
1.0e6 !Rerefs

-0.15 !aRexp exponent for Re-scaling: CD = cd * (Re/Re-ref)^aRexp
1.05 !fexdw wing excrescence drag factor
1.05 !fexc dt tail excrescence drag factor
1.08 !fexcdf fuse excrescence drag factor

0.0 !fBLiw fraction of wing-BL KE defect ingested
0.0 !fBLIf fraction of fuse-BL KE defect ingested
0 !iBLIc 0 = core in clean flow, 1 = core ingests KE defect (if any)

#- fuel parameters
# ifuel = 11 !methane

171
ifuel = 12 ! ethane
ifuel = 13 ! propane
ifuel = 14 ! butane
ifuel = 18 ! octane
ifuel = 24 ! kerosene (C14H30)

rhotfuel = 423.0 methane
rhotfuel = 547.0 ! ethane
rhotfuel = 582.0 ! propane
rhotfuel = 600.0 ! butane
rhotfuel = 700.0 ! octane
rhotfuel = 817.0 ! kerosene

24 ! ifuel
817.0 ! rhotfuel
280.0 ! Tfuel

#----------------------------------------
#- engine temperatures
#---- E3 engine
#  hot day T/O Tt41 = 2480F = 1360K
#  max cruise Tt41 = 2190F = 1199K
#
# 2000 F = 1366 K
# 2100 F = 1423 K
# 2700 F = 1755 K
# 2900 F = 1866 K
# 3100 F = 1977 K

1300.0 ! Tmetal
1760.0 ! Tf4TO takeoff
0.2 ! fTt4CL1 bot of climb Tt4 fraction over Tf4TO .. Tf4CR
0.2 ! fTt4CLn top of climb Tt4 fraction over Tf4TO .. Tf4CR
1575.0 ! Tf4CR cruise

#----------------------------------------
#- turbine cooling parameters
200.0 ! dTstrk hot-streak temperature allowance
1.0 ! Mtexit turbine blade row exit Mach, for temperature drops
0.08 ! StA area-weighted effective Stanton number
0.7 ! efilm blade-to-cooling flow heat transfer efficiency
0.30 ! tfilm cooling-film effectiveness factor
1.0 ! M4a Mach number at start of cooling-air mixing zone
0.30 ! ruc u_cool/u_edge velocity ratio of exiting cooling air

#-----------------------------
#- design pressure ratios, efficiencies, etc.

42.0 ! OPR overall pressure ratio
18.0 ! pihc HPC pressure ratio
1.58 ! FPR fan pressure ratio
0.995 ! pid diffuser pressure ratio
0.94 ! pib  burner pressure ratio
0.985 ! pin  fan nozzle pressure ratio
0.995 ! ptn  core nozzle pressure ratio
0.91 ! epolf fan poly efficiency at FPR = FPRo
0.90 ! epolc LPC poly efficiency
0.89 ! epolhc HPC poly efficiency
0.90 ! epolht HPT poly efficiency
0.90 ! epollt LPT poly efficiency

1.55 ! FPRo  | fan efficiency function constants
-0.077 ! K_epf | epolf_actual = epolf + K_epf*(FPR-FPRo)

8.8 ! BPR  bypass ratio
1.0 ! Gearf LPC/fan speed ratio
0.30 ! HTRf  fan hub/tip ratio
0.60 ! HTRlc LPC hub/tip ratio
0.80 ! HTRhc HPC hub/tip ratio

0.60 ! M2  fan-face Mach number
0.60 ! M25 HPC-face Mach number

#---------------------------
#- fan nozzle area factors relative to cruise design area
1.0 ! static
1.0 ! rotation/takeoff
1.0 ! cutback
1.0 ! climb1
1.0 ! climbn
1.0 ! descent1
1.0 ! descentn

#---------------------------
#- core nozzle area factors relative to cruise design area
1.0 ! static
1.0 ! rotation/takeoff
1.0 ! cutback
1.0 ! climb1
1.0 ! climbn
1.0 ! descent1
1.0 ! descentn

#---------------------------
#- nacelle drag stuff
12.0 ! rSnace  nacelle+pylon wetted area/fan area  Snace/Afan
1.02 ! rVnace  nacelle local freesteam velocity ratio

#---------------------------
#- engine weight model
1 ! iengwgt = 0 MD's original model
   = 1 NF's new model, basic tech  | ungeared if Gearf = 1,
   = 2 NF's new model, advanced tech | geared  if Gearf /= 1
Appendix D

Fixed Cruise Mach Simulation Results

Figure 96: Fixed Cruise Mach 0.68 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space
Figure 97: Fixed Cruise Mach 0.70 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space

Figure 98: Fixed Cruise Mach 0.72 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space
Figure 99: Fixed Cruise Mach 0.74 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space

Figure 100: Fixed Cruise Mach 0.76 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space
Figure 101: Fixed Cruise Mach 0.78 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space

Figure 102: Fixed Cruise Mach 0.80 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space
Figure 103: Fixed Cruise Mach 0.82 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space

Figure 104: Fixed Cruise Mach 0.84 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and Range Space
Figure 105: Fixed Cruise Mach 0.86 Aircraft Selections and System-Level Fuel Benefits Across Design-Payload and -Range Space