A METHODOLOGY FOR EVALUATING FLEET IMPLICATIONS OF MISSION SPECIFICATION CHANGES

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A METHODOLOGY FOR EVALUATING FLEET IMPLICATIONS OF MISSION SPECIFICATION CHANGES

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ACARE	Advisory Council for Aeronautics Research in Europe
ACSYNT	AirCraft SYNThesis
AEDT	Aviation Environmental Design Tool
AERO-MS	Aviation Emissions and Evaluation of Reduction Options – Modeling System
AIM	Aviation Integrated Modeling
ANGIM	Airport Noise Grid Integration Method
APMT-E	Aviation Portfolio Management Tool - Economics
AVID-ACS	AVID AirCraft Synthesis
CAEP	Committee for Aviation Environmental Protection
CO_2	Carbon Dioxide
DNL	Day-Night-Level
EDMS	Emissions and Dispersion Modeling System
EDS	Environmental Design Space
FAA	Federal Aviation Administraion
FLOPS	FLight OPtimization System
GAO	General Accounting Office
GREAT	Global and Regional Environmental Aviation Tradeoff tool
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
IPPD	Integrated Product/Process Development

ISO	Intermediate Stop Operations
JPDO	Joint Planning and Development Office
LQ	Large Quad model
LRC	Long Range Cruise
LTA	Large Twin Aisle model
M&S	Modeling and Simulation
MAGENTA	Model for Assessing Global Exposure from Noise Transport Aircraft
MDCAD	Multi-Disciplinary Concept Assessment and Design
MIDAS	Multi-criteria Interactive Decision-making Advisor and Synthesis
MRC	Maximum Range Cruise
MS-FIT	Mission Specifications and Fleet Implications Technique
MSP	Maximum Structural Payload
MTOW	Maximum Take off Weight
NASA	National Aeronautics and Space Administration
NO_x	Nitrous Oxides
OEW	Operating Empty Weight
OID	Origin - Intermediate Stop – Destination
OPR	Overall Pressure Ratio
PASS	Program for Aircraft Synthesis Studies
PIANO	Project Interactive ANalysis and Optimization
PrADO	Preliminary Aircraft Design and Optimization

RETIVO	Requirements Exploration, Technology Impact, and Value Optimization
RJ	Regional Jet model
SA	Single Aisle model
SAGE	System for assessing Aviation’s Global Emissions
SESAR	Single European Sky ATM Research
STA	Small Twin Aisle model
SUGAR	Subsonic Ultra Green Aircraft Research
TAF	Terminal Area Forecast

SUMMARY

Civil aviation has matured to become a vital piece of the global economy, providing the rapid movement of goods and people to all regions. This has already led to significant growth and expectations of further growth are on the rate of 5% per year. Given the high projected rate of growth, environmental consequences of commercial aviation are expected to rise. To mitigate the increase of noise and emissions, governing bodies such as ICAO and the FAA have established and are considering additional regulation of noise, NO_x, and CO_2 while the European Union has integrated aviation into their Environmental Trading Scheme. The traditional response to new regulation is to integrate technologies into the aircraft to reduce environmental footprint. While these benefits are positive on the aircraft level, fleet growth is projected to outpace benefits provided by technology alone. To further reduce environmental footprint, a number of mitigation strategies are being explored to determine the impact. One of those strategies involves changing the mission specifications of today's aircraft by reducing range, speed, or payload in an effort to reduce fuel consumption and has been predominantly focused at the vehicle level.

This research proposes an approach that evaluates mission specification changes from the aircraft design level up to the fleet level, forecasted into the future, to assess the impact over a number of metrics to fully understand the implications of mission specification changes. The methodology Mission Specifications and Fleet Implications Technique (MS-FIT) identifies stakeholder requirements that will be tracked at either the vehicle or fleet level and leverages them to build an environment that will allow joint evaluation to facilitate increased knowledge about the full implications of mission specification adoption.

Additionally laid out is an approach on how to select prospective routes for intermediate stops based on fuel burn and operating cost considerations. Guidance is provided on how to filter down a list of candidate airports to those most viable as well as regions of the world most likely to benefit from intermediate stops.

Three sample problems were used to demonstrate the viability of MS-FIT: cruise speed reduction, design mission range reduction, and the combination of speed and range reduction. Each problem was able to demonstrate different implications from the implementation of the different specification changes. Speed reduction can negatively impacts cost while range reduction has consequences to noise at the intermediate airports. The combination of the two draws in negative implications from both even though the environmental benefits are better.

Finally, an analysis of some of the assumptions was conducted to examine the sensitivity to the results of speed and range reduction. These include variation in costs, reductions in annual utilization of aircraft, and variation in intermediate stop adoption. Speed reduction is strongly sensitive to increases in crew and maintenance rates while landing fees significantly eat into the benefits of range reduction and intermediate stops. Minor utilization reductions can significantly reduce the viability of speed reduction as the increase in capital costs offset all the savings from fuel reduction while range

reduction is a little less sensitive. Intermediate stop variation does not eliminate the benefits of range reduction and even can provide cost savings depending on the design range of the reduced variant but it can have consequences to airport noise to higher traffic airports.

With the proposed framework, additional information is available to fully understand the implications with respect to fuel burn, NO_x emissions, operating cost, capital cost, noise, and safety. This can then inform decision makers on whether pursuing a particular mission specification strategy is advantageous or not.

CHAPTER 1

INTRODUCTION

Aviation has matured over the last fifty years to become a vital piece of the global economy and critical for the American economy, enabling the rapid movement of goods and people to all regions. Even in the face of growing American trade deficits, aviation continues to be the largest export sector for the United States and contributes to $1.3 trillion of economic activity – consisting of 5.6% of gross domestic product. In 2007 the U.S. airspace was responsible for 767 million passengers, 836 billion revenue passenger miles, 67 billion revenue ton miles of freight, and 61.1 million aircraft operations.[1]

The expected growth of aviation is significant moving forward. The Boeing Current Market Outlook forecasts a 5.1% growth in revenue passenger kilometers from 2010 to 2030.[2] It projects the most significant growth to occur in the Middle East, the Asia-Pacific region, Africa, and Latin America with rates greater than 5% annually compared to the projected 3-4% of Europe and North America. The Airbus Global Market forecast projects an annual growth of 4.8% in revenue passenger kilometers from 2010 to 2029.[3] Growth rates for global regions are similar to those from the Boeing forecast. A comparison of both manufacturers' growth forecasts with respect to global revenue passenger kilometers is provided in Figure 1.

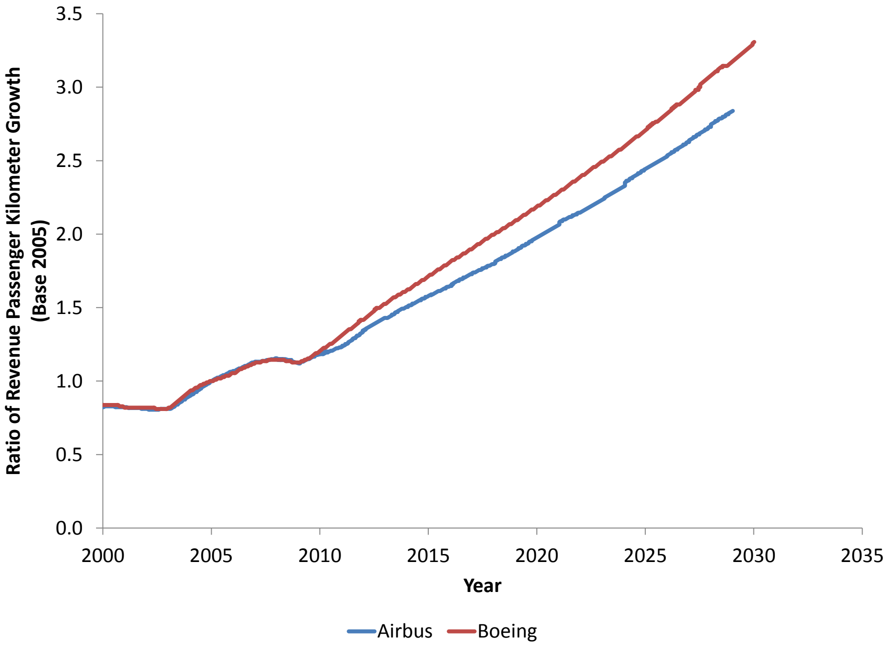


Figure 1. Growth Projections 2010-2030 [2][3]

The only major difference in the two manufacturer forecasts is the projected total fleet deliveries with respect to total global vehicle seat classes. Boeing expects to see far more growth in the single aisle class while Airbus expects significant growth in the large class. These projections are in line with recent and coming products from both manufacturers and are provided in Table 1. These are not individual company deliveries but projections on total fleet future deliveries.

Table 1. Projected Future Deliveries for Total Fleet [2][3]

Seat Class	Airbus	Boeing
Single Aisle	17,870	23,370
Twin Aisle	6,240	7,330
Large Quad	1,740	820

The anticipated growth in aviation will have far reaching effects on a variety of stakeholders, impacting the environment, economics, reliability, sustainability, safety, capacity, and security. A greater number of aircraft operations will result in a negative impact on the environment through increased emissions and noise. From an economic perspective, significant growth results in a greater demand for new aircraft and an increased number of operations provides more revenue for airlines. The reliability of the system could be measured in terms of the total amount of delay. As operations increase, increased traffic will likely lead to an increase in delay due to weather uncertainty, increased congestion, and air traffic control challenges.

Sustainability is impacted by increased growth through a required increase in materials for manufacturing and oil for fuel so more aircraft and operations will demand significantly more resources. Increasing operations around a limited number of airports means that if any delay occurs, more aircraft will be flying in close proximity to both the airport and each other, leading to increased potential for an accident or incident. A similar consequence of limited airports comes with capacity concerns as there is a limit to the numbers of departures and arrivals as capacity projects are unable to keep pace with rising demand. Finally, security becomes much more challenging as there is an increase in both passenger and cargo that is required to be scanned as well as flights in the air.

All of these concerns pose substantial challenges for continued aviation growth but together are too complex to assess simultaneously. The impact of increased aviation operations on environmental concerns of noise and emissions, however, is a major concern that needs to be better understood. Aircraft noise impacts the surrounding airport community and has been the primary cause for delay of expansion projects at airports.[4] Assessing the true impacts of noise is difficult because noise tolerance is subjective though it is important enough to cause health concerns such as sleep disturbance, stress, and cardiovascular problems.[5] The perception of airport noise is still negative such that people living outside of the significant noise areas around airports consist of over half of the related complaints. To offset some of the negative impacts of noise, the Federal Aviation Administration (FAA) has spent $9.1 billion on noise compatibility projects over 256 airports since 1982.[6] For Chicago O'Hare, the specific amount is $565 million to date.[7]

Nitrous Oxides (NO_x) and particulate matter worsen air quality in the airport area. Both of these emissions can damage lung function and worsen respiratory diseases like emphysema and bronchitis while also having a negative impact on the cardiovascular system. In a survey of major airports conducted in 2000, while noise was listed as the primary concern of airports regarding future growth with emissions being third, emissions will become more important in a future timeframe.[8] Significant attention is now starting to be paid to carbon dioxide (CO_2) as climate change concerns increase. There are concerns over the significance of aviation's contribution as the predominant amount of emission is at altitude where the impact is thought to be greater.[9]

Efforts to mitigate the environmental impacts of aviation have been undertaken for over forty years and continue today. Programs from organizations like the FAA, National Aeronautics and Space Administration (NASA), Joint Planning and Development Office (JPDO), and Advisory Council for Aeronautics Research in Europe

(ACARE) are investing a significant amount of money to both understand and mitigate environmental impacts. These programs focus on both technical and operational measures to reach their goals. As a part of International Civil Aviation Organization's (ICAO) efforts to confront climate change, a basket of measures was proposed that member states can adopt to meet climate change goals. These measures can be economic or market-based, regulatory, alternative fuels, improved air traffic management and infrastructure use, more efficient operations, and aircraft-related developments.[10] One of the difficulties of these proposed categories is that ICAO does not tell participating States how to go about identifying or selecting measures to meet environmental goals. It is simply left to each State to select measures that are deemed appropriate. This in itself is a challenging problem as the last four categories can potentially have a significant number of measures that would provide potential improvements.

Tax implementation uses a financial penalty to encourage operators to reduce their impact whether it is through more efficient aircraft or more efficient procedures. Airport specific examples include NO_x emissions taxes implemented in Switzerland in 1994 and the Heathrow airport noise charging.[11][12] At a larger level, the European Emissions Trading Scheme sets a price for carbon in the European market and effective January 1, 2012, aviation has been added to the market.[13]

Unfortunately, economic measures have the shortcoming of simply becoming a part of the cost of doing business. Unlike ground transportation where roads are required to get anywhere, operators build their networks around routes that are profitable such that flights to Switzerland and London are in demand. Within a fleet, operators could simply shift utilization of less emitting or quieter aircraft to the appropriate airports and use the less environmentally friendly aircraft at airports without such a charging scheme. While it does achieve local improvements, there is no real change in the big picture. With respect to the Emissions Trading Scheme, it may press operators to purchase more fuel efficient aircraft but given the recent addition of aviation to the program, it will take some time to see whether it has the desired impact.

Regulation has been introduced through the Committee for Aviation Environmental Protection (CAEP), a subgroup of ICAO. Regulations for NO_x and noise have already been established and recent work has been focused on researching a CO_2 standard. CAEP first established standards for NO_x in 1986 and noise in 1972 and these standards have been updated over time.[14] Regulation offers additional external pressure to manufacturers to develop aircraft that are more environmentally friendly beyond that from business as usual.

NO_x regulations were initially established as D_p/F_{oo}, a measurement of grams emitted during takeoff and landing cycle divided by the rated thrust of the engine vs. the overall engine pressure ratio of the engine. Two sets of regulations exist and are separated at 89 kN (20,000 lb) thrust. Standards have been updated in 1991, 1995, 2004, and 2010 and can be seen in Figure 2. Over time, the standards have become far stricter on engines operating in the lower engine pressure ratios such that under CAEP/8 standards, NO_x emissions are required to be 50-60% of the original standard. Regulations are not as aggressive on the higher side of engine pressure ratio because while the standard goes up to pressure ratios of 80, engines currently max out in the 40s yielding around a 40% reduction from the baseline standards.

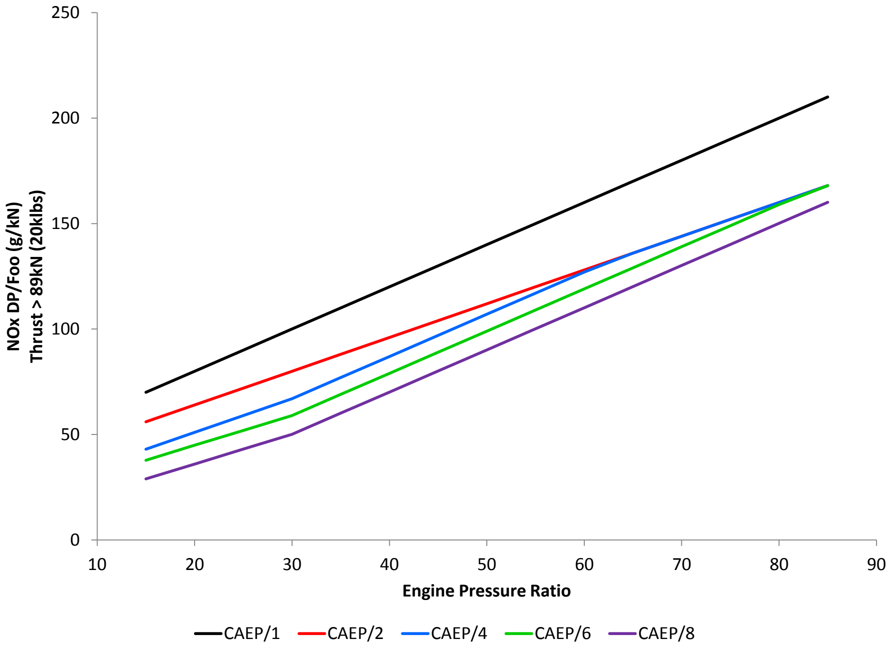


Figure 2. Evolution of NO_x Certification Standards [15]

Noise regulations are split into three points: cutback, sideline, and approach; however, they have been combined in Figure 3 to show cumulative noise. Stage II regulations were initially established as a set noise limit vs. takeoff gross weight. A new standard was developed 12 years later as Stage III and then updated to Stage IV in 2001 with just a 10 dB reduction in cumulative noise. Three sets of regulations exist based on the number of engines on the aircraft and as the number of engines increase, the stringency relaxes. Details on the specific observer locations are available in Figure 4.[16]

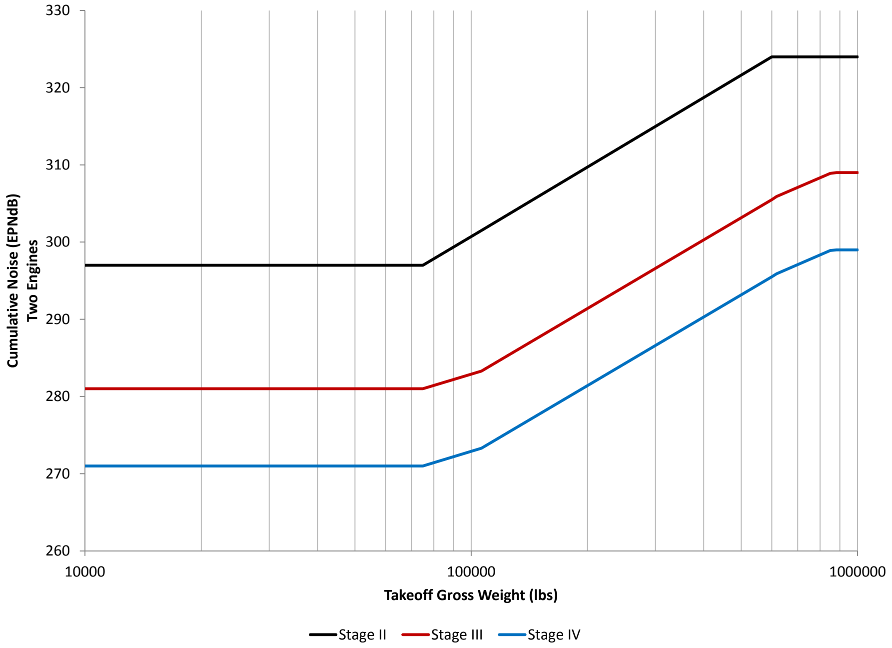


Figure 3. Evolution of Noise Certification Standards [17]

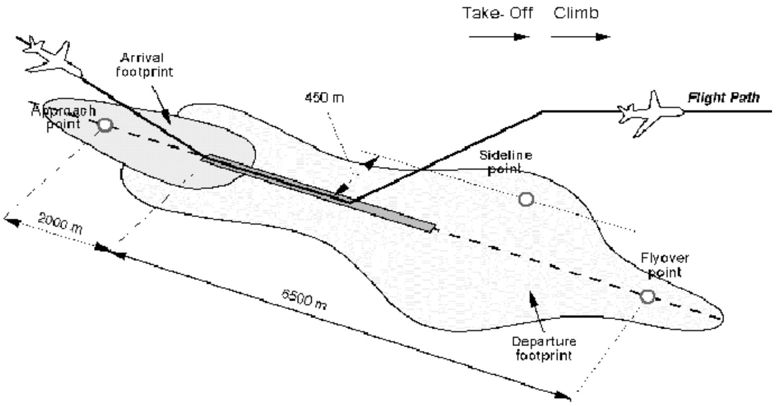


Figure 4. Noise Certification Observer Locations [16]

Even though standards exist for both NO_x and noise, regulations are enforced in two different fashions. The first is a certification standard such that new aircraft must meet the standard. In the event that new regulation would result in an in-production aircraft violating the new standard, manufacturers may either integrate technology improvements into the vehicle or simply cease production on the non-compliant aircraft. All new aircraft must meet the CAEP 8 NO_x and Stage IV noise stringencies.

The other enforcement approach is an operational standard meaning that if an aircraft is unable to meet the standard, it is not allowed to fly regardless of production status. An example of this approach occurred from the Airport Noise and Capacity Act of 1990.[18] This bill required the phase out of all Stage II aircraft by 12/31/1999. Airlines either retired non-compliant aircraft and replaced them with compliant ones or retrofitted the aircraft with newer engines or engine hush kits to meet compliance. This approach is rarely used as it may have severe economic consequences for airlines and manufacturers. All aircraft in service must meet the Stage III noise stringency.

Thus far, CO_2 has largely gone unregulated as there is already existing market pressure to reduce fuel consumption. Figure 5 shows how the energy intensity of aircraft has reduced overtime as a measure of fuel energy per passenger-kilometer. Notice that new aircraft have around a third of the energy intensity of aircraft produced 50 years ago. A large part of this is due to market pressure from airlines and holding companies as reduction in fuel consumption minimizes the variability of their operating costs. However, there is significant pressure growing to address CO_2. As previously mentioned, CAEP members are investigating metrics for a CO_2 regulation as well as the introduction of aviation to the European Emissions Trading Scheme has occurred [19]. During President Obama's 2008 campaign, he laid out national emissions reductions targets 80% by 2050. Finally, the Environmental Protection Agency was granted authority by the

Supreme Court to regulate CO_2 under the Clean Air Act through to the decision of Massachusetts vs. Environmental Protection Agency.

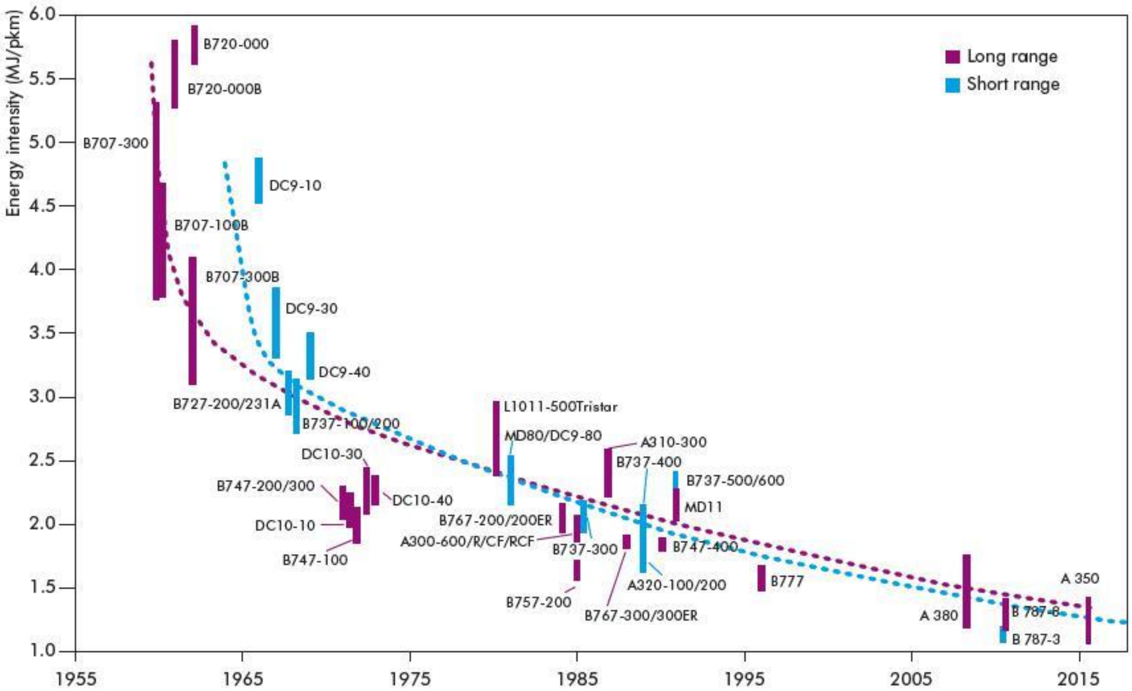


Figure 5. Evolution of Aircraft Energy Intensity [20]

Pressure from both regulation and airlines has encouraged the development and adoption of advanced technologies into new aircraft. One problem is that both pressures operate at the engine/airframe level. Fleet size is projected to double by 2030 such that future growth will overshadow future reductions in both NO_x and CO_2 in future aircraft. Noise exposure was significantly reduced once the Stage II phase outs were completed - population exposed went from 2.7 million people in 1990 to 440 thousand in 2000 as estimated by the General Accounting Office (GAO).[21] While the population exposure was greatly reduced, the GAO estimated this came at a cost ranging from \$3.8 to \$4.9 billion in 2000 dollars. However, number of operations has a great influence on the number of people exposed and there is the potential that the trend will reverse and this may limit increases in future growth. NO_x reductions are occurring in all modes of transportation but other transportation sources are being reduced more quickly so that aviation's impact is becoming more significant in comparison. Emissions growth is also expected to be a growing concern among airports per a GAO survey of the United States' 50 busiest commercial service airports.[8]

The other challenge of fleet impact reduction is that an aircraft's lifespan is significant. The FAA Terminal Area Forecast (TAF) assumes a retirement age of 25 years.[22] The Boeing projections indicate that in 20 years almost a third of the original fleet still remains in service as shown in Figure 6. A consequence of the lifespan is that technical measures take a significant amount of time to take full effect due to slower adoption rates. By 2030, the fleet is predominantly newer aircraft but now twice the size of the original 2010 fleet. If 2030 fleet-wide emissions are to match the baseline, the new vehicles would need to have their environmental impact halved and significantly more so if the objective is to reach some target such at Obama's 80% of 2005 CO_2 emissions. NASA N+2 targets are particularly aggressive but the expected entry into service date of 2030-2035 results in zero fleet penetration in the short term.[23] This leads to a significant gap between vehicle level improvement and fleet-wide environmental targets.

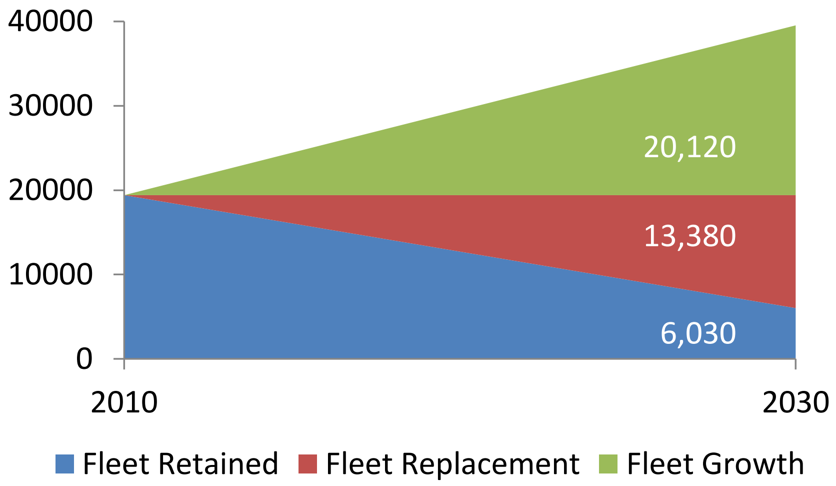


Figure 6. Projected Future Fleet Composition [2]

Given these potential shortcomings, efforts have branched out to many research areas to attempt to find a combination of solutions that will reduce the environmental impact of aviation at both the vehicle and fleet levels. At the aircraft level, this includes technology infusion, advanced vehicle concepts, mission specification changes, and alternative fuels. Operation changes, more frequent maintenance, inventory changes, and infrastructure improvements are proposed strategies to make improvements to utilization of the existing aircraft that will be unable to benefit from the vehicle level improvements.

Technology has long been the major driver in reducing aviation's environmental impact and will continue to be an important enabler going forward. Examples of these improvements include more efficient combustors, lighter vehicle materials, and acoustic dampening materials. NASA, FAA, and ACARE have laid out aggressive goals for significant reductions in fuel burn, NO_x, and noise.[23][24]

An extension of technology development is the development of advanced airframe and engine concepts. While the wing tube concept continues to see reductions in environmental impact, physical limitations of the vehicle will eventually be reached. An example would be as engine noise reductions continue, there is some floor that exists such that airframe noise becomes dominant and either more technology development is required or this leads to a shift to an alternative airframe concepts. Additionally as technology progresses, one will also encounter increased difficulty in reaching those limitations such that transitioning from the traditional wing tube concept may not only yield greater benefits but also have room for additional improvements at far less difficulty. Examples of these concepts are found in Figure 7 and include the hybrid wing body and truss braced wing airframe concepts and geared turbofan and open rotor engine concepts.

Figure 7. Proposed Advanced Airframe and Engine Concepts [25][26][27][28]

Mission specification changes will be addressed in more detail in Chapter 2 but the objective is to change the baseline speeds, ranges, or payloads in order to reduce the environmental impact of aviation.

Alternative fuel could hold promise as these fuels may have different emissions characteristics such that significant reductions may be possible. The objective is to reduce the net increase in atmospheric carbon through the usage of various feedstocks, such as biodiesel, plant oils, synthesis of natural gas or coal, and alcohols, to use existing carbon in the atmosphere to produce the fuels as opposed to using carbon found in underground oil.[29] Alternative fuels could potentially also penalize aircraft performance if there is either a lower energy density or greater fuel density. The Commercial Aviation Alternative Fuels Initiative (CAAFI) is a United States research effort that focuses on providing increased energy security and sustainability through the usage of alternative fuels.[30] Partners in this effort include airlines, manufacturers, researchers, and government agencies.

Reynolds et. al. took a different approach and broke the mission down into its individual segments to identify potential operational improvements.[31] This study was purely qualitative with respect to fuel, climate, air quality, noise, difficulty to implement, and system impact. Categories include surface, departure, cruise, approach, landing, and miscellaneous. Surface is primarily focused on ground optimization at airports. Departure and approach are geared towards finding optimum noise procedures. Proposed cruise improvements include technologies that allow for reduced vertical and horizontal separation minima or cruise climb. Miscellaneous discussed multiple solutions at the air traffic control level but also contains contingency fuel reduction.

Part of the more efficient operations measure involves maintenance procedures. In 2002 ICAO conducted two fuel burn workshops that identified a variety of techniques that would provide savings to fuel burn. Weight management encompasses passenger service items, potable water, cargo and baggage containers, and removal of trapped moisture or dirt from surfaces to minimize the excess weight in the vehicle. Airframe concerns include seal maintenance, surface mismatches, and surface cleanliness to reduce excess drag buildup. Engine maintenance includes seal and valve replacement and engine wash to minimize efficiency losses from operation. The impact of engine wash can be seen in Figure 8. While all these savings are individually small, they can become quite significant if implemented together and when considered over the lifespan of the aircraft. Boeing and Airbus each have produced their own documentation on this matter as well.[32][33]

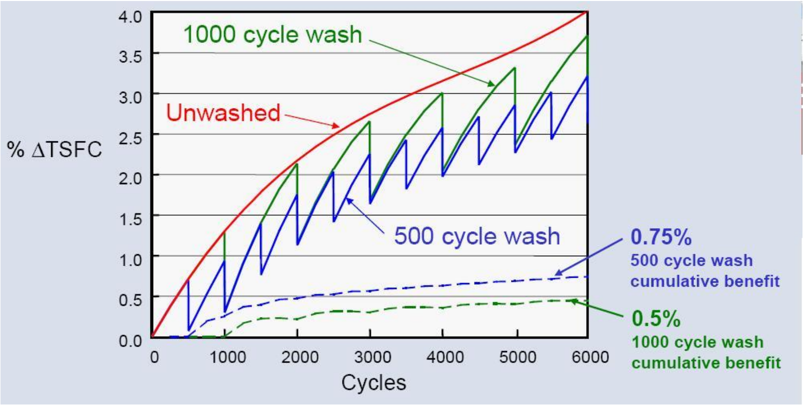


Figure 8. Impact of Engine Wash on Fuel Efficiency [32]

Given the significant lifespan of aircraft in the fleet, one needs to identify measures to improve performance of aircraft within the fleet. One approach could be an accelerated phase out of older aircraft within the fleet to reduce environmental impact. As opposed to being required to do so by regulatory measure, this would be an entirely voluntary process. These older aircraft would be replaced with newer aircraft that would provide similar capability at reduced impact. Another approach would involve the retrofit of existing vehicles with technology packages such as winglets or a new engine. Azzam proposed a different method to reduce emissions through shifting the distribution of aircraft size to larger vehicles.[34] Figure 9 shows that the baseline fleet lies predominantly with vehicles sized in the 90-150 seat range. When shifting the aircraft distribution to 330-420 seat range, one can get a 10% fuel burn reduction but this may come at increased noise at airports given the utilization of larger vehicles even considering the removal of multiple smaller aircraft operations.

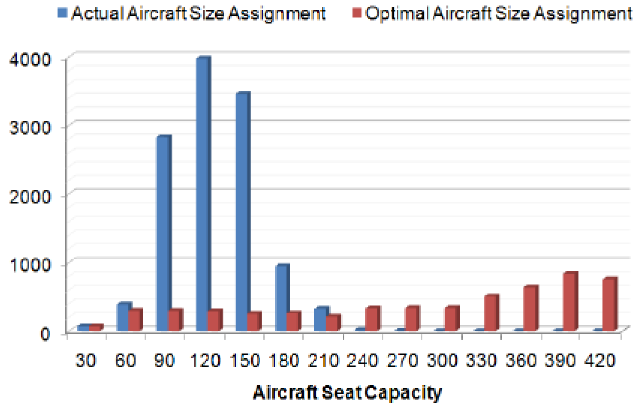


Figure 9. Aircraft Size Distribution Comparison of Actual and Optimal Aircraft Assignments [34]

One of the challenges in adopting these measures is that cost considerations can be quite significant for operators and ICAO even identifies this as a potential drawback. The purchase of new aircraft cannot be made solely with environmental concerns alone. Additionally, most operators have developed fleet plans to address both growth and retirement of aging aircraft. While some measures like retrofitting could be done fairly quickly in the short term as a part of maintenance, other measures such as aircraft replacement or fleet composition distribution shifts would require a significantly long timeframe to be implemented and may run contrary to operator business plans.

As a part of improving air traffic management and infrastructure use, governments on both sides of the Atlantic have established programs focusing on updating and improving the existing traffic management systems. Next Generation Air Transportation System (NextGen) and Single European Sky ATM Research (SESAR) are the respective American and European efforts to upgrade the air transportation networks. Objectives include improved safety, reliability, and efficiency. These programs are working jointly to ensure that all measures are capable of working seamlessly with each other as well as standardize procedures to protect the environment. NextGen currently estimates that by 2018, total flight delays will be reduced by 21% and save 1.4 billion gallons of fuel.[35] SESAR projects that by 2020, the total cost savings will be approximately €8 billion, the average air traffic flow management delay per flight will be half a minute from 2.2 minutes, and fuel savings of 17 Megatonnes will be possible.[36]

While there has been a significant level of interest in all of these different approaches, mission specification changes are significantly interesting as there are implications at the vehicle level that will have additional impacts at the fleet and will be further detailed in Chapter 2. These changes are with respect to modifying the design capabilities of future aircraft through range, speed, or payload changes for a new aircraft. Unlike technology infusion, vehicle concepts or alternative fuels, these aircraft cannot simply be considered direct replacements of existing vehicles as they can operate differently in the fleet, resulting in a linkage of aircraft design characteristics and fleet operational capability. This is unlike the four fleet level strategy categories where the aircraft impacted are already in operation and cannot be modified to capture potential benefits of mission specification changes. However, the implementation and introduction of these modified specification aircraft may have impacts beyond the traditional environmental metrics that are typically analyzed and need to be quantified.

1.1 Research Objective

The objective of this research is to develop a methodology that will enable the evaluation of aircraft mission specification changes at the fleet level over a multitude of metrics. To meet this objective, a series of questions are posed here and addressed in Chapter 2.

- What is the current state of the art of mission specification analysis?
- What modeling and simulation tools are available?
- What capabilities will be required?
- What techniques are available to capture changes in aircraft design range on flown routes?

CHAPTER 2

BACKGROUND

This chapter's focus is on providing insight into the questions posed in the previous chapter, addressing the research objective. It is organized as follows: an analysis of the current state of the art of mission specifications, an analysis of the various stakeholders and their metrics of interest, followed by a review of vehicle and fleet modeling and simulation tools, and concludes with the methods for identifying airports for intermediate stop operations.

2.1 How One Conceptually Designs an Aircraft

Before discussing the existing literature regarding mission specification changes, a brief overview of how one designs an aircraft will be provided.

The process begins with a set of customer requirements regarding cruise speed, flight range, and payload. Given the maturity of the aviation industry today, this might include conversations with major customers to determine what their needs and interests are, particularly with respect to prospective new routes of interest. Or in the case of the military, a request for proposal will be issued detailing specific requirements for the aircraft. However, these aircraft are more complicated and outside the scope of this work and will not be focused on here. However, the steps required are similar.

Once these requirements have been established, a mission profile is defined based on the needs of the customer. An example commercial aviation profile is provided in

Figure 10. This entails a taxi out period to the runway, takeoff, climb to cruising altitude, primary cruise, descent, landing, and taxi in. In this example, the primary cruise mission is a step cruise mission where cruising altitude is held constant until it is more fuel efficient to operate at a higher altitude. In addition to primary mission, there is also a reserve mission in the event that one cannot land at the arrival airport due to some reason. This is also defined in the right portion of Figure 10. This assumes a climb to a lower altitude, a short cruise leg to an alternate airport, and descent and landing there. A loiter phase is often modeled as part of this mission as well.

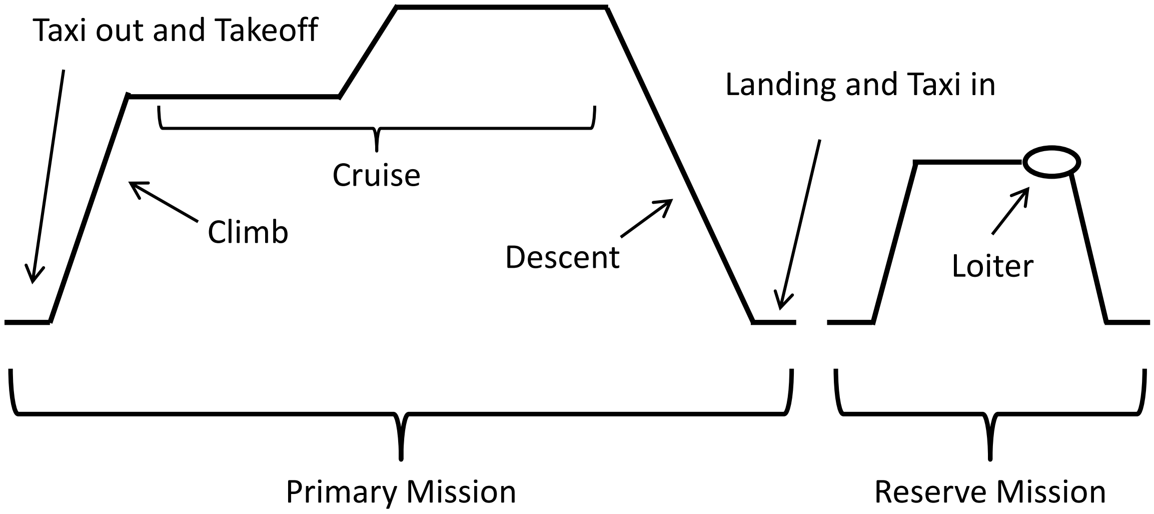


Figure 10. Notional Commercial Aircraft Mission Profile

With requirements and mission defined, the next step is to evaluate aircraft performance. But to do this, one first needs to have an idea of the vehicle concept used to conduct the mission. This will entail making some decisions about the concept itself is some of these components were not defined from customer requirements. This includes things like aircraft body shape (wing tube or an advanced concept), number of engines, engine location, and tail location.

From a simplified perspective, the Bruguet range equation can be used to calculate overall mission performance. This is demonstrated in Equation 1. A number of vehicle characteristics are required to fully conduct this analysis. The design range R and cruise speed V are defined by customer requirements. Engine fuel consumption c_T is defined by engine analysis or provided by engine manufacturers. This can also be assumed from historical data. Aerodynamic performance of the aircraft is defined by L/D, which represents the lift to drag ratio of the vehicle and represents the overall efficiency of the airframe. Finally, the weights of the vehicle W_i and W_f represent the initial takeoff weight and the fuel weight respectively. All of these inputs can be defined from historical data; however, more advanced analysis methods could be used to provide numbers that better reflect true performance.

$$R = \frac{V}{c_T}\frac{L}{D}\ln\frac{W_i}{W_i - W_f} \tag{1}$$

Additionally, using constraint analysis one can also better understand the feasible design space using constraint analysis to better understand what requirements drive performance requirements. These can include takeoff field length, approach speed, cruise speed, and climb performance and will provide insight in terms of the required thrust and wing areas to complete the mission. This information is invaluable to better estimate the weight and fuel burn estimates for the vehicles.

It is an iterative process to determine the overall aircraft design as one guesses an initial weight and the outcome then defines what the new guess should be until the desired range is met. Even using far more advanced tools to conduct different parts of the analysis, the approach is still the same.

2.2 Mission Specification Changes

As technology and design knowledge has improved, aircraft have become capable of carrying far more passengers further distances at slightly increased speeds. The first DC-9 aircraft delivered in 1965 was capable of carrying 90 passengers a distance of 1,265 nm at 561 miles per hour. Just over forty years later marked the delivery of the first A380, which is capable of hauling 644 passengers a distance of 8,300 nm only slightly faster. The premise of mission specification changes is to reduce design parameters from where they are now to lower values to reduce excess fuel carried during long range flights or drag due to higher cruise speeds.

2.2.1 Rationale for Future Aircraft Designs

This work is framed solely for new designs and not for existing aircraft. Airlines can purchase aircraft at lower takeoff weights than the certified maximum takeoff gross weight (MTOW); however, for a given flight that is within both payload-range envelopes they will see identical performance. This is shown in Figure 11. The baseline 777-200ER is represented by the black line and a purchased 777-200ER with a lower gross weight is the red line. These aircraft are identical so although the red line represents a reduced range aircraft, the performance at a point within both payload-range diagrams, like the one represented by the star at 4,000 nm, is identical.

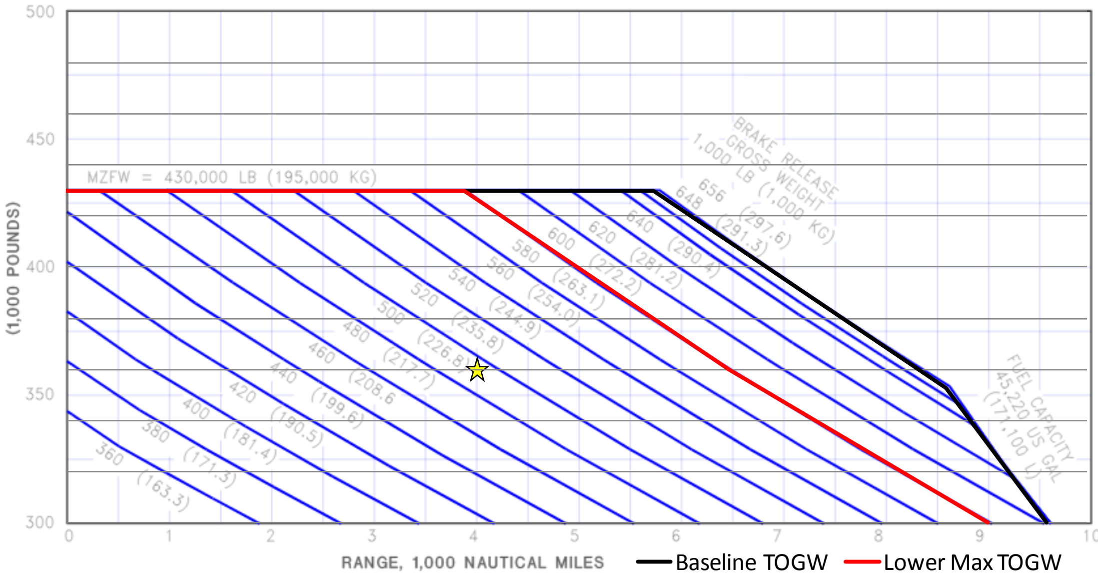


Figure 11. Comparison of Range Reduction on an Existing Aircraft [37]

With respect to speed reduction, one approach to reduce fuel consumption would be to fly slower as this would reduce drag on the aircraft. This practice does not necessarily translate to improve fuel burn as seen in Figure 12. For a given aircraft at a given altitude and weight, there is a cruise speed that provides the best fuel efficiency called maximum range cruise (MRC) speed where the nautical air miles (NAMs) per pound of fuel is maximized. Although cruise speeds can vary based on a variety of conditions, typically airlines operate at long range cruise (LRC) where the speed is such that the fuel efficiency of the aircraft is 99% of the maximum range cruise value. This allows the airline to reduce the costs associated with crew. Slowing from LRC to MRC provides increases in fuel efficiency but further reductions beyond MRC result in losses in specific range such that aircraft fuel burn will increase. For these reasons, this work will focus on mission specification changes to future aircraft designs.

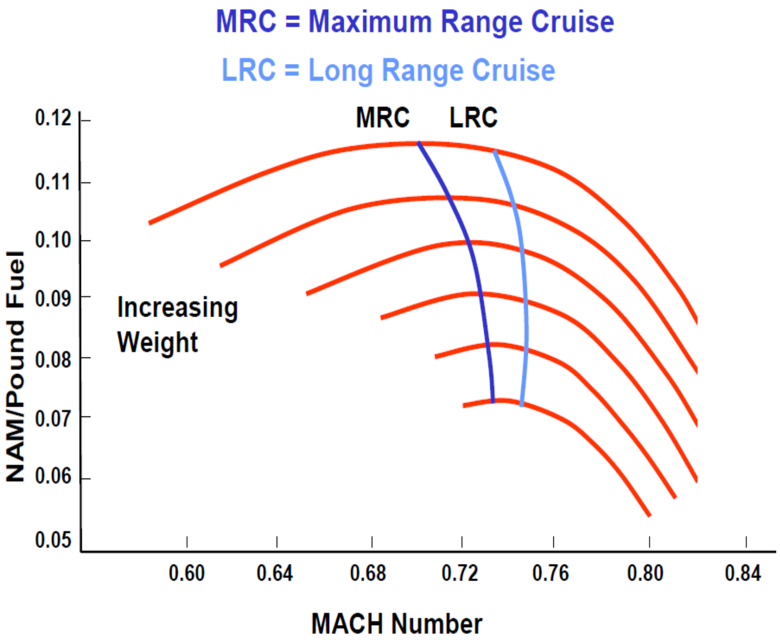


Figure 12. Impact of Cruise Speed Reduction on Fuel Efficiency on Existing Aircraft [38]

2.2.2 Literature Review of Mission Specification Work

A review of the state of the art regarding mission specification changes has been conducted to identify areas where contributions can be made. These changes are associated with how much payload is moved, how far it can be moved, and how quickly it reaches the destination.

2.2.2.1 Payload Modification

Payload refers to passenger and cargo transported for a given operation. Aircraft are typically designed with a particular passenger payload in mind and then include additional payload over this for a maximum structural payload (MSP) for operators that utilize their aircraft as a freighter. Economon lowered MSP requirements for a small twin aisle aircraft and found that fuel savings were 1% for every 10% reduction in payload.[39]

Yutko looked at the impacts of varying design payload of 25 to 1,500 passengers over a significant design range and multiple cruise speeds.[40] The objective of the work was to identify a handful of aircraft that if introduced into the fleet would have the greatest impact on fleet fuel burn. Vehicle selection was conducted through evaluating the design space by stepping through all three design parameters and each vehicle was flown in the fleet for feasible flights. Figure 13 demonstrates the results of that analysis with contours of fuel burn and the minimum fuel burn aircraft is identified by the red dot. Further vehicle selection was conducted with all the previously identified vehicles placed into the fleet. The observation of this work is that the selected vehicles provided designs that were fairly similar to existing aircraft with respect to payload and the final vehicles are provided in Table 2. Additional analysis was conducted with respect to speed and range variation as well as intermediate stops analysis (ISO). Outcomes from those studies are included in Table 3.

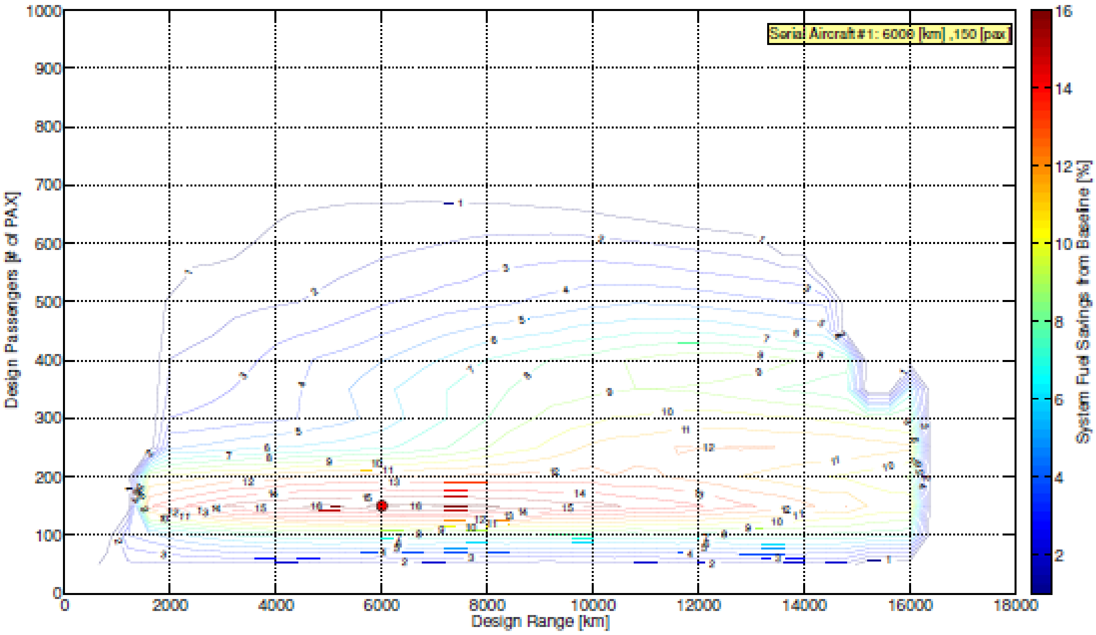


Figure 13. Yutko Approach to Identifying Fleet Minimum Fuel Burn Aircraft [40]

Table 2. Yukto Results with Approach with Fixed Speed [40]

Aircraft	Passengers	Design Range (nm)	Design Mach
1	150	3,240	0.84
2	250	7,775	0.84
3	400	7,130	0.84
4	100	2,590	0.84

Table 3. Yutko Results with Joint Variation and Fuel Stop Introduction [40]

Passengers	Joint Variation		Mach 0.84		Mach 0.72	
	Range (nm)	Speed	No ISO Range (nm)	ISO Range (nm)	No ISO Range (nm)	ISO Range (nm)
150	3,480	0.681	3,240	3,240	3,455	3,455
250	6,870	0.718	7,775	5,400	6,700	4,100
400	7,685	0.752	7,130	4,320	6,480	5,185
100	2,515	0.689	2,590	1,944	2,160	2,160
200	-	-	6,050	4,536	5,830	4,320
50	1,200	0.68	-	-	-	-

Payload modification has received fairly limited interest in literature. Figure 14 helps to illustrate why the results from Economon indicated that payload reduction would yield a trivial impact to fuel burn. The aircraft in this figure is Boeing 777-200ER with the y-axis representing operating empty weight (OEW) and payload – the minimum value is the OEW value. MSP is represented by the horizontal line at the top of the payload range diagram while the design passenger payload is represented by the dashed line within the chart. As MSP is nearly twice the passenger value, any reduction in MSP would not significantly impact the vehicle design as the maximum takeoff gross weight has not changed.

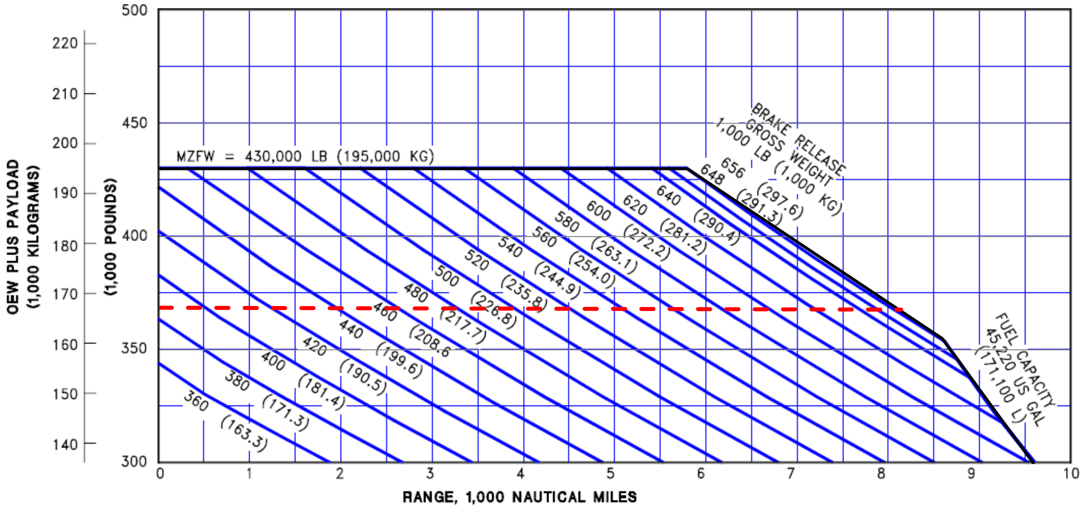


Figure 14. Comparison of MSP to Maximum Passenger Payload [37]

Payload variation alone provides a challenge though as payload is also a measure of aircraft capability. Suppose the maximum design payload was varied significantly such that the observations from the previous figure were neglected. Figure 15 contains the payload-range diagrams of the various Boeing aircraft in operation today with data collected from airport planning documents.[37] Dashed lines represent the design payload for each aircraft. If one was to take the B767 aircraft, represented by the red line, and increase the maximum payload, the aircraft would become sized enough to compete with the B777 aircraft. On the other hand, reduction in payload would put it in the same size as the B737. Because aircraft are designed to operate within particular seat classes, utilization of different aircraft for different seat classes will essentially capture payload variation. If usage of only one aircraft model is desired, then payload variation should be conducted in a process somewhat similar to Yutko.

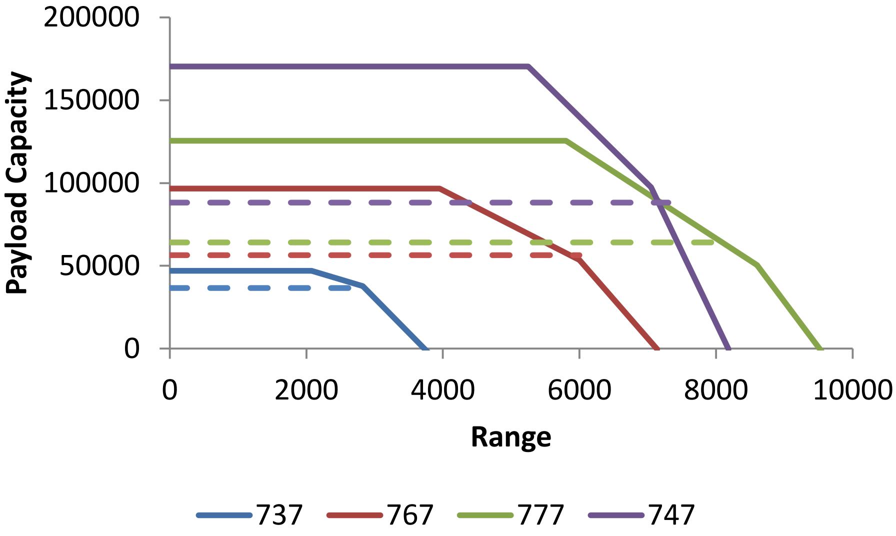


Figure 15. Comparison of Payload Characteristics of the Four Aircraft

2.2.2.2 *Range Reduction and Intermediate Stop Operations*

Range reduction has seen an increase in interest since the early 2000s. But this is not a particularly new idea. A comparison of BTS data for the Boeing 777 and Boeing

747 are compared to the payload-range diagram for the aircraft in Figure 16 (777 top, 747 bottom).[37][41] This comparison demonstrates that many operations do not fly close to the maximum design range on the aircraft and by reducing the aircraft design range, the vehicle would be better sized to operate for these reduced range missions.

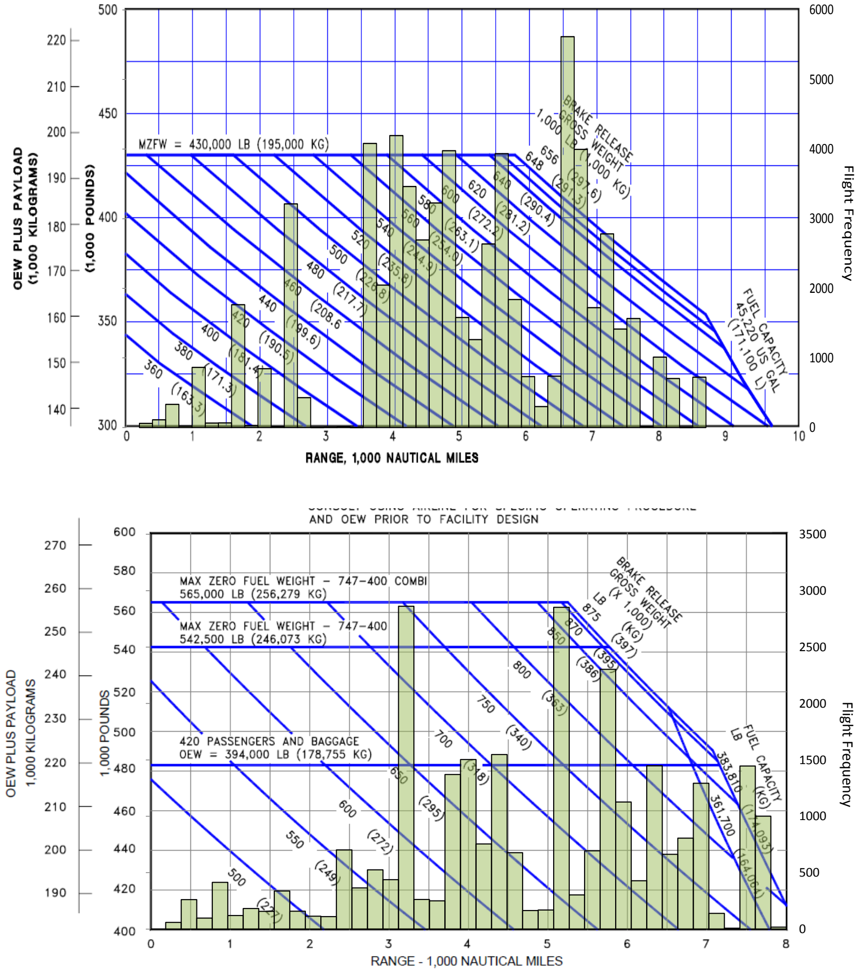


Figure 16. Comparison of Operations to Design Capabilities of the B777 and B747 [37][41]

The Greener by Design technology group proposed that payload range efficiency (measured as Range * Payload Weight / Mission Fuel) would be maximized by segmenting long range flights into multiple shorter stages.[42][43] Nangia builds off of this work and suggests that aircraft can reduce fuel consumed in long range cruise by 50% by breaking the flight into three stages (this will be referred to as intermediate stop operations (ISO) from here on) and conjunction with redesigning the aircraft for this shorter range.[44] One of the limitations of this work is the low fidelity modeling conducted by the Breguet range equation. Another is the usage of the payload range efficiency metric as it is inherently weighted against long range flights. A third is the assumption that the airport considered for intermediate stops will lie directly along the route

Hahn conducts a similar analysis with a higher fidelity model and finds savings are closer to 22.5%. A comparison of his results to that of Green and Nangia is provided in Figure 17 as well as that of the B777-200 and B737-900. He also comments on potential negative impacts of ISO airliner service. These include safety reductions through additional takeoff and landing cycles, increased travel time due to additional refueling stops, increased environmental impact at the intermediate stop airports, and the impact of fatigue on the aircraft due to the increase in cycling.

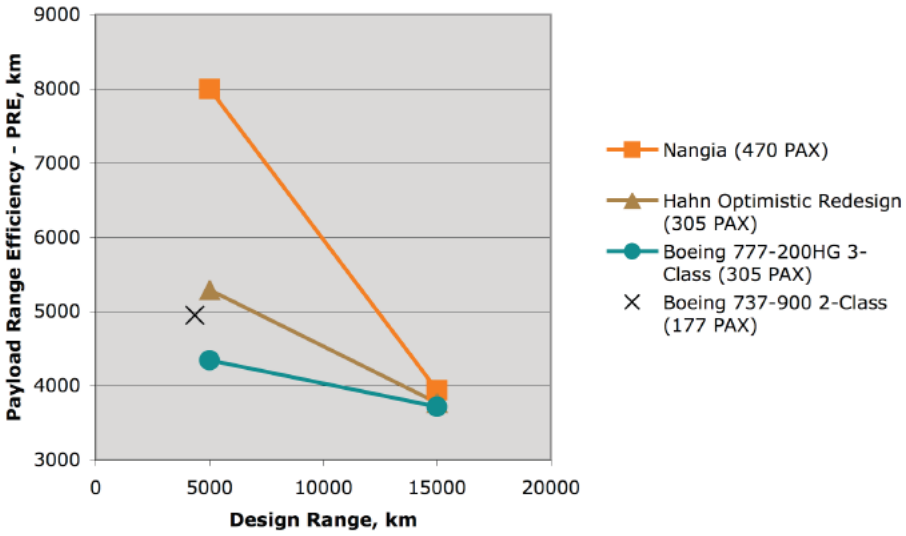


Figure 17. Comparison of Tool Fidelity on Reduced Range Aircraft Design [45]

Tyagi conducted trade studies on the number of intermediate stops with respect to fuel burn, block time, and operating cost. Three scenarios are considered: a direct flight, one intermediate stop, and two intermediate stops. The results of this work are shown in Figure 18 and each dot for a given number of stops represents variation in cruise Mach number – baseline is 0.85 and it is reduced in 0.05 steps to 0.70. Transitioning to one stop from a direct flight provides 27% fuel burn savings and a 12% operating cost savings for an hour increase in trip time. The move to a second stop provides some savings but there is a significant reduction in impact. Additionally, it provides a significant increase in operating cost and trip time.

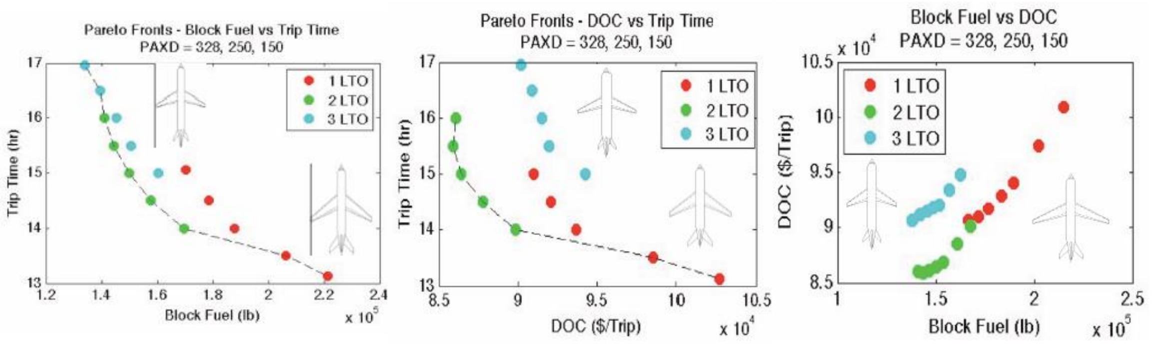


Figure 18. Impact of Intermediate Stop Count on Fuel, Time, and Cost Metrics [46]

Creemers conducts analysis similar to Green and Nangia but for a B747 sized aircraft.[47] This uses Breguet as well and finds a 27% increase in fuel efficiency when the aircraft is designed for medium range operation instead of long range. However, the wrong conclusions are drawn from this work. Creemers contends that intermediate stop operations would enable more airports to be used and this would open up new markets. Additionally, he mentions that these new aircraft would produce less noise since the takeoff thrust requirements are lessened. While the observation that those aircraft would produce less noise is true, it neglects the aircraft contribution at the airport level. These new airports that would be served will see an increase in noise as they are receiving more operations than in the existing operational framework. On the other hand, the airports that currently operate these larger may see reductions in noise to the community but this would also depend on the total number of operations occurring at a given airport. For a sufficiently large airport, one may find that the impact is trivial to the total noise exposure.

Kenway conducted analysis comparing the performance of a short range A330-200 derivative against the baseline A330 and two A320s.[48] Reductions in CO_2 per passenger were reduced by 13% and 5.4% for the two other aircraft operations. Operating cost benefits of the reduced range aircraft are in the range of 10% for both alternatives. Economon conducts a similar analysis on a small twin aisle aircraft and finds that a R_1 range (maximum range at maximum payload in the payload range diagram) reduction of 30% can yield a 4-5% reduction in fuel consumption.[39]

From the fleet perspective, Langhans conducted an analysis of both the offset and detour of airport locations for a large twin aisle aircraft using Official Airline Guide operations data.[49] Offset measures the location of the intermediate airport from the origin airport such that a value of 0.5 represents the midpoint between the origin and destination. Detour represents the excess distance added due to the usage of an intermediate airport and the benefits are linearly reduced as more excess distance is added. For a 6,400 nm mission with no resizing, the benefits are around 6.5% savings in fuel burn for an airport located at the midpoint and ISO provides savings until the excess distance is approximately 7% of the great circle distance. Resizing this aircraft for a 3,200 nm range provides 15.5% fuel burn savings when operated under intermediate stops for the 6,400 nm mission. Additional analysis is undertaken to identify which airports become optimum utilization under the ISO concept and these are presented in Figure 19. The five busiest airports are marked – three lie in eastern Canada, one lies between Russia and Alaska, and the other lies in Turkey. It is noted that many of these airports may suffer problems with respect to capacity as well as inclement weather but it is expected that this concept would ease in and allow these airports to grow sufficiently. Langhans conducted a secondary study to identify ideal locations for intermediate airports, neglecting whether an airport was there. Promising locations were again in Alaska, Canada, and Turkey as well as Russian and India. For both studies, fleet analysis was conducted for only one year.

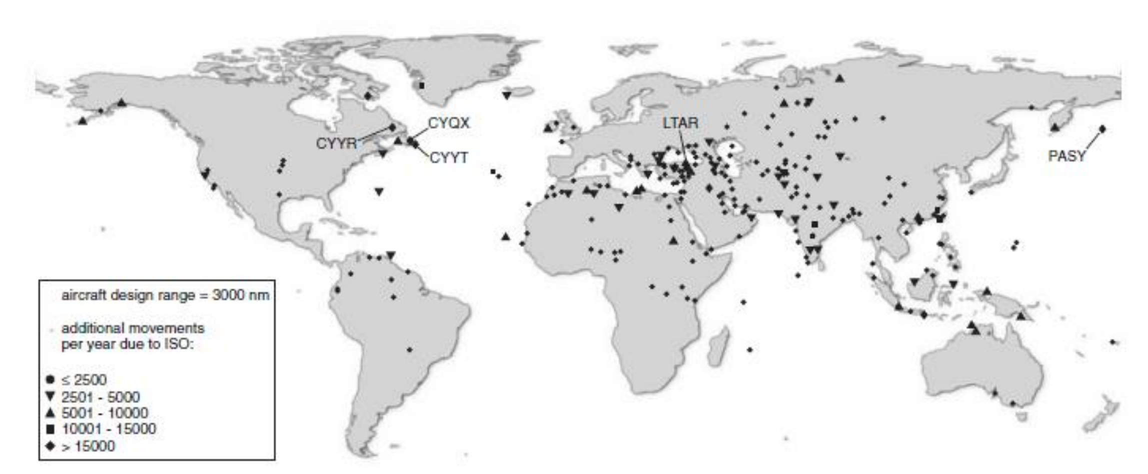


Figure 19. Distribution of Optimum Intermediate Airports for 3,000 nm Design Range [50]

Martinez-Val assessed both the environmental and operating cost savings potential through the usage of short-range aircraft with intermediate stops.[51] Although this analysis is predominantly focused on the aircraft level, the relevance to the fleet is due to the analysis of routes departing from London, Paris, Frankfurt, and New York City with intermediate airports in real cities rather than along the great circle path. The aircraft design elements are on the same level as Green and Nangia while the cost models are first order but capture depreciation, crew, fuel, tax, and maintenance as a function of range and weight ratios. Findings suggest that minimizing extra distance is of far greater importance than finding an airport along the midpoint. Other performance findings are similar to Langhans. From an economic perspective, only long range flights (>6,500 nm) provide operating cost savings when conducted with intermediate stop operations. When no detour and perfect splitting is assumed, the cost savings are around 10%.

2.2.2.3 Cruise Speed Reduction

Cruise speed reduction has also been proposed as a means to reduce aircraft fuel consumption. Drag is proportional to the square of the flight speed such that flying slower will provide some fuel savings if aircraft are designed for these speeds. Economon analyzed the impact of cruise speed reduction and found that moving from Mach 0.84 to 0.70 will allow for a 13.1% fuel savings but 11.4% of these savings have been realized at Mach 0.74.[39] The Subsonic Ultra Green Aircraft Research study identified that if meeting the NASA fuel burn goal was the only objective, aircraft cruise speed would be Mach 0.60. However, economic concerns set the minimum cruise Mach to 0.70 as seen in Figure 20.[52] Lower speeds increase the operating costs on airlines as well as reduce the utilization of the aircraft.

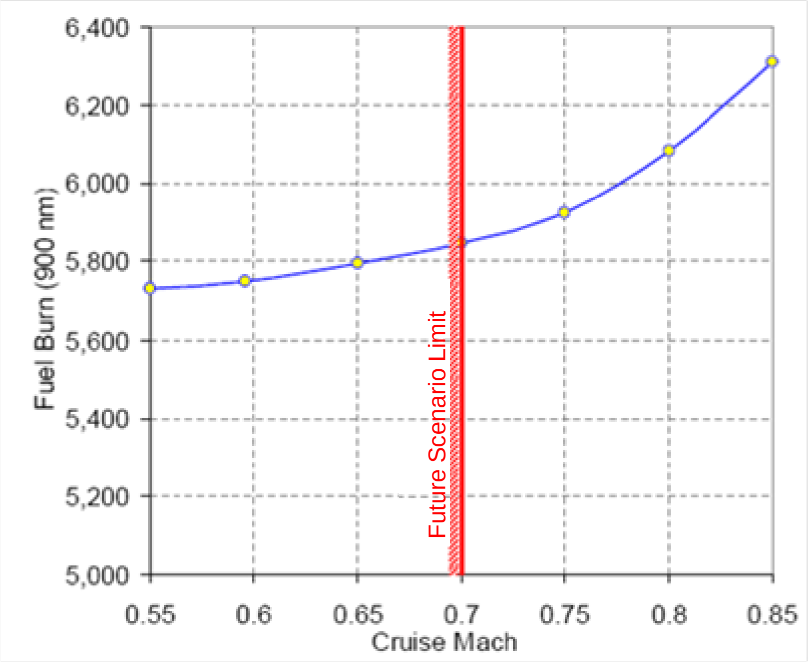


Figure 20. Analysis of Design Cruise Mach on Vehicle Fuel Burn [52]

Bonnefoy demonstrated that modification of both cruise speed and vehicle concept could provide significant reductions in fuel consumption.[53] Additional analysis was conducted with respect to airline scheduling such that only a slight shift in departure time was found to be required for 30-65% of flights and these modifications could be absorbed in the slack in the schedule. Fan continued this analysis with respect to airline economics of speed reduced aircraft.[54] Cost analysis included fuel, crew, maintenance, and depreciation elements and was conducted over five seat classes. The cost elements were then combined with airliner scheduling to determine what levels of cruise reduction may cause schedule disruption to set lower bounds on what speeds could be considered.

2.2.3 Observations

For range reduction, all of the vehicle level work presented has been primarily focused on fuel burn. Vehicle level analysis has assumed that the intermediate stop locations lie along the route and that is not likely to be true as seen in work by Langhans. An additional point of concern is the assumption of fixed technology levels. It is likely that future technology infusion will reduce the benefits of mission specification changes. Fuel burn has also been the predominant focus of speed reduction as well. Although some analysis has focused on airline impacts, the analysis neglects the prospective impact of block time increases on annual aircraft operations by assuming that slack in the schedule can be absorbed. The airline operating costs analysis also neglects the impact technology has on reducing fuel usage such that the operating cost savings should be less due technology reducing the impact of cruise speed reduction on fuel burn.

A couple of authors with range reduction work have made reference to other metrics that may improve or degrade but minimal quantitative analysis has been done. In many cases, conflicting results are present. Hahn proposes that noise will increase while Creemers suggests that range reduction will reduce noise. Kenway observed operating cost savings when a range reduced aircraft is used for short ranges while Martinez-Val concluded that costs savings are only possible for long range flights. However none of these metrics have been quantified at the fleet level. Speed reduction may have less impact on other metrics but there is little work done to quantify change to other metrics either. The speed reduction analyses have typically focused on the assumption that slack in the schedule can be freely used and would not require additional aircraft.

From the fleet perspective, the predominant metric of interest is again fuel burn. Langhans briefly touches on capacity in his work but it is not the focus of the work. Safety is mentioned only by a bubble in the Langhans work that suggests ISO would provide a minimum impact. Noise is not run for any of these fleet analyses.

Literature typically neglects the impact of fleet evolution by conducting complete vehicle replacement instead. This results in an overestimation of the benefits with respect to fuel burn as in reality, airlines would not replace entire portions of their fleet. The Langhans and Yutko analyses ultimately capture a maximum potential benefit but one that is not achievable. Additionally, the fleet benefits are often conducted for a given year of operations as seen with Langhans and Yutko. Overall operating cost has not been considered at a fleet level. Langhans focused on life cycle cost of the aircraft and Martinez-Val looked at a handful of operations for cost analysis.

This literature research has yielded three additional research questions:

- What are the other metrics that should be considered for aircraft mission specification changes?
- How does the introduction of mission specification changed aircraft impact these metrics?
- Are the impacts of mission specification changes reduced when technology is introduced to the aircraft?

2.3 Stakeholder Interests

To quantify the implications of aircraft mission specification changes, one needs to identify metrics that would be impacted by these design changes. The first step would be to identify the relevant stakeholders and then from there, determine what their interests are. Those interests then define the metrics that would be potential implications.

Stakeholders include passengers, flight crew/mechanics, airlines, airports, manufacturers, regulators, air traffic control, airport area residents, and technically everyone. Although this list may not be entirely comprehensive, it serves as a starting point.

Passenger priorities depend on whether the customer is a leisure or business traveler. Wessels conducted a study on consumer loyalty in the airline industry.[55] The number one leisure passenger concern is price followed by safety and then ease of scheduling and non-stop flights. On the other hand, safety leads for business travelers and then is followed by price, scheduling ease, and on-time performance. The top 10 for both is provided in Figure 21. This prioritization of fare price can also be observed by the success in low cost carriers such as Jet Blue, Southwest Airlines, and the former airline Airtran.

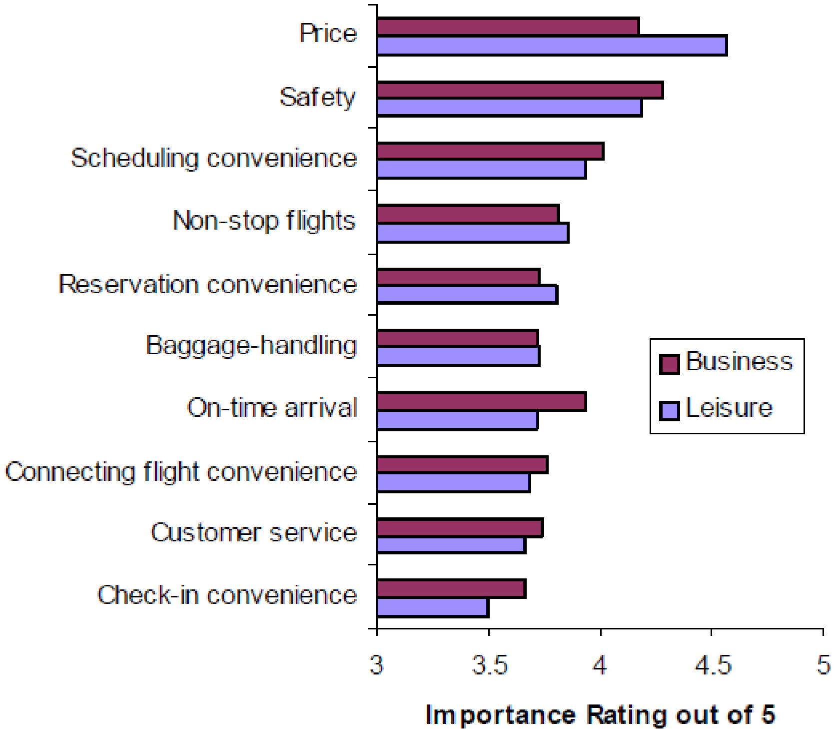


Figure 21. Passenger Priorities in Airline Selection [55]

Flight crew and mechanics both have an interest in maximizing safety as ensuring safety provides job security. However, pilots are facing new challenges in the cockpit as fatigue and more automation in the cockpit can result in crew sleeping in the cockpit. This has resulted in recent changes to some of the rules involving pilot daily work hours, rest hours, and limits on hours on duty per month. Another interest for flight crew and mechanics is income, which is something that one would always enjoy being maximizing.

Airline priorities are focused on reliability, costs, and route selection. Reliability relates to downtime of aircraft as well as on-time performance of the flights. The introduction of intermediate stops to the flight schedule can have significant consequences as this increase the total stress on the aircraft such that failures may be more likely to occur. This behavior can be observed from Southwest Airlines flights 812 and 2294 where significant cycling of the aircraft led to fuselage failures.[56] Minimizing downtime has been a priority of manufacturers as well because this is a selling point for airlines. On-time performance improvements have also increased recently; however, these improvements are also due to increased schedule padding such that many flights are arriving early.[57] The other perspective is operating costs – indirect and direct. Indirect operating costs include staff, marketing, administrative, and interest/depreciation. Direct operating costs include fuel, flight crew, maintenance, route fees, and landing fees.[58] As fuel is a significant contributor to airline costs, this has been the major driver for fuel burn reduction for manufacturers. Route selection is the other realm of interest as identifying new market pairs is a critical asset for future profitability as well as deciding to end service on a particular route.

Airport concerns focus on capacity and environmental concerns with respect to future growth. Some facilities are currently operating near their maximum capacity such that future growth will quickly lead to delays or airlines moving to other facilities. Part of these capacity limits are due to environmental concerns via noise or emissions. New runways will greatly increase airport capacity but this will increase the noise footprint of the airport in the surrounding community and increase emissions in the area. These concerns along with others are illustrated in Figure 22 for present and future concerns. Safety is another concern of increased operations as this brings even more aircraft into a fixed airspace.

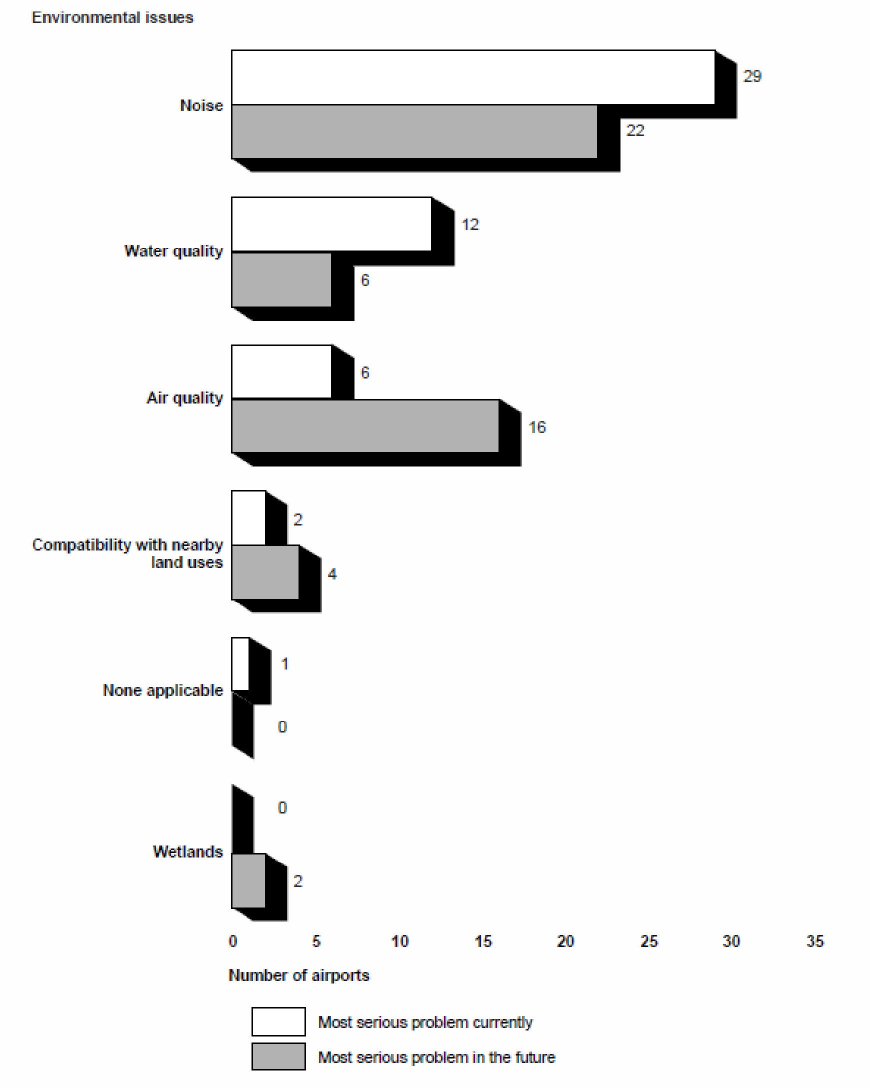


Figure 22. Airport Environmental Concerns – Present and Future [8]

Manufacturer objectives are focused on providing the most competitive aircraft on the market that complies with current regulations but also provides a significant buffer to potential future regulations. Competitiveness has partially been driven by minimizing fuel burn as airlines are interested in reducing their operating costs. However, manufacturer decisions are also made with respect to decisions from their competitors. Boeing had originally planned on replacing the B737 with a clean sheet design rather than refreshing the existing airframe with some new technology. When Airbus announced the A320 NEO, airline interest was significant and resulted in significant pressure to upgrade the B737 over developing a new vehicle.[59]

Regulators have an interest in making sure everything works properly. The objective is to maximize safety while making sure all participants in the system follow the established regulations. Additionally, they set regulations on emissions and noise limits and these rules are updated to help reduce environmental footprints, spurring new developments in aircraft technology. Other rules are updated to address new circumstances such as rules addressing pilot fatigue.[60] This job is critical to ensure that the air transportation system maintains such a high level of safety.

Air traffic control is a particularly stressful job with a very heavy workload required to maintain the level of safety that exists today. Aviation growth will only increase the work level required. Although the Next Generation Air Transportation System is projected to provide significant improvements to traffic control, changes to the system, such as the introduction of intermediate stop operations will result in an increase in takeoff and landing at the stop airports and result in greater workload.

Residents in the airport area face constant disturbance from airport operation. Each departure and arrival generates noise, which can be particularly problematic in the evening even though the number of operations has been reduced. The impact of noise disturbance on a variety of different human factors has been studied extensively and will likely continue going forward. The other impact is emissions that impact air quality. It is much harder for individuals to identify as it is not directly observable to the naked eye but the emissions can cause a variety of health related issues. Aviation growth will only make both of these concerns worse.

Technically, everyone is a stakeholder in aviation as well. Any source of energy or mode of transportation that emits CO_2 contributes to climate change. Consequences include changing weather patterns, increases in temperature, and rising ocean levels. These changes will have significant impacts to civilization. Concerns have also been raised that aviation's contribution is more significant as the CO_2 release is at cruise altitude instead of near the ground.

These stakeholder interests can be translated into a smaller list of metrics that can then be used for analysis. Some interests have been combined together into one metrics like fares, salary, and research and development have been compiled into cost but this is not meant to be one all-encompassing metric. Block time is kept separate as total increase in flight time is of interest. Noise, emissions, and fuel burn are kept separate as each is a particular metric of interest for environmental research. Capacity, safety, and reliability are also metrics of interest with respect to future impacts. A mapping of stakeholders to this reduced metric set is provided in Table 4.

Table 4. Mapping of Stakeholders to Metrics of Interest

Stakeholder	Travel Time	Cost	Fuel Burn	Noise	Emissions	Regulations	Capacity	Safety	Reliability
Passengers	✓	✓						✓	
Flight Crew	✓	✓				✓		✓	
Maintenance Crew		✓						✓	✓
Airlines	✓	✓	✓			✓	✓		✓
Airports				✓	✓	✓	✓	✓	
Manufacturers		✓	✓	✓	✓	✓		✓	✓
Regulators			✓	✓	✓	✓	✓	✓	✓
Air Traffic Control						✓	✓	✓	
Airport Area Residents				✓	✓				
Everyone			✓						

These metrics can then be separated into the aircraft level and the fleet level. At the aircraft level, regulations currently include certification noise and NO_x and will include CO_2 in the near future. Research and development and acquisition costs are important in evaluating vehicle level changes. Finally, mission performance will be necessary to measure fuel burn, emissions, and travel time. The fleet perspective shifts to total numbers with respect to emissions, fuel burn, block time, operating costs, and operations. Airport noise is a function of the operations schedule and future growth. Safety, capacity, and reliability are also metrics of interest at the fleet level.

2.4 Modeling and Simulation

Fulfilling the objective of providing a methodology to evaluate the implications of aircraft mission specification changes at the fleet level requires detailed, complex, quantitative analysis, relying on sophisticated modeling and simulation (M&S) tools.

There is no one tool that is capable of handling the job alone such that this task requires tools modeling the aircraft level and the fleet level. The following section addresses the requirements needed for tools in both realms, provides background on existing tools, and ranks the tools against the mentioned criteria.

2.4.1 **Aircraft Level Modeling**

To capture the impacts of mission specification changes, an aircraft level tool should be able to capture the engine thermodynamic cycle, engine mechanical design, aircraft design and performance, and noise and emissions analysis. There are a number of existing tools that meet this capability either at a disciplinary level or as an integrated toolset. Preference is given to an integrated toolset as this eliminates the need to link disciplinary codes together, thus integrated tools will be the primary focus of this literature search. In the event that a capability is lacking in a selected toolset, appropriate discipline level tools will be identified to fill that gap.

2.4.1.1 Criteria

The previous section outlined metrics of interest with respect to various stakeholders. These include mission performance with respect to fuel burn, flight time, and emissions. Mission performance is critical for capturing fleet level impact. Future aircraft will also be subjected to certification requirements for noise and NO_x. If these future aircraft are unable to meet these regulations, the prospective fuel savings are irrelevant as they will not be allowed to operate. Additional noise data is required to capture noise for the airport beyond the certification requirements in the form of noise-power-distance curves that measure the noise emitted from an aircraft at a given power setting and altitude from an observer point. Changing aircraft design requirements will impact a variety of costs – specifically research and development, operating, and acquisition costs. These cost changes could mean the difference between these aircraft entering production or not because market viability. These metrics are then required outputs from the vehicle level analysis.

Other characteristics for M&S tools include physics based analysis. One of the common shortcomings in mission specification changes is a lack of analysis with respect to technology integration. Although one approach of modeling technology is to use factors within a tool to scale outputs up or down (examples include reducing wing weight by 20% to account for a materials change or a reduction in fuel consumption to represent engine technology), this method does not capture the true physics of the problem and can break the interdependencies between different metrics. By modeling an engine technology as just a percent reduction of fuel consumption, one may not capture changes to the engine exhaust that results in different noise outcomes. For this reason, the aircraft design tool utilized needs to capture this behavior as accurately as possible and necessitates the need for physics based analysis.

Other desired criteria include automation and rapid analysis. Automation allows for a removal of a human in the loop with respect to running the analysis code and can help expedite analysis time. However this does not remove the user from data analysis as automation is not capable of identifying whether a given design is feasible or not. Rapid analysis is clearly beneficial as it allows for faster turnaround between problem definition and data analysis.

On the inverse side of rapid analysis is modeling fidelity. Tool fidelity is critical for whether the analysis being conducted should be taken seriously. Anyone can create their own design capabilities in a tool but that does not mean the results are reputable. To remove doubt regarding confidence in the analysis, utilization of established design tools with a reputation of high fidelity is critical. Previous work in mission specification changes has made extensive use of the Breguet range equation and other first order sizing principles. These techniques are incredibly rapid and if one built a spreadsheet with the correct linkages, it would take seconds to provide results. The problem is that these analysis methods are very low fidelity. On the other hand, computational fluid dynamics is a very detailed analysis technique. It provides very high fidelity to a designer but suffers from lengthy analysis time such that one may only be capable of running a few different designs. This trade requires perspective on the scope of the problem at hand to determine the appropriate level of fidelity and analysis time.

Any aircraft design tool should be capable of modeling mission specification changes such that this consideration is simply assumed. A summary of the vehicle level modeling and simulation criteria and the associated rationale and importance is provided in Table 5.

Table 5. Vehicle Level Modeling and Simulation Selection Criteria

Criteria	Importance	Rationale
Physics-based	High	Modeling of mitigation strategies requires capturing the physics of the problem
Fidelity	High	Tool fidelity is critical to assurance that the resulting analysis is reasonable
Automation capability	High	Removes need for human in the loop
Rapid	Low	Reduces cycle time
Noise	High	Noise is one of the key drivers for this research
Emissions	High	Emissions is one of the key drivers for this research
Cost	Medium	Cost captures changes in acquisition and R&D costs which can impact the fleet
Source code	Low	Capability to develop higher fidelity if needed

2.4.1.2 Aircraft Level Tools

The Environmental Design Space (EDS) is a physics-based aircraft design environment that has been developed at the Georgia Institute of Technology within the Aerospace Systems Design Lab.[61] This effort has been developed through the FAA, NASA, and Transport Canada as a part of a suite of tools to enable analysis of the environmental impact of aviation.[62] EDS is an integrated tool suite capable of performing engine thermodynamic cycle, engine mechanical design, aircraft design and performance, and noise and emissions analysis. The underlying tools are Compressor Generator for compressor performance, Numerical Propulsion System Simulation for engine cycle, Weight Analysis of Turbine Engines for mechanical design, Flight Optimization System (FLOPS) for aircraft performance, P_3-T_3 methods for NO_x emissions, and Aircraft Noise Prediction Program for noise. Further information on the development history of EDS is available in Kirby.[61]

Capability exists in EDS to model both current and future vehicles whether they contain new technologies or use advanced concepts such as the hybrid wing body airframe or open rotor engine. EDS has been applied to analysis conducted for technology assessments for both the FAA and NASA as well as policy making for CAEP.[63][64] A flowchart of EDS is provided in Figure 23.

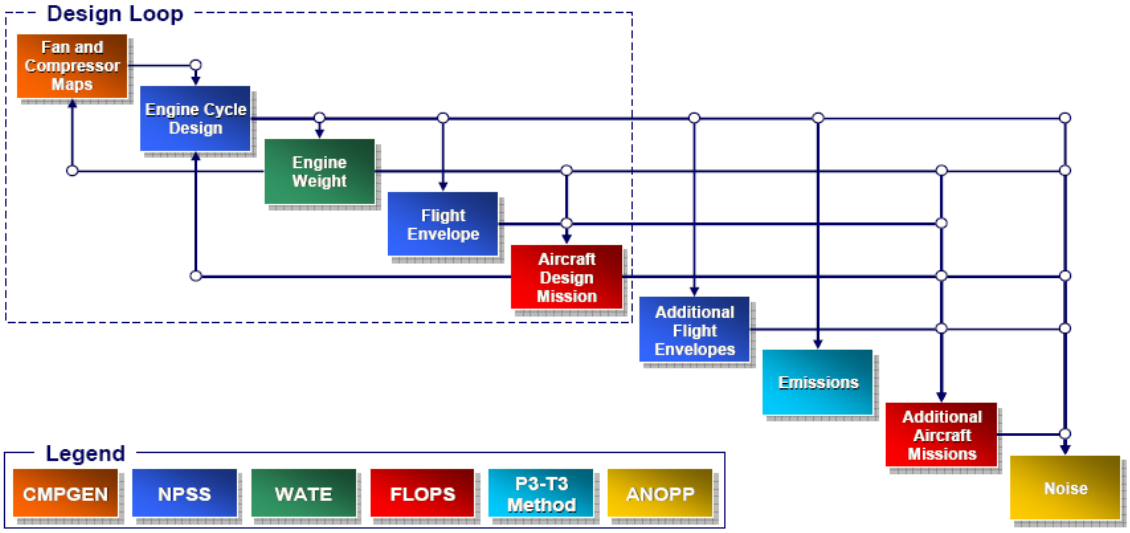


Figure 23. EDS Framework [61]

Developed at the Technical University of Brunschwig, the Preliminary Aircraft Design and Optimization (PrADO) is capable of iterative multidisciplinary design of aircraft. It is capable of being run in analysis, parameter study, or optimization modes. PrADO contains 19 modules that capture geometry, aerodynamics, engine rubberizing, flight simulation, weight prediction, center of gravity, and takeoff and landing constraints.[65] These modules are run consecutively and then checked against constraints in the final module. The design process of PrADO is provided in Figure 24.

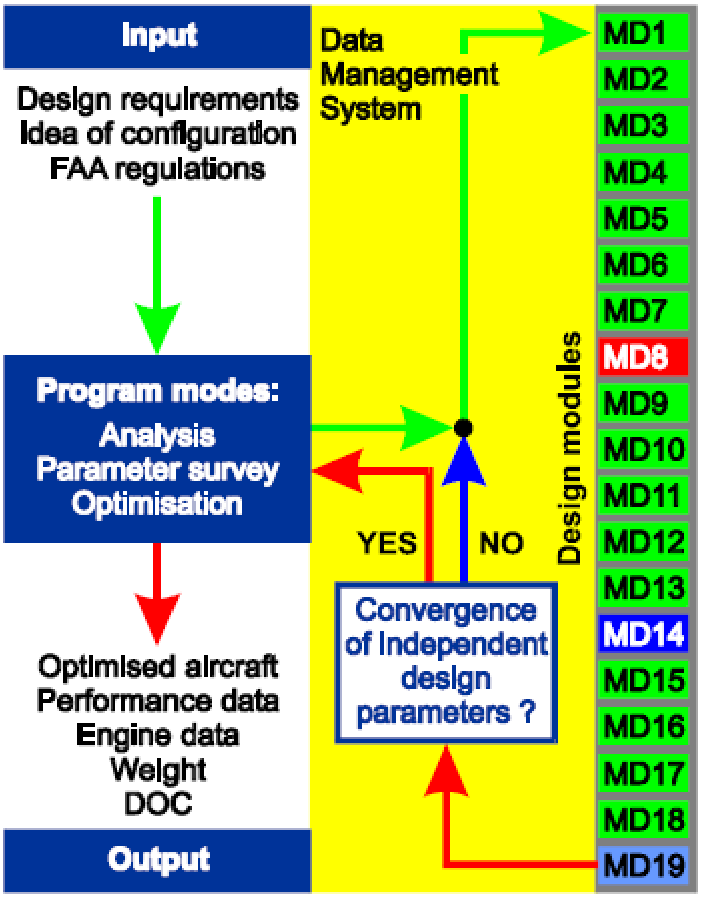


Figure 24. Design Process of PrADO [66]

The British company QinetiQ has developed a tool called Requirements Exploration, Technology Impact, and Value Optimization (RETIVO) to calculate basic engine and aircraft performance to model the impact of technologies.[67] It was developed as a part of the Integrated Wing Aerospace Technology Validation Programme, a United Kingdom project funded through both the government and industry partners. Another QinetiQ capability is the Multi-Disciplinary Concept Assessment and Design (MDCAD) tool that allows for a more detailed geometry to be represented and designed. The two capabilities are somewhat different with RETIVO being considered a broad but shallow approach versus MDCAD being a narrow but deep one.[68] However, usage of both tools provides a basis for both types of studies.

Lissys Ltd has developed Project Interactive ANalysis and Optimization v5 (PIANO) is an aircraft conceptual design package that is built on methods from industrial and academic sources.[69] It additionally comes with a database of existing aircraft with sources being both public and private; however, all aircraft are considered Lissys' best estimate and are not endorsed by any manufacturer. PIANO has been used in support of CAEP analysis and has a large list of customers within industry.[70] Some drawbacks of PIANO include a required human in the loop, a lack of capability to capture unconventional vehicles, and no internal noise calculation though it does have the capability to link required information to an appropriate noise tool.

Stanford University developed Program for Aircraft Synthesis Studies (PASS) to perform aircraft analysis but is now maintained by Desktop Aeronautics.[71][72] It was originally developed for conventional aircraft but can perform analysis of non-conventional aircraft such as hybrid wing bodies. It is capable of full mission analysis as well as optimization. Capabilities are similar to other tools but one point of interest is that all analyses are capable of using both gradient and non-gradient based optimizers. PASS also ensures that resulting designs meet a variety of real-world constraints such as field lengths, noise requirements, and climb gradients.

AVID AirCraft Synthesis (ACS) was developed by Avid Aerospace based on experience gathered from research at NASA and Virginia Tech. ACS is a successor to the

NASA software package AirCraft SYNThesis (ACSYNT).[73] ACSYNT was originally developed at NASA Ames as a tool for preliminary aircraft design and is on par with the capabilities of FLOPS. AVID integrated an optimizer with components from ACSYNT and the result is ACS. It is an interdisciplinary tool capable of propulsion, aerodynamics, trajectory, geometry, and takeoff and landing analysis.[74]

2.4.1.3 Evaluation of Tools

Physics-based and fidelity are fairly intertwined and while some elements of a particular tool might be physics-based, others are not and that can impact the overall fidelity. Generally ranking lower on physics-based analysis will result in similar fidelity scores. PIANO is an outlier as many methods used in the code have been drawn from industry sources such that it may use less physics-based analysis but be higher fidelity. If the objective of this work was to extend to advanced vehicle concepts, then many of these tools would score even lower.

Many of these tools do not appear to be capable of being automated such that the human in the loop is required. Analysis speed runs counter to fidelity. Only a couple of these tools are capable of modeling noise (EDS, PrADO, PASS, and AVID ACS) although, only EDS is capable of modeling airport noise as it is the only tool that generates noise-power-distance curves. The only emission modeled in most of these tools is NO_x. Cost can be captured in many of the tools but fidelity level is somewhat uncertain. Source code availability is determined with respect to the author.

Table 6. Rankings of Vehicle Modeling and Simulation Environments

Criteria	Imp	EDS	PrADO	RETIVO	MDCAD	PIANO	PASS	AVID ACS
Physics-based	High	High	Low	Low	High	Low	Med	Med
Fidelity	High	High	Low	Low	High	Med	Low	Med
Automation capability	High	Yes	No	No	No	No	Yes	Yes
Rapid	Low	No	No	Yes	No	Yes	Yes	Yes
Noise	High	Yes	No	No	No	No	No	No
Emissions	High	Yes	Yes	Yes	No	Yes	Yes	Yes
Cost	Med	Yes	Yes	No	No	Yes	Yes	Yes
Source code	Low	Yes	No	No	No	No	No	No

2.4.2 Fleet Level Modeling

To capture the impact of mission specifications at the fleet level, an initial operations schedule will need to be grown to capture the impact of future demand growth as well as introduce new aircraft in the fleet to address the new operations. There are a number of integrated toolsets that address the fleet level metrics.

2.4.2.1 Criteria

The previous section also outlined the metrics from the fleet perspective for the different stakeholders. Reducing the growth in aviation’s fuel consumption is the main driver of aircraft mission specification changes and must be captured to assess the benefits due to their introduction and adoption into the fleet. This requires analysis over a significant time frame to assess the impact of future demand as well as the impact of fleet evolution. Fleet evolution is critical as some analysis assumed complete replacement of all aircraft impacted. This decision does not reflect reality as complete fleet replacement would bankrupt an airline and no manufacturer could afford to produce enough aircraft to replace the entire fleet and then shut down a significant portion of the manufacturing capacity.

At the fleet level, the primary metrics of interest include total fuel burn and NO_x emissions as the overall environmental benefits are the main driver for proposing the adoption of mission specification changes. The analysis of stakeholder interests also identified airport noise, total block time, total operating costs, safety, capacity, and reliability as other responses to consider. Airport noise can be measured either by overall contour area or by a measure of population exposed. Block time can be used to measure changes to the number of aircraft required. Operating costs are important as it provides a measure of whether adoption of mission specification changes provides savings to the airlines. Safety, capacity, and reliability are somewhat more difficult to measure at a fleet level but can use the total number of operations to measure the impact. Other criteria include analysis speed, setup time, ease of vehicle integration, and fidelity. These criteria are provided in Table 7.

Table 7. Fleet Level Modeling and Simulation Selection Criteria

Criteria	Importance	Rationale
Analysis Speed	High	Allows for more fleet analysis
Setup Time	High	Enables more fleet analysis
Ease of Vehicle Integration	Medium	Documented vehicle format for new vehicles
Fidelity	High	Provides confidence in the results
Fuel Burn	High	Key driver behind mission specification adoption
Emissions	High	Key driver behind research
Noise	High	Airport impact of mission specifications
Block Time	High	Passenger impact of mission specification
Operating Costs	High	Airline impact of mission specifications
Safety	Low	System impact of mission specifications
Capacity	Low	System impact of mission specifications
Reliability	Low	Airline impact of mission specifications
Source Code	Low	Add new capability if necessary

2.4.2.2 Integrated Tools

The University of Cambridge's Institute for Aviation and the Environment is managing the Aviation Integrated Modeling (AIM) project. AIM is focused on the development of a tool capable of policy assessment to capture the environmental impact of aviation.[75] AIM has multiple modules capable of capturing aircraft technology and costs, aircraft movements, airport activity, air transport demand, global climate, local air quality and noise, and regional economics. Associated linkages are provided in Figure 25.

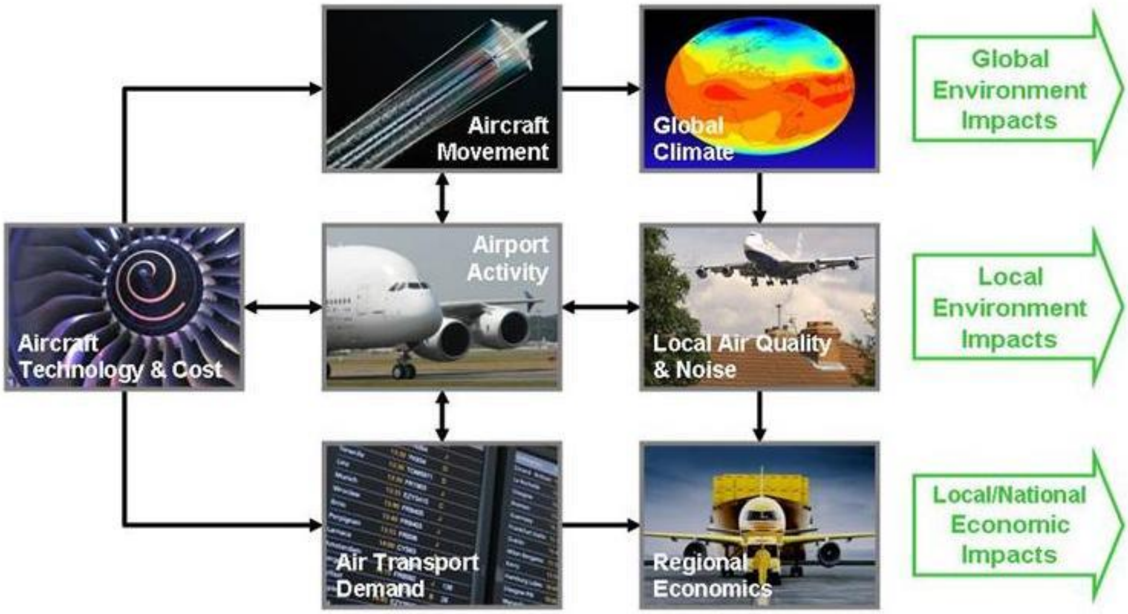


Figure 25. Structure of AIM [76]

In 1994, CAEP sponsored the Dutch Civil Aviation Authority to develop the Aviation Emissions and Evaluation of Reduction Options - Modeling System (AERO-MS). AERO-MS contains similar modules to those in AIM such as aircraft technology development, air traffic demand, operating costs, direct economic effects, and emissions. The organizational framework of AERO-MS is provided in Figure 26. For some time traffic demand was scaled to a base year of 1992 but that has been updated to 2006.[77] Regardless, technology is modeled through post-processing with input from industry such that it fails to capture interdependencies and is not physics-based.[78]

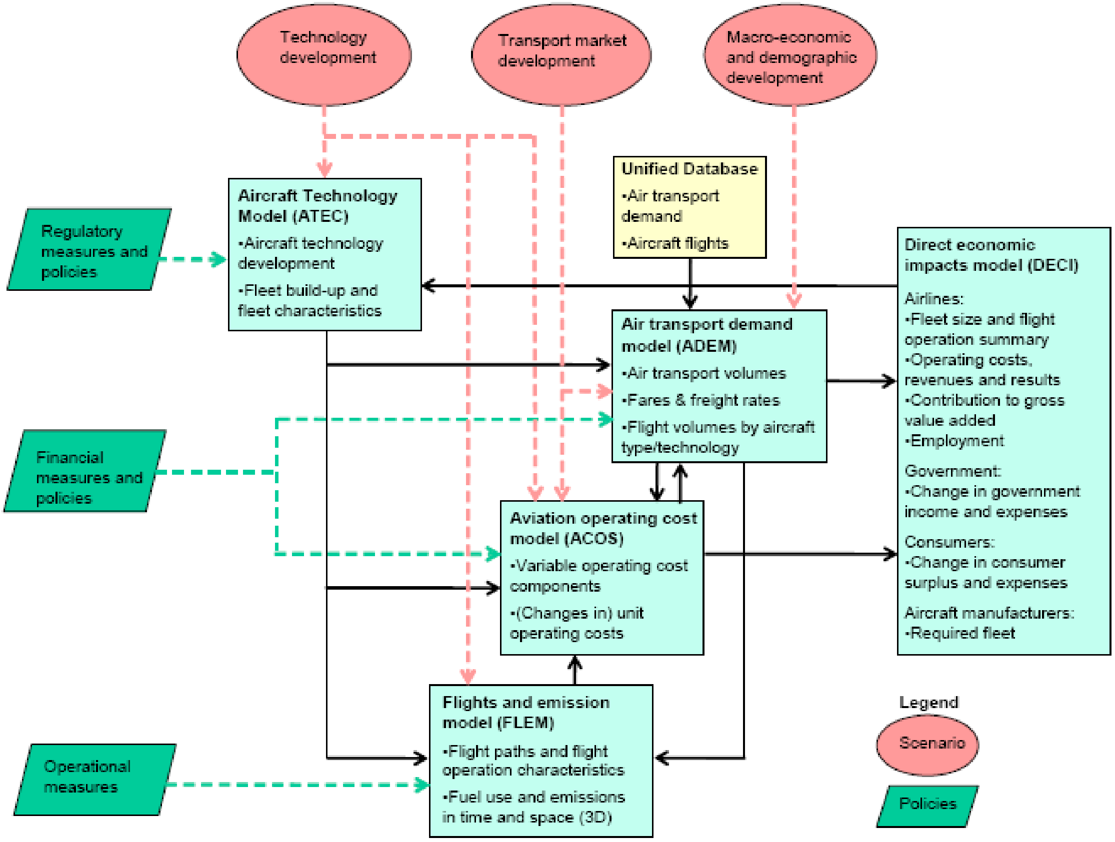


Figure 26. Framework of AERO-MS [78]

The Aviation Environmental Design Tool (AEDT) is another component of the tools being developed out of the FAA.[62] It provides the capability to perform aircraft fleet analysis. AEDT comprises of four existing FAA tools: the Integrated Noise Model (INM), the Emissions and Dispersion Modeling System (EDMS), the Model for Assessing Global Exposure from Noise Transport Aircraft (MAGENTA), and the System for assessing Aviation's Global Emissions (SAGE). INM and EDMS are the components for modeling local noise and emissions respectively. MAGENTA and SAGE capture global level noise and emissions. The strength of this approach is that the tools are integrated in a consistent fashion, which allows for assessment of the interdependencies at the fleet level.[79] Figure 27 provides the development history of AEDT.

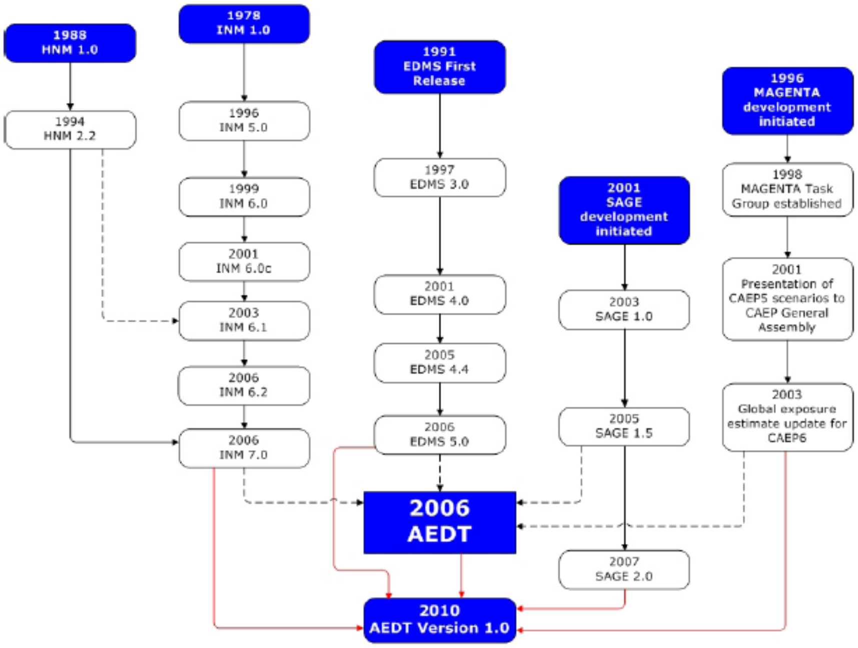


Figure 27. Development History of AEDT [79]

The Aviation Portfolio Management Tool for Economics (APMT-E) was developed as a part of the FAA/NASA/Transport Canada tool suite to be capable of modeling airline and aviation market outcomes to changes in environmental policy.[80] It projects future operating cost, demand projections and capacity requirements, fleet development projections, and fleet assignment over a set of operations with the objective of assessing the interdependencies between aviation environmental impacts and costs. It can address three different types of policy options: supply side responses where airlines changes their fleet mix, demand side responses where passengers may forego air transportation if fares significantly rise, and operational responses where airlines change operations to offset policy related cost increases. The flowpath of how APMT-E runs is provided in Figure 28.

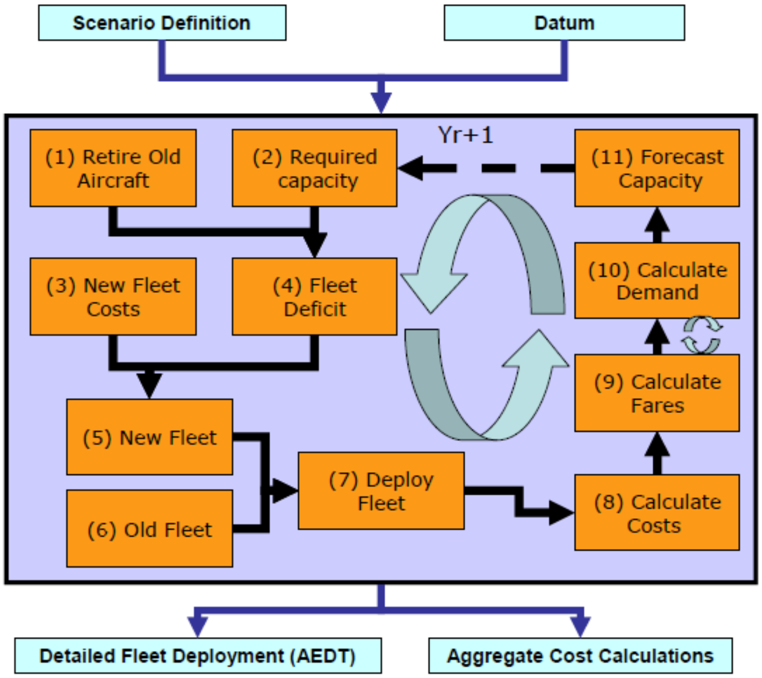


Figure 28. Overview of APMT-Economics Modeling Process [80]

Two challenges regarding these tools are the required setup time and the analysis times are significantly lengthy. This poses a particularly large challenge as it will be difficult to assess the implications of mission specification changes with a limited amount of fleet data. Therefore, a capability is needed to provide rapid fleet analysis with many of the same assumptions with limited sacrifices in fidelity. This was the main driver behind the following two tools.

The Global and Regional Environmental Aviation Tradeoff tool (GREAT) was developed to be an interactive, rapid aviation tradeoff capability that utilized a surrogate fleet representation developed by Becker with a surrogate representation of both current and future operations.[81] GREAT allows for vehicle-level technology infusion and propagation to the fleet, linking EDS and AEDT capabilities.[82] It is capable of utilizing various demand forecasts and calculates the total global or US centric fuel burn, NO_x, and airport specific operations sets for noise analysis. The process by which fleet-level assessments are performed is provided in Figure 29.

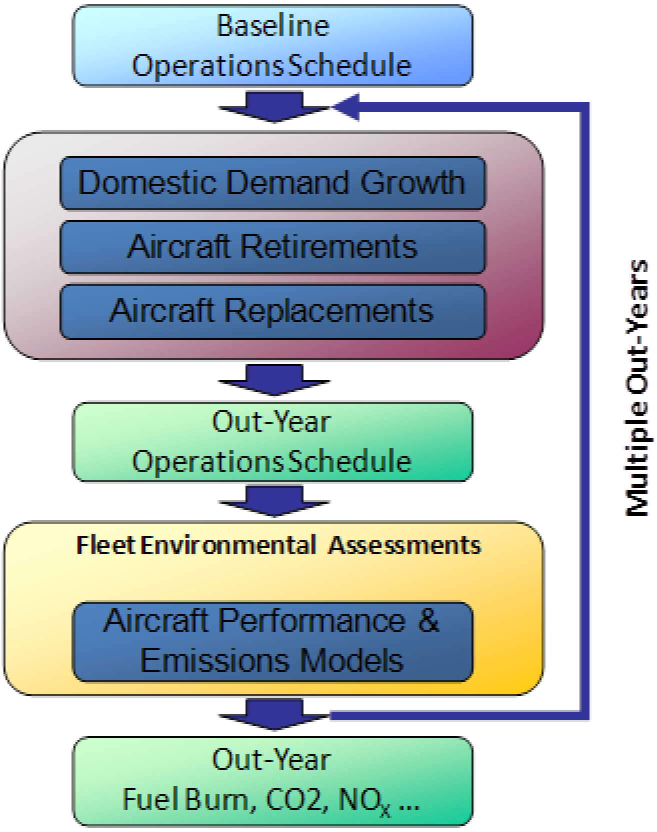


Figure 29. Overview of the GREAT Process [82]

As GREAT is only capable of fleet-level emissions, the Airport Noise Grid Integration Method (ANGIM) was developed to capture noise contours for individual airports. ANGIM operates on a set of pre-computed aircraft single-event noise grids and then converts them to sound pressure levels, applies operation quantity adjustments, adds multiple event noise-grids, converts to DNL in decibels, and finally exports the accumulated levels at each point in the grid.[83][84] Multiple runways are combined, rotated as appropriate, and finally calculate a representative contour area. This process is demonstrated in Figure 30. The linkage to GREAT is in the yearly flight data, which can be manipulated to provide noise contours for different airports. ANGIM can also process noise grids produced within EDS, linking the vehicle- and fleet-level assessments for noise.

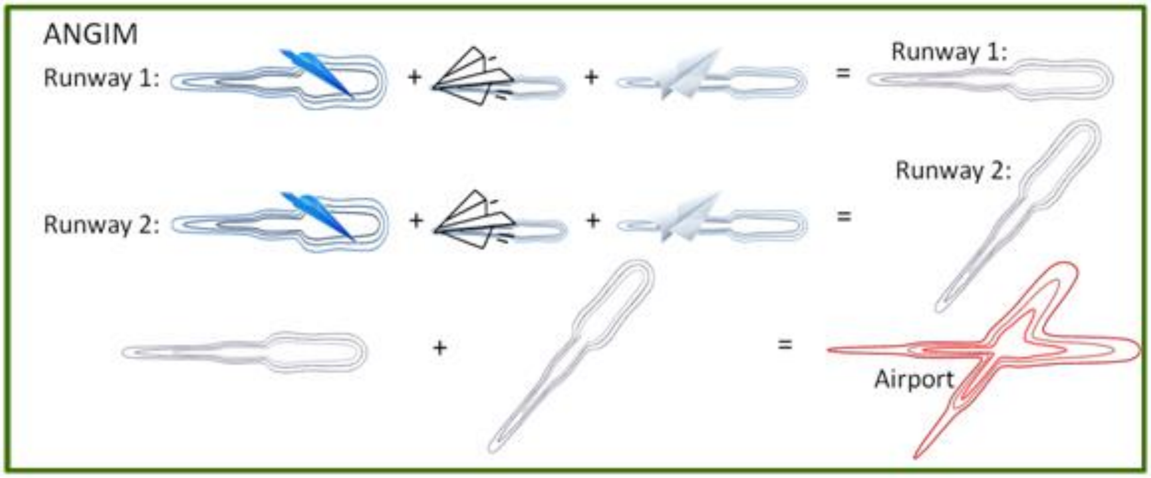


Figure 30. ANGIM Approach for Calculating Airport Noise [83]

2.4.2.3 Evaluation of Tools

An evaluation of the mentioned tools was conducted and the results are in Table 8. Based on this analysis, GREAT and ANGIM would both be excellent fits based on the criteria used but neither tools addresses operating costs or flight time; however, the source code for GREAT is available such that this lack of capability could be created. With respect to broader metrics such as safety, capacity, and reliability, it appears that these are much harder to capture and other considerations must be made, potentially using total number of operations or flight time as surrogates for these metrics and analyzing how changes in the flight numbers impacts them.

Table 8. Rankings of Fleet Modeling and Simulation Environments

Criteria	Imp	AIM	AERO-MS	AEDT	APMT-E	GREAT	ANGIM
Analysis Speed	High	Med	Med	Low	Low	High	High
Setup Time	High	Med	Med	High	High	Low	Low/Med
Ease of Vehicle Integration	Med	N	Y	N	N	Y	Y
Fidelity	High	Med	Med	High	High	Med	Med
Fuel Burn	High	Y	Y	Y	Y	Y	N
Emissions	High	Y	Y	Y	N	Y	N
Noise	High	Y	N	Y	N	N	Y
Block Time	High	Y	Y	Y	Y	N	N
Operating Costs	High	Y	Y	N	Y	N	N
Safety	Low	N	N	N	N	N	N
Capacity	Low	N	N	N	N	N	N
Reliability	Low	N	N	N	N	N	N
Source Code	Low	N	N	Y	N	Y	Y

2.5 Identifying Intermediate Stop Airports

The final challenge lies in identifying routes for intermediate stop airports at the fleet level. Note that this is a concern only when range reduction is introduced. When modeled at the vehicle level only, the analysis does not capture the reality that intermediate airports do not lie along the direct route so the benefits will be overestimated as there is no additional flight distance added to reach the intermediate airport.

However, this problem has been approached in literature by both Langhans and Yutko. Langhans looked at a selection of long range flights that could benefit from intermediate stops but the process for identifying the airports is not directly specified beyond the usage of a fuel ratio between the two airports.[49][50] The process itself is still somewhat vague. The analysis by Yutko is more clear as airport viability is based around a fixed runway length but route selection is predominantly focused on fuel burn.[40] The cost impacts are modeled only as a minimum improvement factor which would prevent intermediate stop adoption if fuel savings are small.

Graph theory is another approach that has been used to model relations between objects. A graph is simply a pairing of a set of vertices and edges which then represent a system in a simpler form. It has been applied to a number of problems in different fields but of particular interest are route problems. The most famous of these examples is the traveling salesman problem; however, the shortest path problem is of particular interest as it in many ways is similar to the problem at hand.[85][86][87]

The objective is to introduce intermediate stops to minimize fuel burn and given an origin (O), destination (D), and some number of prospective airports (a->e_2), there is a path that will provide the minimum fuel burn and minimum cost. Those two routes may be the same or they may be different depending on how much fuel is saved in comparison to the fees associated with the deviation from the original flight. An example of the problem at hand is in Figure 31.

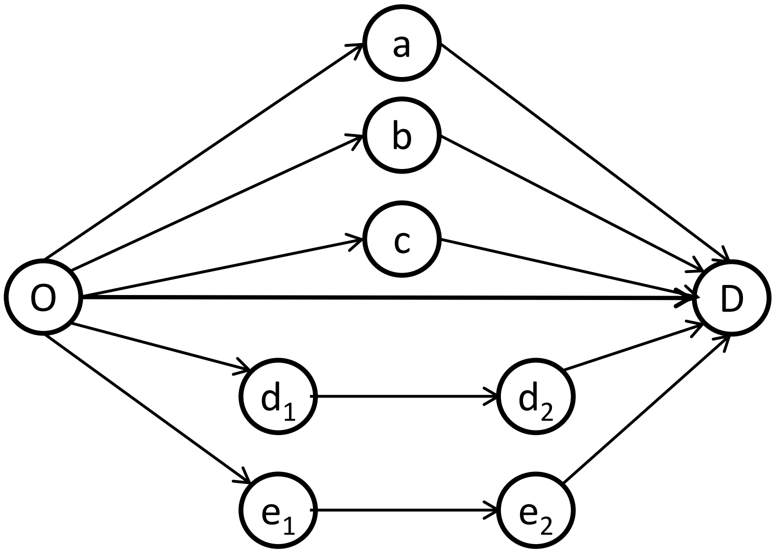


Figure 31. Example of Graph Theory Applied to Intermediate Stops Analysis.

That in itself is a graph, although simple in comparison to many of the other applications that graph theory has been used in. As aircraft range is reduced, the direct path OD may no longer be viable such that one of the other routes will become the most viable option.

Other techniques do exist for determining interconnectivity between different fixed hubs. One such method is trip generation and distribution modeling.[88] The objective of trip distribution modeling is to link up regions based on trips generated This area is primarily utilized in ground transportation and its application to intermediate stops could be interesting. The most commonly used is the gravity model and there have been a number of gravity models developed for aerospace purposes but they are predominantly limited to small network expansion problems.[89][90][91] Another popular model is the entropy model but both it and the gravity model require significant calibration efforts.[92] Based on these example problems, it would appear that these techniques would be overboard for this problem.

The objective here is not necessarily to identify the best method for conducting intermediate stops, but one that works and can be understood transparently. Graph theory appears to fit this need well and will be used to address this.

2.6 Hypotheses

The literature review has provided insight into the research questions. The first two questions are provided below.

- What is the current state of the art of mission specification analysis?
- Are the impacts of mission specification changes reduced when technology is introduced to the aircraft?

Literature has primarily been focused on mitigating fuel burn. While this is an important metric, it is plausible that mission specification changes will impact other metrics. This led to further research in addressing the various stakeholders in aviation and then determining their metrics of interest.

Research Question 1: What other metrics should be considered when looking at mission specifications?

Research Question 2: How does the introduction of mission specifications impact those metrics?

This review led to the development of the first hypothesis.

Hypothesis 1: Fuel burn only analysis is insufficient to adequately capture the impact of mission specification changes at the fleet level.

A review of the current state of the art provided the observations that the analysis is primarily at the vehicle level and technology infusion is largely neglected.

Research Question 3: How does future growth impact the fleet level metrics?

Research Question 4: How significantly different are the results comparing the immediate replacement vs evolution?

Research Question 5: Does the introduction of advanced technology reduce the impact of mission specification changes?

This yields the next three hypotheses.

Hypothesis 2: Mission specification changes must be evaluated at the fleet level and forecasted into the future to capture the overall impact.

Hypothesis 2a: Fleet evolution will be a significant contributor to reducing the overall impact at the fleet level.

Hypothesis 3: Aircraft technology infusion will reduce the sensitivity of mission specification changes at the fleet level.

Finally, a review was conducted to address the final research question.

Research Question 6: How does one select intermediate airport locations?

Research Question 7: How does airport location impact results in comparison to vehicle level analysis?

Multiple methods exist to capture schedule changes due to design range changes that would require the adoption of intermediate stop operations. However, the focus here is using a graph theory based approach to modify an operations schedule for intermediate stops.

Hypothesis 4: A graph theory approach can be used to modify an operations schedule to conduct intermediate stop operations analysis.

CHAPTER 3

METHODOLOGY

With the background information in mind, the next step is creation of a methodology to address the research objective. Development of a new methodology involves starting with an initial set of steps and then adapting them to fit the problem at hand. This research uses the generic Integrated Product/Process Development (IPPD) that was developed at Georgia Institute of Technology by Schrage.[93] The IPPD methodology is provided below in Figure 32. The key steps of any process are as follows: establish the need, define the problem, establish value, generate feasible alternatives, evaluate alternatives, and then make the decision.

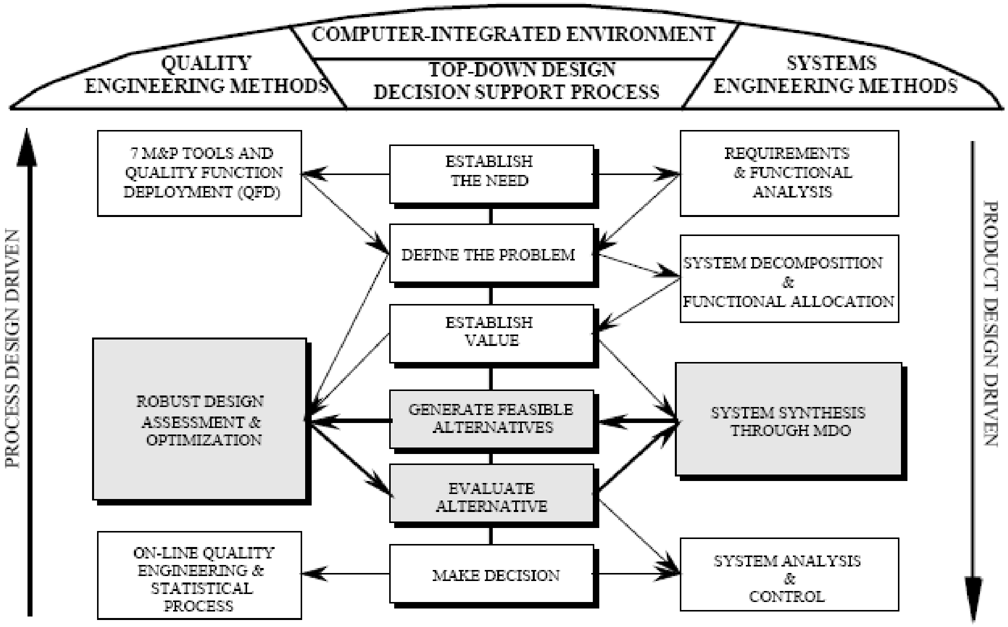


Figure 32. Generic IPPD Methodology [93]

These initial steps can then be expanded to develop the methodology that will be used for this research. As a reminder, the objective of this research is to develop a methodology that is capable of evaluating the implications of aircraft mission specification changes at the fleet level.

Starting from the standpoint of just comparing different mitigation strategies such as advanced technologies, operational changes, and others, there are five general steps that must be conducted to capture the fleet level implications. The first is to identify the stakeholders so that the potential metrics can be selected. The next step is to select the mitigation strategies of interest as they will in combination with the metrics selected define the modeling and simulation environment required. The third step is to create the M&S environment based on the criteria defined in this document. The remaining steps consist of evaluating the strategies, and assessing the implications.

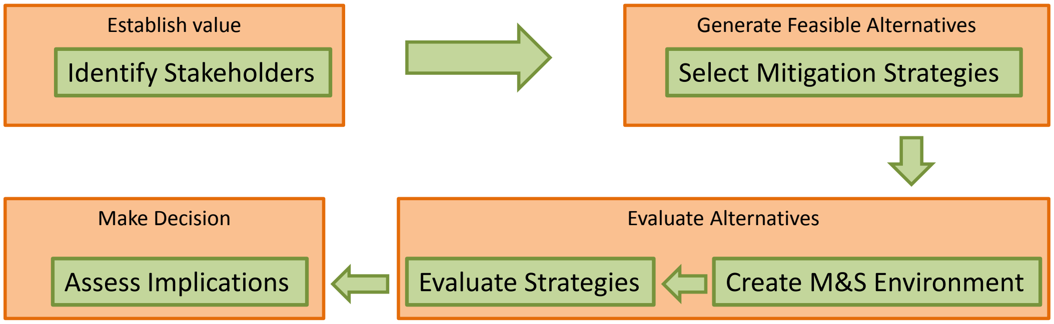


Figure 33. Generic Mitigation Strategy Analysis Framework

Now this framework is overly broad. One particular reason is that no one methodology will be capable of capturing all the considerations for different categories of mitigation strategies as each will have different requirements for modeling and simulation due to impacts on the system. However this serves as a starting point to generate a specific methodology for evaluating aircraft mission specification changes. Therefore, this generic framework needs to become further detailed to create the methodology. For the problem of mission specification changes, there are six necessary steps that need to be undertaken to fully analyze their impacts through the fleet level.

Step 1: Problem Definition

Capturing the impact of global aviation growth is a significant task and will take a considerable amount of work to provide a high level of confidence in the results. Therefore, the first step is to scope the problem to a manageable level.

Metric selection will provide insight into the problem being addressed and this is defined by the list of stakeholder needs that will be evaluated. This will set requirements for all the analysis going forward and will drive modeling and simulation environment decisions. Back in Chapter 2, an examination of different stakeholders was made and their associated interests which is provided here for reference. This list can be expanded based on what the needs are for the problem at hand and are meant only to serve as a starting point.

Table 9. Mapping of Stakeholders to Metrics of Interest

Stakeholder	Travel Time	Cost	Fuel Burn	Noise	Emissions	Regulations	Capacity	Safety	Reliability
Passengers	✓	✓						✓	
Flight Crew	✓	✓				✓		✓	
Maintenance Crew		✓						✓	✓
Airlines	✓	✓	✓			✓	✓		✓
Airports				✓	✓	✓	✓	✓	
Manufacturers		✓	✓	✓	✓	✓		✓	✓
Regulators			✓	✓	✓	✓	✓	✓	✓
Air Traffic Control						✓	✓	✓	
Airport Area Residents				✓	✓				
Everyone			✓						

The next step will be to select the mission specifications of interest and the associated ranges of interest. There are three specification changes as aircraft capability is measured as a function of how much payload can be moved, how far it can be moved, and how fast it can get there. Not all of these specification changes are necessarily applicable to all vehicle sizes. This can require modeling aircraft sizes through representative models or utilizing one aircraft model and scaling it throughout the boundaries of interest. Selection decisions can be made by prior design knowledge, literature review, left to the choice of the researcher, or vehicle level analysis can be conducted and not passed to the fleet if there is insufficient benefits.

As the objective is to assess how mission specification changes impact the future fleet, technology infusion should be considered as future aircraft designs will always integrate some level of new technology. This package should contain improvements to both the engine and the airframe and would be expected to impact the metrics selected. Technologies in the package should also have a relatively similar entry into service date as technology does not necessarily phase in while the aircraft is in production. Data can come from a variety of sources such as current technology programs if specific technologies are of interest or general targets for future impact.

Finally, the prospective future needs to be defined. This requires an initial operations set for the fleet, a demand forecast to grow the initial operations, a retirement schedule to remove aging aircraft from the fleet, and a replacement schedule to define when new aircraft will enter service. The baseline operations set is what will be used to forecast all future operations information. One source of data can be from the Department of Transportation Bureau of Transportation Statistics. The T100 is a collection of 10% of monthly flight totals but does not contain tail tracking.[94] The DB1B is a 10% ticket sample containing the number of passengers and the origin and destination airports.[95] On-time performance data contains data for domestic flights with flight numbers and origin and destination airports along with where delays were experienced.[96] Another operations set is the Common Operations Database developed by the Modelling and Database Task Force within CAEP which consists of six weeks of global operations.[40] Commercial entities such as Official Airline Guide also have compiled data for use.

Forecasts define what future growth will look like with respect to vehicle size and location of growth over particular regions. The Terminal Area Forecast is developed by the FAA and focuses on activity at FAA facilities to develop planning needs.[22] The

TAF is focused on the growth rates of specific facilities and much less detail on international flights.

Retirement curves can be provided from industry, they can be generated through usage of a mathematical function, or could simply be a hard cap which would suggest that once an aircraft reaches a certain age, it is removed from the fleet. Replacement schedules set when new aircraft are introduced into service. This schedule could be as simple as a switch at a given year from the current aircraft to the future one or a phase-in where the current aircraft is reduced over time and the future aircraft is gradually introduced.

Step 2: Create Modeling and Simulation Environment

Modeling and simulation will be required to enable analysis of aircraft mission specification changes at both the aircraft and fleet level. As mentioned in Chapter 2, there is no one tool that is capable of conducting the entirety of the work. This will require the creation of an environment that will enable the analysis. This methodology is intended to be independent of tool selection and instead lays out criteria that will enable this analysis.

As this is a two-tier problem, both an aircraft level sizing and performance tool and a fleet forecasting tool will be required. Although the criteria for both tiers are provided in Chapter 2, they will be provided here again.

A summary of the vehicle level modeling and simulation criteria is provided in Table 10. Physics-based analysis is critical to capture the interdependencies of technology integration and mission specification changes on the various vehicle level metrics. High fidelity is desirable as it increases confidence in the resulting analysis; however, it comes at a cost with respect to execution time. Rapid analysis enables significantly more alternatives to be evaluated and that additional analysis can provide further insight into understanding the impacts of mission specification changes. Automation capability can remove the need for having a human in the loop in terms of generating data. Noise, emissions, and cost are all important as they are the drivers of this research. Noise specifically requires curves measuring aircraft noise, power, and distance such that airport noise can be quantified. Finally, source code is a benefit if the desired capability is unavailable. Ideally, one would select a tool that predominantly meets the other criteria but if there is limited availability of other tools or a tool of interest meets most of the metrics, then developing a capability can be a solution.

Table 10. Vehicle Level Modeling and Simulation Selection Criteria

Criteria	Importance	Rationale
Physics-based	High	Modeling of mitigation strategies requires capturing the physics of the problem
Fidelity	High	Tool fidelity is critical to assurance that the resulting analysis is reasonable
Automation capability	High	Removes need for human in the loop
Rapid	Low	Reduces cycle time
Noise	High	Noise is one of the key drivers for this research
Emissions	High	Emissions is one of the key drivers for this research
Cost	Medium	Cost captures changes in acquisition and R&D costs which can impact the fleet
Source code	Low	Capability to develop higher fidelity if needed

The criteria for fleet modeling and simulation tools are available in Table 11. The most important two are analysis speed and setup time. There are a number of high fidelity fleet analysis tools in existence; however, many of them require significant computation and setup times to conduct the modeling. This is limiting in terms of data available for analysis. Ease of vehicle integration is not as critical but it is preferable that introducing the new vehicles to the fleet would not require significant amounts of additional analysis at the aircraft modeling level. This could result in greatly lengthening the run-time of the vehicle tools. Fuel burn, emissions, noise, block time, and operating costs are necessary to quantify the impact to various stakeholders such as airlines, airports, and passengers. Safety, capacity, and reliability are not as critical as these are challenging to capture from a modeling perspective and impacts can be measured through changes in operations.

Table 11. Fleet Level Modeling and Simulation Selection Criteria

Criteria	Importance	Rationale
Analysis Speed	High	Allows for more fleet analysis
Setup Time	High	Enables more fleet analysis
Ease of Vehicle Integration	Medium	Documented vehicle format for new vehicles
Fidelity	High	Provides confidence in the results
Fuel Burn	High	Key driver behind mission specification adoption
Emissions	High	Key driver behind research
Noise	High	Airport impact of mission specifications
Block Time	High	Passenger impact of mission specification
Operating Costs	High	Airline impact of mission specifications
Safety	Low	System impact of mission specifications
Capacity	Low	System impact of mission specifications
Reliability	Low	Airline impact of mission specifications
Source Code	Low	Add new capability if necessary

The overall flowchart of data should follow Figure 34. Problem definition will establish which mission specifications will be modeled, what technologies will be integrated into the aircraft, and the operations information necessary for future forecasting. The mission specification and technology information will be passed to the vehicle design tool to capture engine and aircraft performance with respect to the metrics of interest. This vehicle performance information is passed to the fleet level analysis but also to an operations modification module. This module would then update the operations set and then fleet analysis could be conducted. Then the fleet results will be analyzed to assess the overall impact of mission specification changes and determine the implications. Depending on the mission specifications analyzed, metrics could be considered a cost, a benefit, or neither. An example would be that speed reduction will not provide a change in the number of operations being conducted while intermediate stop operations will see an increase based on the number of flights modified.

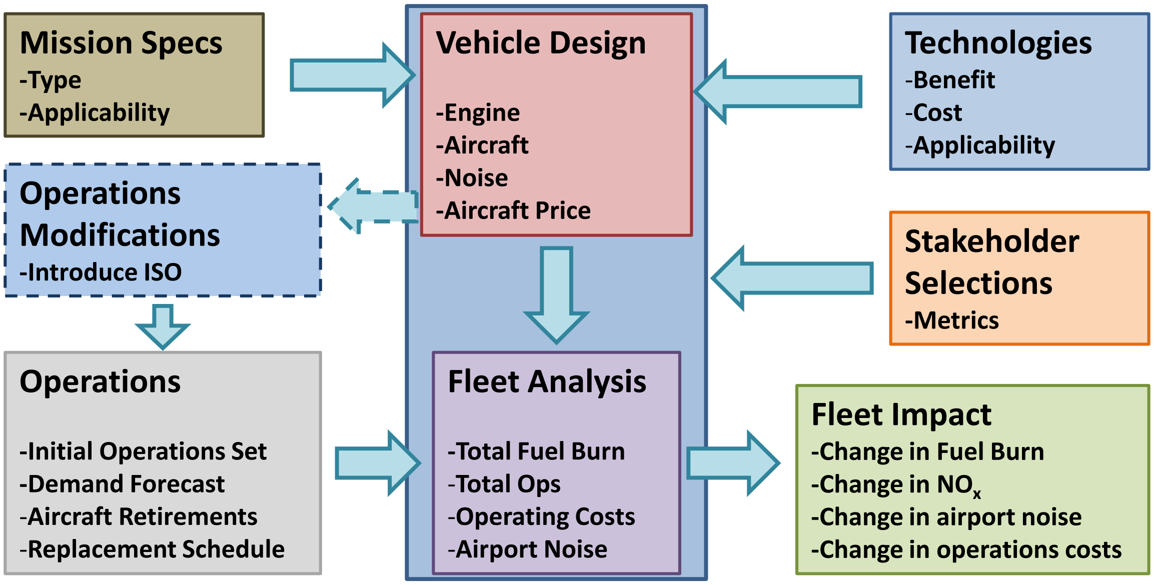


Figure 34. Flowchart of Modeling and Simulation Data Linkages

An explanation of the data flow between elements will help provide insight into what is required for each set of arrows. Stakeholder selections ultimately define the modeling and simulation environment and the only data flow here is what metrics need to be tracked at both the vehicle and fleet levels to quantify the impact of mission specifications. Mission specification selection established what inputs will need to be modified for vehicle design to thoroughly conduct design space exploration to identify the optimal aircraft for a given mission specification setting. Technology definitions indicate what vehicle level inputs need to be changed to model its integration.

The pertinent data from the vehicle design that passes to operations modification is the fuel burn and block time performance to model the environmental and cost impacts of intermediate stop operations. The vehicle design data that passes to the fleet requires more information than the operations modification data pass. Not only does the fuel burn and block time performance need to be passed, but the NO_x, aircraft price, and noise information also need to be passed. Of those three, the noise is the most complicated as it is more than just certification values. Detailed noise contours for each aircraft is needed to understand how the noise of all the different aircraft at the airports of interest should be integrated to determine the overall airport noise impact. This noise contour information from the vehicle level is a critical part of the vehicle level modeling.

The operations information is equally important even though it serves as just an input to the fleet level analysis. One needs to come up with a representative operations set to use for fleet modeling that is driven by the scope of the problem. The rest of the data – the forecast, the retirement schedule, and the replacement schedules – need to be defined and just passed into the fleet analysis. The last data flow is the fleet analysis results being available for processing. For cost metrics and all the environmental metrics that aren't noise, this should be the cumulative total from the years of investigation. The noise should be contours on an airport by airport basis over the years selected for that particular analysis.

Step 3: Develop Future Vehicles

Future vehicles will need to be designed for mission specification changes and technology infusion. This entails more than just running the sizing code for the new design parameters. The baseline aircraft performance constraints must also be considered. These include takeoff field length, landing field length, approach speed, and time to climb as any new aircraft would have to match performance of the baseline aircraft at a minimum. To further increase efficiency of the engine for cruise speed reduction, the engine can also be slightly redesigned for this new speed; however, this requires consideration of various engine constraints. Range reduction does not require this engine redesign if cruise speed is held constant as the engine itself could be scaled to provide adequate thrust.

Aircraft and engine technologies will also need to be modeled in this step. This will require linking the associated impacts to inputs within the aircraft modeling and simulation environment to capture the changes due to technology infusion. To establish the performance constraints for the future aircraft, the baseline aircraft must first be modeled to establish the new baseline performance values. Then these values can then be used as constraints for the mission specification aircraft or if one has a particular set of customer requirements, then those values can be used to further guide the future technology vehicle design.

As a part of this step, one can also evaluate the performance of the different vehicles with respect to the mission specifications of interest. If there is clear evidence that a particular aircraft size does not benefit from its introduction, then there is no need to evaluate it at the fleet level to further demonstrate that it does not benefit.

Step 4: Modify Operations Set

Operations modifications are required for range reduction to account for the introduction of intermediate stop operations but this step could be considered whether or not range reduction is being considered. This could be done by hand for a small operations set; however, if dataset is sufficiently large, this would be a significant time investment as one would need to evaluate the performance of the direct flight against all prospective airports within some range of the operation. To expedite this analysis, an automated module should be utilized. The module will need to start with the initial operations set and an airport list and then return modified routes for the long range flights based on the aircraft design ranges generated. The selection criteria for the intermediate stop location should be based on minimizing fuel burn or operating cost and this outcome should be repeatable.

This process starts with identifying the candidate airports that might be used as intermediate stop locations. This will require latitude and longitude information of the airport as well as runway length and width information for all the runways. Runway information can be used to filter out airports that will be unable to allow for operation of the aircraft of interest. An example would be considering DeKalb Peachtree Airport, a general aviation reliever airport, as an intermediate stop for a B747.

With the airport list compiled, the next step is to calculate the distance between the airports as flight distance will be used to evaluate performance to assess which route should be taken between the origin and destination airports. The distance calculations can be calculated using great circle distance equations between the two points. Additional distance can be added to address that the flown distance rarely matches the great circle value due to wind optimized routing and inefficiency in the air transportation system. Once the distances between airports have been calculated, the next step is to generate prospective routes.

Using the airport list and the flight distances, prospective routes can be generated by evaluating each airport as an intermediate airport by comparing the distance between the origin and destination airports. For a large number of airports, this would generate a significantly lengthy list of routes. However, additional filtering can be performed based on distance.

Now that the route pool has been generated, the final step is to evaluate aircraft on the routes. Route selection is a function of the chosen metrics. Traditionally, range reduction has primarily focused on fuel burn savings such that fuel burn should always be considered. Operating cost could also be considered between the baseline route and the prospective origin-intermediate-destination (OID) routes. Calculation of both metrics will require aircraft performance data to get the total fuel and cost for each route as well as the associated cost information.

After all the prospective OID routes have been evaluated, the final step is to find the top handful of routes for each metric so the final selection can be made. In some cases, one may find multiple airports in close vicinity in terms of metric performance. An example would be John F Kennedy, LaGuardia, and Newark airports that serve the New York City region. This will also help identify regions that will be expected to see a significant rise in total operations.

This process will need to be conducted for all the origin/destination pairs of interest for all the aircraft of interest. This process is illustrated in Figure 35.

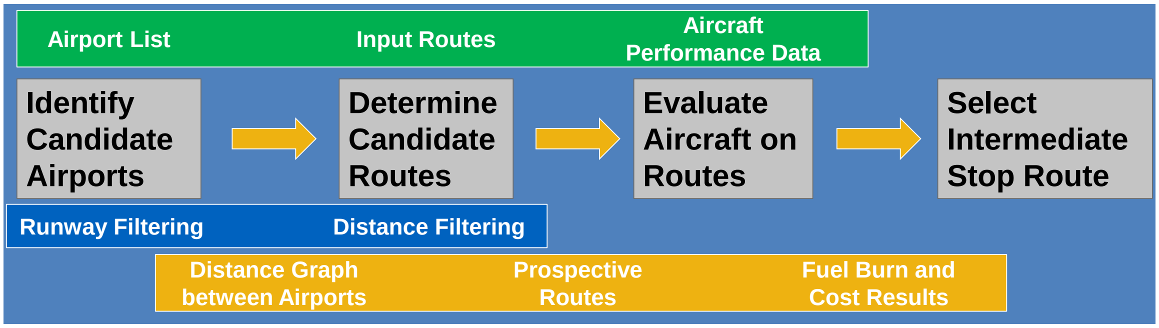


Figure 35. Intermediate Airport Selection Process

The assumption for operations modification is that only the airport that could handle the modified aircraft at the baseline technology level can be used for the future technology aircraft. Handling includes considerations such taxiway and gate infrastructure that are not information that is as easily available as runway data. While future aircraft could see reductions in field length constraints, it would be challenging to determine whether the airports that were filtered out due to baseline runway information would build the infrastructure necessary to accommodate aircraft in larger seat classes.

Step 5: Evaluate Fleet Performance

The new aircraft are then introduced to the fleet. The operations set, demand forecast, retirement curves, and replacement schedule are used in the fleet analysis tool to evaluate the impact of mission specification changes at the fleet level.

Seat classes should be evaluated individually initially to quantify the fleet level sensitivity of mission specification changes. Comparisons of ISO vs direct flights can also be conducted with and without redesigning the aircraft in this step.

Once the seat class outcomes are fully understood, one can then look to combine different designs to evaluate the full impact at the fleet level whether it is through a minimizing fleet fuel burn or minimizing operating cost or a different metric.

Noise will need to be modeled through a set of airports for associated years of interest. Those operations will need to be identified and the vehicles need to be made available to assess the impact. Although one could look at the noise impacts of airports through contours, a potentially safer approach is to use models that represent existing infrastructure and only look at changes to the area of the contours. This approach may not work when considering population exposure and a suitable method would be needed.

Step 6: Assess Implications

With the fleet level analysis concluded, the final step is to examine the impacts due to changes in mission specifications. This will involve comparisons of the different vehicle designs against the baseline results where the existing replacement aircraft are used. Once all the data is compiled, one can assess the benefits and costs of adopting the respective mission specification changes. This could be comparisons in fuel burn vs operating cost or benefits of intermediate stops vs the noise impact at those new airports. Additional exploration could be conducted by varying the assumptions used to further understand the sensitivities of mission specifications to those assumptions.

In summary, this chapter has proposed a new methodology for evaluating the fleet implications of aircraft mission specification changes. A visual of where each step of Mission Specifications and Fleet Implications Technique (MS-FIT) occurs is included in Figure 36.

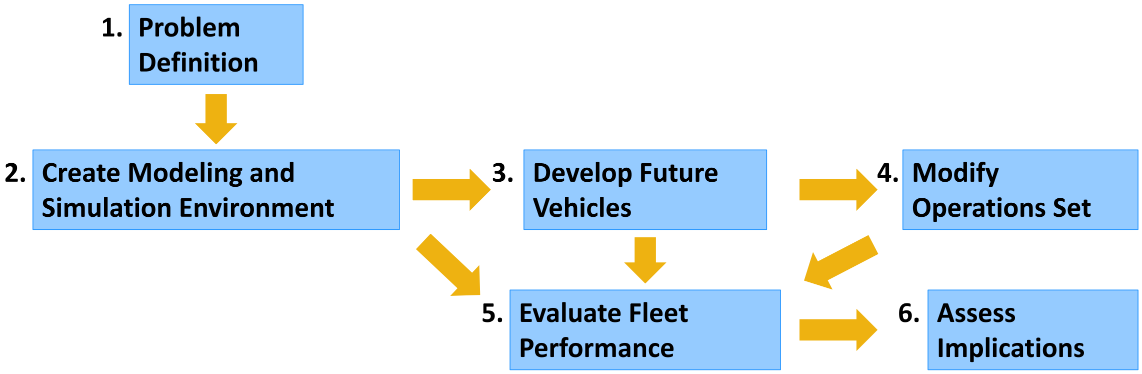


Figure 36. Steps of MS-FIT

CHAPTER 4

TECHNICAL APPROACH

In order to evaluate the hypotheses, a research plan is required. This chapter will discuss the process utilized and the experiments conducted in the following three chapters.

4.1 Experimental Setup

The first step is to select the mission specifications and metrics of interest for this research. Mission specification changes are not a particularly lengthy list with only cruise speed and mission range being of interest. In Chapter 2, a variety of stakeholders and their associated concerns were presented. This research will focus on two levels of metrics: aircraft and fleet specific. Aircraft metrics include mission performance with fuel burn, NO_x emissions, and mission time and design attributes with acquisition costs and certification noise and NO_x values. The fleet level will focus on total annual fuel burn, NO_x emissions, and costs, airport noise from a select number of generic airports, and less quantitative metrics such as safety.

To begin evaluating mission specification changes, one must redesign aircraft for speed and range reductions. At this level, the objective is to identify which seat classes benefit from mission specification changes so that selected vehicles can then be carried through to the fleet level for further analysis. Additionally, any vehicles that show benefits for both speed and range reductions independently can then be considered together. These three problems will represent demonstrations of MS-FIT. Vehicle redesigns will be conducted for both existing technology as well as a future technology package.

Five seat classes will be modeled: regional jet (RJ), single aisle (SA), small twin aisle (STA), large twin aisle (LTA), and large quad (LQ). Representative reference vehicles have been identified for demonstration purposes and are provided below in Table 12.

Table 12. Aircraft Models Used for Study

Seat Class	Airframe	Engine
Regional Jet	CRJ900	CF34-8C5
Single Aisle	B737-800	CFM56-7B26
Small Twin Aisle	B767-300ER	CF6-80C2
Large Twin Aisle	B777-200ER	GE90-94B
Large Quad	B747-400	PW4056

For each specification change, bounds need to be established with respect to the original baseline values. These will be open to be reevaluated based on performance data as the analysis is conducted in the event that further exploration is deemed unnecessary. However, Table 13 contains the initial bounds intended to be used in this study for cruise speed and mission range. Steps in speed reduction will be conducted in intervals of Mach 0.02 from the baseline. The initial minimum speeds will likely be far less than that for minimum fuel burn; however, the objective is to insure thorough coverage of the space. Steps of range reduction will be conducted increments of 5% from the baseline down to 35% of the baseline value, represented by the initial minimum in Table 13. Boundary readjustment will be driven by analysis of results based on level of benefit. Speed reduction will stop after the minimum fuel burn design has been identified while the range reduction analysis would conclude if benefits are limited at 50% range with one intermediate stop.

Table 13. Initial Boundaries for Speed and Range Reduction

Seat Class	Initial Min. Mach Number	Baseline Mach Number	Initial Min. Design Range (nm)	Baseline Design Range (nm)
Regional Jet	0.60	0.80	693.0	1,980
Single Aisle	0.60	0.78	1,036.0	2,960
Small Twin Aisle	0.60	0.80	2,072.0	5,920
Large Twin Aisle	0.66	0.84	2,635.5	7,530
Large Quad	0.67	0.85	2,471.0	7,060

Additionally, all aircraft designs have been evaluated at an economic range at full passenger payload to compare performance beyond just the baseline design mission. These economic ranges are points within the payload range diagram that represent flown distances more commonly seen in operation. These ranges are provided in Table 14. As range reduction results in large twin and large quad variants with a maximum range less than the primary economic range, a secondary economic range was also used to additionally evaluate economic performance.

Table 14. Economic Ranges for Each Seat Class

Seat Class	Economic Range 1 (nm)	Economic Range 2 (nm)
Regional Jet	800	-
Single Aisle	900	-
Small Twin Aisle	1,800	-
Large Twin Aisle	4,000	2,500
Large Quad	4,400	2,400

The baseline vehicles were first run through EDS to generate the necessary files for use in a Modelcenter FLOPS based environment. This was done to facilitate design optimization for each speed and range redesign for each aircraft. To generate the associated speed reduction engine decks, the aircraft were run through EDS with reduced speeds. This process is documented in Chapter 6.

The primary objective of the optimization was minimization of design mission fuel burn by varying both engine thrust and aircraft wing area, though wing sweep and thickness were varied for speed reduction as a function of cruise Mach.[97] To capture changes in takeoff and landing maximum lift coefficient from wing changes, RELACS was used.[98] It was also used to generate the respective drag polars for all designs.

The aircraft was subject to the following performance constraints: takeoff field length, landing field length, approach speed, excess thrust, and time to climb. Constraint limits were taken from the respective technology level baseline aircraft model results.

The Modelcenter environment was run with multiple starting points to ensure that the optimum result truly was the global outcome. After the optimum vehicles were designed, the corresponding vehicle was then run in EDS and evaluated to ensure sufficient similarity in performance. Comparisons of the results between the two environments required that design mission fuel burn results were within 1% of each other.

Technology assessment requires a set of technologies that will be integrated into the vehicles. There are a variety of sources that one can use for this analysis as the number of aviation technology programs provides a large number of options. For this research, a review of current aeronautical research and development programs was conducted and a subset of technologies was selected that impacted fuel burn, NO_x, and noise. Note that technology selection is not the objective of this work, such that there will only be one technology package. This group was compiled based on technologies that would be available in the middle of the 2020s. Table 15 contains the name of the technologies used and their respective designations from the referenced report. All technologies were applicable to all representative aircraft.

Table 15. Future Technology Package

Technology Name	Designation
Composite Technologies (2010 Baseline)	T01
Excrescence Reduction	T02
Continuous Moldline Link for Flaps	T03
Landing Gear Integration	T04
Advanced Powder Metallurgy Disk - HPC Last Stage Disc/HPT Disc/LPT First Stage Disc	T05
Advanced TBC Coatings - Turbine Blades	T06
N+2 Advanced TBC Coatings - Turbine Blades	T07
Advanced TBC Coatings - LPT Blade	T08
Advanced Turbine Superalloys - HPT Blades/LPT Last Stage Disc	T09
CMC HPT/LPT Vane + Hi Temp Erosion Coating	T10
CMC Exhaust Core Nozzle	T11
Polymer Matrix Composites (PMC) - Nacelles/Fan/Bypass Duct	T12
PMC Fan Blade with Metal Leading Edge	T13
Aft Cowl Liners	T14
Combustor Noise Plug Liner	T15
Fixed Geometry Core Chevrons	T16
Over the Rotor Acoustic Treatment	T17
Soft Vane	T18
Zero Splice Inlet	T19
Lightweight CMC Liners	T20
RQL Combustor (TALON X)	T21
Advanced Engine Components	T22
Low Interference Nacelle	T23
Blisk	T24
Ti-Al - LPT Aft Blades	T25

From the fleet perspective, forecasting was done using a number of forecasts from various sources such that they were combined to get a representative forecast for fleet evolution. As the forecast extends only to 2036, growth rates have been exponentially extrapolated up to year 2050. The datum set of operations is six weeks of global flights from 2006 originating from BTS data.

For range reduction, it is from this datum set of operations that the determination of viability for intermediate stops will be made. An overview of the modeling and simulation analysis for intermediate stops is located in Chapter 5 and the range reduction problem is in Chapter 7. To evaluate the fleet level performance, GREAT and ANGIM will be used.

Aircraft designed using existing technology were introduced in 2020 and phased in as replacements over a four year period. Designs that have future technology integrated into them were phased in at 2024 with the same four year integration timeframe in mind. This is reflected in terms of what aircraft are used for the new operations in a given year. So for years prior to entry into service in Figure 37, all the new operations for that year consist of the baseline aircraft. In 2020 or 2024, 25% of the new operations are the replacement aircraft and continues to grow such that in EIS + 3 and beyond, all the new operations consist solely of the replacement aircraft.

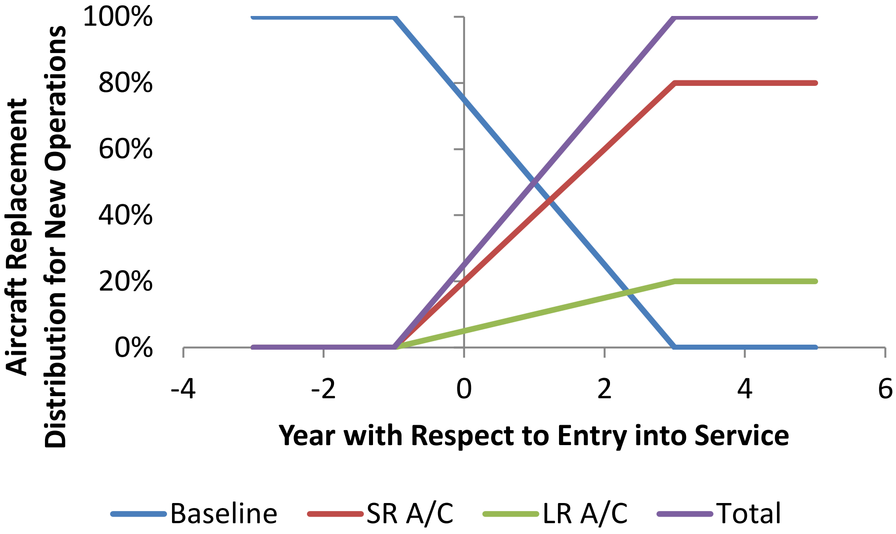


Figure 37. Replacement Strategies of New Vehicles

For the range reduced aircraft, there is a need for two variants. Figure 38 demonstrates that the short range variant is viable up to a particular range threshold and beyond that value, the long range variant is the only one used. This threshold is defined by the maximum range of the aircraft for a particular payload. In the short range variant regime, the distribution can be varied to allow for long range variants to operate there as well and this is investigated from a 100%-0% of SR-LR to a 50%-50% in increments of 10%.

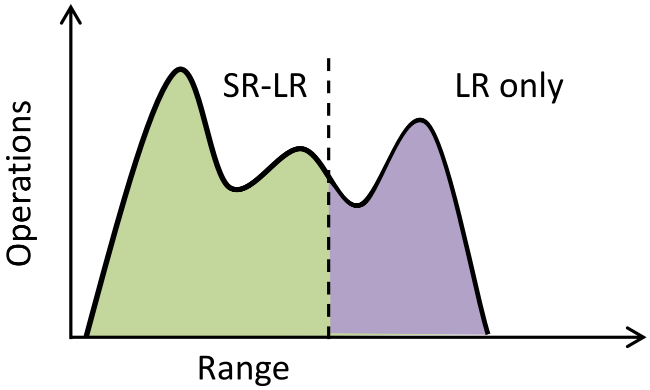


Figure 38. Distribution Replacement of Short Range and Long Range Variants

An example of how this is implemented for the 80%-20% distribution for a future technology scenario is in Figure 37 for range reduction. For ranges below the threshold values, the red line represents the new operation distribution of the short range variant while the green line represents the long range aircraft. Combined, they equal the same purple line as before. And for operations to the right of the threshold value, only the purple line is used as there are no short range variants and the operations are entirely the long range aircraft.

To capture elements regarding aviation safety, Boeing documented historical trends of accident rates from 1959-2012 for worldwide operations.[99] This data is provided in Figure 39. This trend will be fitted from 1985 to 2012 and extrapolated to 2050.

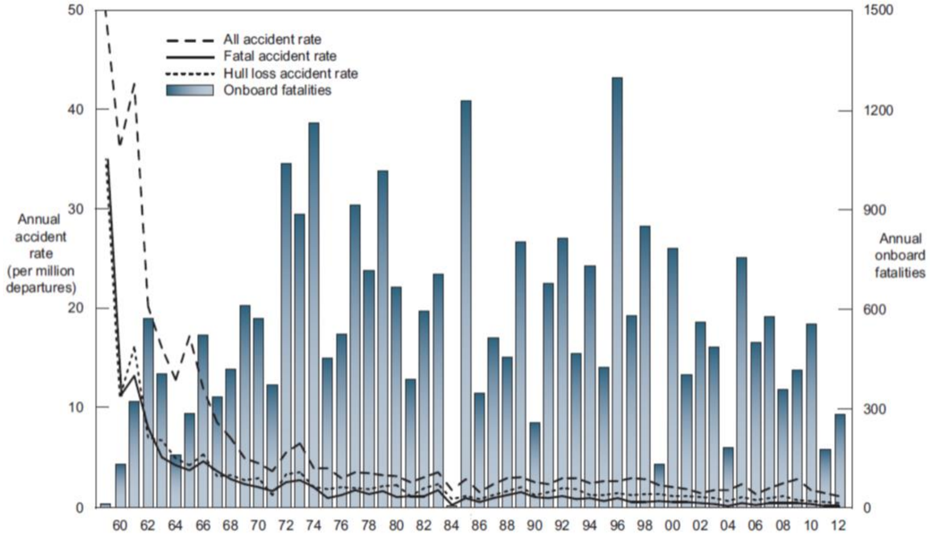


Figure 39. Accident Rate per Million Operations [99]

However, accident rate per million operations does not adequately capture any changes that are due to speed reduction. This same presentation has data linking annual departures to flight hours from 1993-2012 such that speed reduction can be assessed as well. This data is in Figure 40 and will be fitted and extrapolated through 2050.

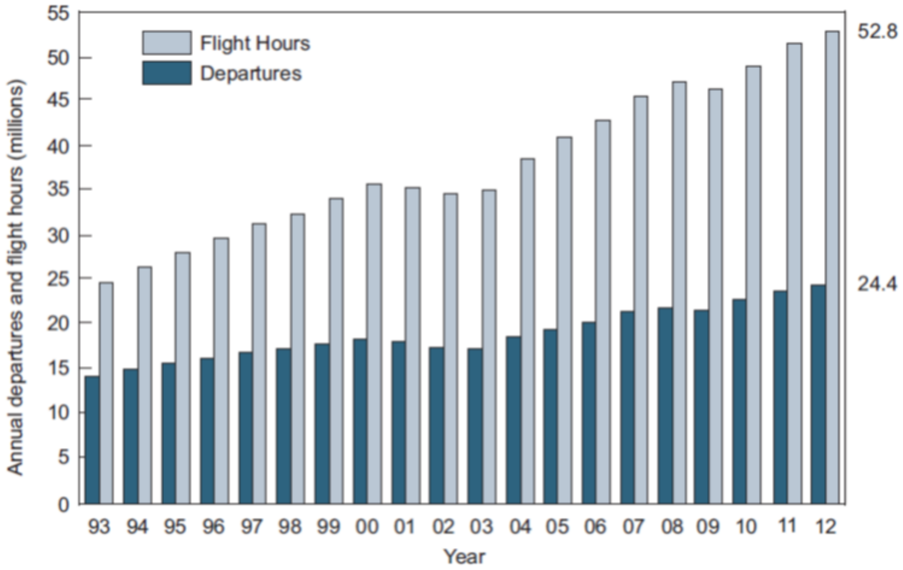


Figure 40. Linkage of Flight Hours to Operations [99]

For the noise analysis, a subset of global airports was selected to represent high, medium, and low traffic levels and world regions. Data used to select these airports came from a couple of sources. The Port Authority of New York and New Jersey's 2013 Airport Traffic Report contains a significant amount of data regarding the top 50 domestic and top 50 international airports by traffic.[100] Much of their data comes from Airports Council International, which tracks passenger, cargo, and movements globally.[101] In addition, the top five airports from intermediate stop traffic analysis were also added to capture the effect that this operating strategy impacts these otherwise, limited traffic airports. Given potential concerns of using actual airport layouts, generic airport configurations have been used to represent them as documented in Bernarndo.[102] Classifications of the airports as well as generic runway configuration is provided in Table 16.

Operations for each airport will be generated using the operational data from GREAT and then scaled to represent a single day. This does bring some challenges as one could look at every individual year to assess the annual growth of a particular set of airports. That is not the objective of this research such that each year is not necessary. Instead, the years 2036 and 2050 were selected. As the new mission specification aircraft are being introduced in 2020 or 2024, operations before 2030 will not have allowed enough time to ensure significant numbers in operation of the new aircraft.

Table 16. Airports Modeled for Fleet Noise Analysis

Traffic Level	Airport	Configuration
High	Hartsfield-Jackson – Atlanta, USA	Parallel Single
	O'Hare – Chicago, USA	ORD
	Capital Intl – Beijing, China	Parallel-Single
	Heathrow – London, UK	Parallel
	Dubai Intl – Dubai, UAE	Parallel
	Charles De Gaulle – Paris, France	Parallel
Medium	John F Kennedy – New York City, USA	Parallel-Intersecting
	San Diego Intl – San Diego, USA	Single
	Salt Lake City Intl – Salt Lake City, USA	Parallel-Single
	Incheon Intl – Seoul, South Korea	Parallel
	Eleftherios Venizelos Intl – Athens, Greece	Parallel
Low	Palm Beach Intl – Palm Beach, USA	Intersecting
	Cincinnati/Northern Kentucky Intl – Cincinnati, USA	Parallel-Intersecting Single
ISO	Gander Intl – Gander, Canada	Intersecting
	Goose Bay – Goose Bay, Canada	Intersecting
	Lajes – Lajes, Portugal	Single
	Amilcar Cabral Intl – Sal, Cape Verde	Single
	Petropavlovsk-Kamchatsky Airport – Yelizovo, Russia	Single

Contours of interest are 55 and 65 dB. Noise results will be represented as a summation of the group rather than individual airport. Specific airport noise contours will not be provided. A summary of the modeling and simulation environment showing how data is passed is provided in Figure 41.

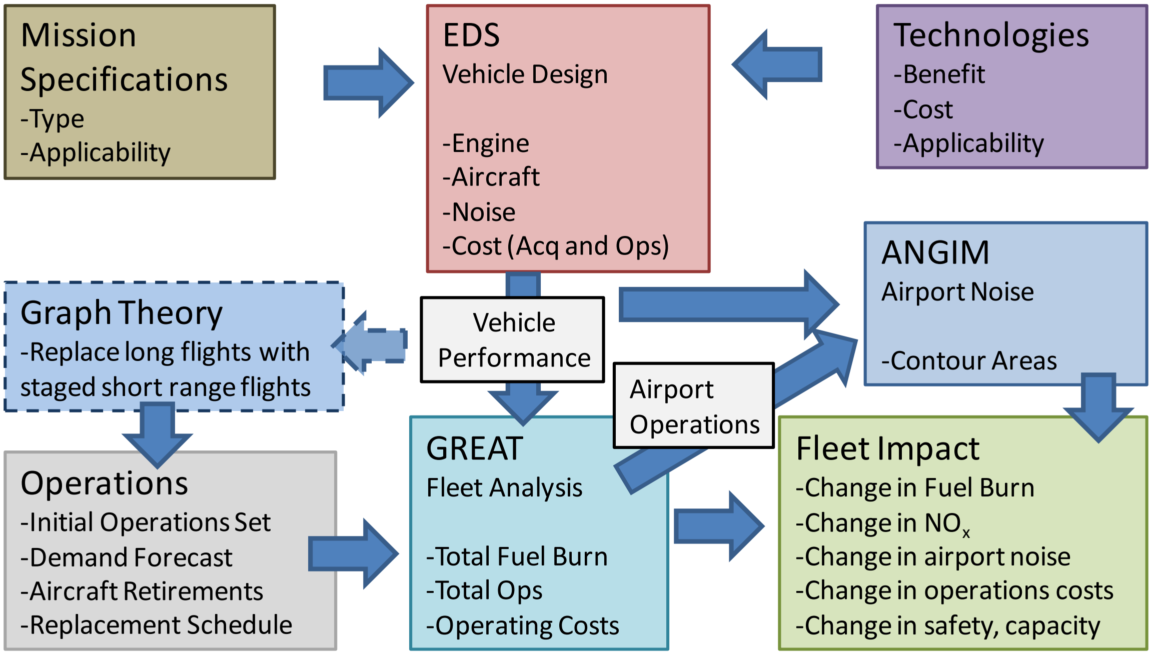


Figure 41. Modeling and Simulation Environment

There are a number of assumptions that have been made in order to conduct this analysis. They have been summarized in Table 17 so that they are available in one location for both vehicle and fleet analysis.

Table 17. Summary of Research Assumptions

Vehicle
Engine modeling • Speed: OPR increase and airflow scaling • Range: airflow scaling • Joint: OPR increase and airflow scaling
Aircraft are design with minimizing fuel burn as the target objective • Wing area and engine thrust were varied • Wing thickness and sweep are defined as a function of cruise Mach number • All other parameters were kept at existing values or sizing ratios
Sizing subject to performance constraints • Takeoff field length • Landing field length • Approach speed • Excess engine power • Time to climb
Aircraft price is calculated as a function of takeoff gross weight • Future aircraft price is an increase based on fuel burn savings over the lifespan of the vehicle • Both are defined in Chapter 5
Technologies were modeled as k-factors to the respective inputs of interest in the model
Intermediate stops were modeled directly along the route • Halfway for one stop • Even thirds for two stops

Fleet
Fixed cost assumptions over the timeframe of interest • Fuel price fixed at $3.00/gallon • Crew, maintenance fixed at seat class rates • Route and landing fixed at their regional values
Fleet results are for the six week operation set
Fleet results for each year are cumulative
Noise is 55 and 65 dB contour areas over the airports of interest
Airports are modeled through generic runway configurations
Datum set of operations are from 2006 for a six week period
Forecast was generated by combining various sources to get a representative approach for fleet evolution
New vehicles are phased in over a four year period • 2020 for baseline technology • 2024 for future technology
Range reduction requires a short range and a long range variant – threshold of maximum range dictates with replacement strategy is used • Defined mix for short ranges • Long range aircraft only for long range

4.2 Experimental Plan

Throughout Chapter 2, a number of observations were made that led to a number of hypotheses. In order to test these hypotheses, a number of tests need to be conducted.

The following section will explain the design and objectives of the experiments conducted in the following chapters.

Hypotheses 1 is focused on metrics beyond the traditional metric of fuel burn. The sole focus of much of the analysis of specification changes in literature has been on fuel burn and that does not address that many other requirements are at play in making a decision to use an aircraft. For this work, those other metrics will be operating cost and total cost (the combination of operating and capital costs). An example of how this might look is presented in Figure 42.

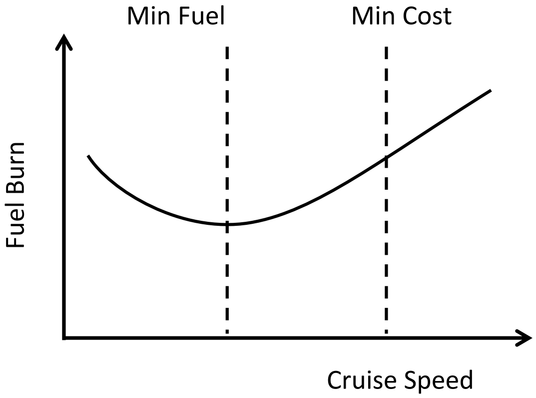


Figure 42. Generic Presentation of Hypothesis 1 Test

Testing Hypothesis 2 concerns differences between aircraft and fleet level impact and forecasting those aircraft into the future. Figure 43 compares what the fuel burn results might look like for range reduction at the aircraft level. The best fuel burn aircraft might occur at the minimum bounds of interest; however, when introduced to the fleet, the operational distribution and fleet growth would yield an aircraft that has a longer range than the optimal aircraft level vehicle but better fleet fuel burn.

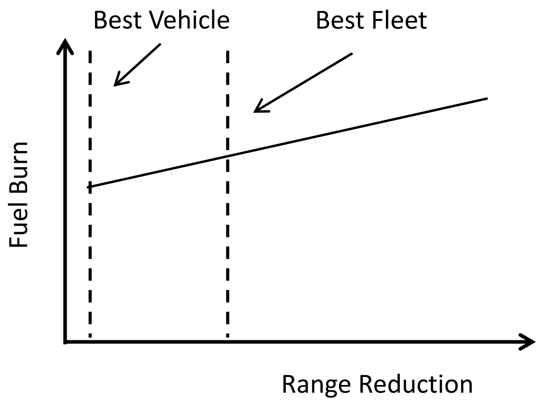


Figure 43. Generic Presentation of Hypothesis 2 Test

To test the sub hypothesis that is concerned with fleet evolution being a significant contributor to reducing the overall impact, the fleet results with fleet evolution will be compared to complete replacement results at the entry into service for both technology levels and then forecasted through to the year 2050. The objective will be to see what fleet level impacts occur because of this. It is expected that fuel burn savings will be overestimated. Additionally, as the forecast reaches the year 2050, the difference in the two results should become close. A generic presentation of the results is provided in Figure 44.

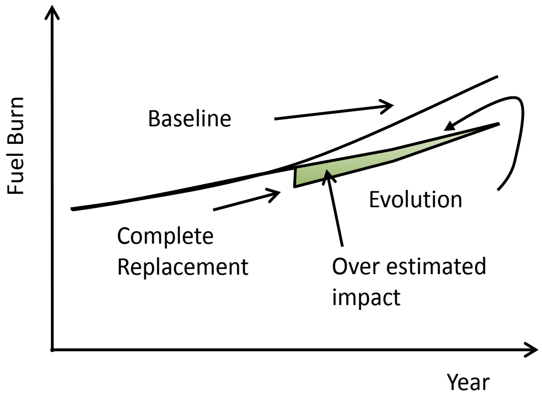


Figure 44. Generic Presentation of Hypothesis 2a Test

To test Hypothesis 3 with respect to aircraft technology infusion reducing the impact of mission specification changes at the fleet level, both vehicles will be introduced in 2020 and the fleet results will be analyzed. The predominant metric of interest is fuel burn as it is the motivating factor but impacts to NO_x, operating cost, and total cost will also be examined. A notional figure is provided in Figure 45 highlighting how these results will be presented.

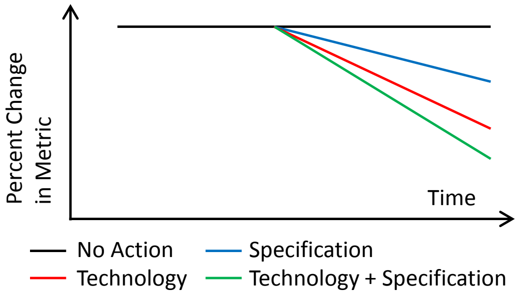


Figure 45. Generic Presentation of Hypothesis 3 Test

In order to test Hypothesis 4 regarding the usage of graph theory to modify an operations schedule, a demonstration will be conducted as a part of this work. This will be found in Chapter 5.

Additional trade studies will be conducted and briefly mentioned here. The first looks at variation in the cost elements impacted by specification changes to understand how their changes will impact the economic desirability of making these changes. The next one addresses the impact that annual utilization changes will have on capital costs and ultimately the total fleet cost. There may be consequences in terms of aircraft positioning due to specification changes such that the actual utilization will be less than the assumed values. This study will help understand this sensitivity.

The final study looks at how modifications in the intermediate stop distribution will impact desirability of short range variants. This study attempts to model how some airlines may elect to not adopt intermediate stops or business travelers may prefer to pay a premium to get a direct flight while leisure travelers will not such that potential benefits cannot be fully realized.

CHAPTER 5

MODELING AND SIMULATION

This chapter will document modeling approaches used for both the cost model and intermediate stop models in this research. Although this chapter comes in advance of the following results chapters, some of the results presented here were dependent on that work being done later. It is presented here to allow the future results chapters to remain more focused on the mission specification analysis.

5.1 Cost Modeling

This section documents the logic and assumptions used in the fleet cost analysis.

5.1.1 Operating Cost Model

So although AEDT and APMT-E meet the fidelity requirements desired from a modeling and simulation standpoint, the lengthy analysis time is a limiting factor to conducting any significantly large trade study in a timely fashion. This led to the original development of GREAT for fuel burn and NO_x analysis and ANGIM for airport noise assessment to allow for much more rapid analysis at the fleet level. Neither tool computes fleet operating cost and this capability needs to be developed to capture the impact that mission specification changes will have on the relevant cost metrics – operating cost and capital cost. An initial capability exists through a post-processing of GREAT results but this requires simplifying assumptions.

The operating cost model consists of six elements: fuel cost, crew cost, maintenance cost, route fees, landing fees, and capital cost. The first five are calculated for both existing aircraft as well as the future replacement aircraft. Capital cost is only calculated for the replacement aircraft and the rationale is provided in the associated section.

Fuel cost calculations are actually straight forward as one multiplies the fuel burn by the fuel price but to maintain consistency with the other elements, their calculation is conducted the same way.

On an annual basis, the fuel burn, NO_x, and block time for each route is calculated using the input aircraft performance data. Equation 2 represents the necessary computation to determine annual fuel cost. Every year is a double summation of all the routes and each individual aircraft's performance. The total fuel cost for a given route/aircraft combination is the total number of flights on that route for the aircraft multiplied by the aircraft's fuel burn on the route multiplied by the fuel price.

$$
\begin{aligned}
&Fuel\ Cost_{year\ y} \\
&\quad = \sum_{i=\ route_i}^{n=all\ routes} \sum_{j=aircraft}^{m=all\ aircraft} \#Flights_{yij} * FuelBurn_{ij} \\
&\quad * FuelPrice_y * Conversion
\end{aligned}
\tag{2}
$$

GREAT measures fuel burn in kilograms and fuel price is input in $/gallon such that a conversion factor is required. The value used in this research is 0.328 as the conversion factor for kilograms to pounds is 1:2.2 and fuel is 6.7 pounds per gallon. For implementation in other models, the conversion factor should be modified as appropriate based on the units used in the tool. Also worth noting is that fuel price is input on an annual basis such that changes to fuel price can be made to capture the introduction of new fuel taxes, price fluctuations due to scarcity, or a notional fuel price forecast. For the purposes of this research, fuel price was fixed at $3/gallon.

Crew and maintenance costs are a function of block time, which is calculated for each flight per aircraft, via hourly rates. Block time is calculated in a similar fashion to fuel burn or NO_x in GREAT through second order equation as a function of flown distance.

Hourly rates for crew and maintenance costs are user input as a function of seat class. Both costs also are input on an annual and seat class basis to allow for increases in costs over some of all seat classes.

Both crew and maintenance costs are calculated in a similar fashion to fuel cost, a summation of performance over all the routes for all aircraft. For a given route, aircraft, and year combination, the total number of flights is multiplied by the block time of the flight and the associated hourly rate for the aircraft. Hourly rates vary with seat class, which requires knowledge of the seat class for the aircraft. Maintenance cost can also be dependent on production status of an aircraft with the implication that out of production aircraft will require greater maintenance rates than in production aircraft. Equations for both crew and maintenance cost are provided in Equation 3 and Equation 4.

$$Crew\ Cost_{year\ y} = \sum_{i=\ route_i}^{n=all\ routes} \sum_{j=aircraft}^{m=all\ aircraft} \#Flights_{yij} * BlockTime_{ij} * CrewRate_{y,SeatClass_j} \tag{3}$$

$$Maintenance\ Cost_{year\ y} = \sum_{i=\ route_i}^{n=all\ routes} \sum_{j=aircraft}^{m=all\ aircraft} \#Flights_{yij} * BlockTime_{ij} * MaintenanceRate_{y,ProductionStatus_j,SeatClass_j} \tag{4}$$

Route fees represent the costs associated with air traffic management and are dependent on what regions the aircraft is flying over. The forecast utilized for this study has 23 different regions and these are defined in Table 18. Note that while regions may sound similar between groups 11-16 and 18-23, the difference is that intra-region contains flights like United States to Mexico or Canada to Mexico while domestic region refers to flights within Mexico or Canada exclusively.

Table 18. Route Group Definitions

Route Group	Definition	Route Group	Definition
1	North Atlantic	13	Intra Europe
2	South Atlantic	14	Intra Latin America
3	Mid Atlantic	15	Intra Middle East
4	Transpacific	16	Intra North America
5	Europe - Asia / Pacific	17	Other International Routes
6	Europe - Africa	18	Domestic Africa
7	Europe - Middle East	19	Domestic Asia / Pacific
8	North America - South America	20	Domestic Europe
9	North America - Central America / Caribbean	21	Domestic Latin America
10	Middle East - Asia/Pacific	22	Domestic Middle East
11	Intra Africa	23	Domestic North America
12	Intra Asia / Pacific		

Route fee implementation is similar to the others where the routes and aircraft are iterated through on an annual basis. In this case, the number of flights is multiplied by the flight distance, the route fee, a conversation from nautical miles to kilometers, and a fee growth rate. The need for a conversion factor is due to the fact that flight distances are measured in nautical miles and the route fees are input as $/km. This results in a factor value of 0.539957.

The route fees vary over seat class such that larger aircraft pay larger route fees. The growth rate allows for freedom to annually vary all route fees. Additional modifications could be made such that each route group could be varied individually in the event that particular routes become crowded due to increased growth and costs rise to address the issue.

The equation for calculating route fees is provided in Equation 5.

$$Route\ Fees_{year\ y} = \sum_{i=\ route_i}^{n=all\ routes} \sum_{j=aircraft}^{m=all\ aircraft} \#Flights_{yij} * FlownDistance_i * RouteFee_{i,SeatClass_j} * Conversion * FeeGrowthRate_y \tag{5}$$

Landing fees are the cost associated with using the arrival airport. Countries are separated into seven regions, as defined in Table 19, and the respective airports are assigned to their regions.

Table 19. Landing Region Definitions

Landing Region	Definition
1	Africa
2	Asia/Pacific
3	Europe
4	Central America / Caribbean
5	Middle East
6	North America
7	South America

For all routes and aircraft per year, the number of flights is multiplied by the landing fee for the arrival airport determined by aircraft seat class and the fee growth rate. This fee growth rate is separate from that of the route fees to allow for different levels of variation between the two fees. It currently impacts all landing fees equally but it could also be expanded on to allow for variation between each of the landing regions. The equation for landing fees is below in Equation 6.

$$Landing\ Fees_{year\ y} = \sum_{i=route_i}^{n=all\ routes} \sum_{j=aircraft}^{m=all\ aircraft} \#Flights_{yij} * LandingFee_{y,ArrivalAirport_i SeatClass_j} * FeeGrowthRate_y \tag{6}$$

Landing fees are defined as a fixed dollar fee as a function of airport and seat classes.

Capital cost represents the annual cost of owning all the aircraft in the fleet. If the fleet level analysis tracks the total number of aircraft for each year, calculating this component would be simple as one just multiplies this number by capital costs of the individual aircraft. In the event that total aircraft numbers are not tracked, a scheme will be required to determine the fleet size from other means. As an example, GREAT does not technically track the number of aircraft in the fleet – just the number of operations.

The next logical means to calculating fleet size involves looking at total flight time. Using the same block time information from the crew and maintenance cost section, one can determine the total flight hours of a given aircraft on an annual basis. Provided assumptions regarding annual aircraft utilization, getting the total number of aircraft is feasible.

To calculate the total number of aircraft required, the annual block time per seat class is divided by the utilization and multiplied by a conversion factor to correct the annual utilization to be in line with the size of the initial operating set – in this case, it is six weeks so the factor is 8.69 (52.14 weeks in a year/ 6 week operations set size). This is demonstrated by Equation 7.

$$AircraftNumber_{seatclass} = \sum_{j=aircraft}^{m=replacements} \frac{AnnualBlockTime_j}{Utilization_j} * Conversion \tag{7}$$

For this research and modeling effort, the capital cost of the existing aircraft was neglected. The rationale is that any changes to the fleet composition through something like accelerated retirement would manifest as increased capital costs from replacement aircraft. Additionally, for a fixed set of retirement assumptions, one can consider the capital costs of the existing aircraft to be constant and therefore not critical for this research.

Once the number of aircraft is determined, the next step is to calculate the equivalent annual cost (EAC). This represents the annual component of an aircraft's capital cost that is paid and determined from aircraft price and a couple other assumptions. This process is as follows[103][104]:

1. Calculate the present value of the scrapped item PV_{scrap} using the scrap value SV, depreciation rate d, and number of years of useful life n. Scrap value can be any percent of the initial price but the general assumption is 10% of the price.
2. Calculate the present value of annuity due $ä_{ni}$ using the finance rate i, the depreciation rate d, and the number of years of useful life n. Assumptions for this

work was a finance rate of 5%, a depreciation rate of 3%, and a useful life of 25 years.

3. Finally calculate the equivalent annual cost using the purchase price PC, the present value of the scrapped item, and the present value of annuity due.

The necessary equations are summarized in Equation 8 through Equation 10.

$$PV_{scrap} = SV * \frac{1}{(1+d)^n} \tag{8}$$

$$\ddot{a}_{ni} = \frac{1-(1+i)^{-n}}{d} \tag{9}$$

$$EAC = \frac{(PC - PV_{scrap})}{\ddot{a}_{ni}} \tag{10}$$

To calculate aircraft price, a variety of means can be used. Aircraft costing tools can be used to calculate the vehicle acquisition cost. This requires a variety of cost input data for the aircraft such as component weights, labor and material rates, and complexity factors to determine what an aircraft's price should be. Many of these numbers can be somewhat difficult to ascertain as cost is something that many companies hold close to their chest; however, one could calibrate costs somewhat using information from different publicly available sources. This also would be sufficient for this problem if the work was limited to only to baseline technology levels. For the future technology levels, these values are generally unknown which could lead to problems with confidence in the future technology price estimates.

Historical data was used to calculate price as a function of maximum takeoff weight. The data used to develop this model is provided in Table 20 and the corresponding price model is in Equation 11. For future technology, the aircraft price reduces since technology infusion results in a reduction in aircraft weight.

Table 20. Aircraft Price Data

Aircraft	MTOW (lbs)	Price	Source
Embraer 190	114,200	$ 31,540,792	[105]
Boeing 737-700/700LR	133,000	$ 74,909,381	[106]
Airbus Industrie A319	141,096	$ 82,400,319	[107]
Boeing 737-800	155,500	$ 89,201,302	[106]
Airbus Industrie A320-100/200	162,040	$ 90,186,952	[107]
Boeing 737-900	174,200	$ 89,600,000	[106]
Airbus Industrie A321	182,984	$ 105,760,218	[107]
Boeing 767-200/ER/EM	345,000	$ 157,901,090	[108]
Boeing 767-300/300ER	380,000	$ 183,133,723	[106]
Boeing 767-400/ER	400,000	$ 166,751,945	[109]
B787-800 Dreamliner	476,000	$ 208,760,617	[106]
Airbus A330-300	507,064	$ 235,964,550	[107]
Airbus Industrie A330-200	507,064	$ 212,998,911	[107]
Boeing 777-200ER/200LR/233LR	580,000	$ 257,747,409	[106]
Boeing 747-400	800,000	$ 244,270,927	[109]
B747-800	975,000	$ 351,400,000	[106]

$$
\begin{aligned}
&Baseline\ Technology\ Price \\
&\quad = 7870984.5 + 506.5455 * \mathrm{MTOW} - 0.000184104 \\
&\quad * MTOW^2
\end{aligned}
\tag{11}
$$

To rectify this shortcoming, a different approach was taken to model the impact of technology on aircraft price. The process is to take operations data, compare the fuel burn savings between the two technology levels for a comparable aircraft, extrapolate savings out to the aircraft's useful life to determine lifetime fuel savings, calculate the total fuel cost savings from that value, and finally apply a percentage of the fuel savings as a price premium. This process is illustrated in Figure 46.

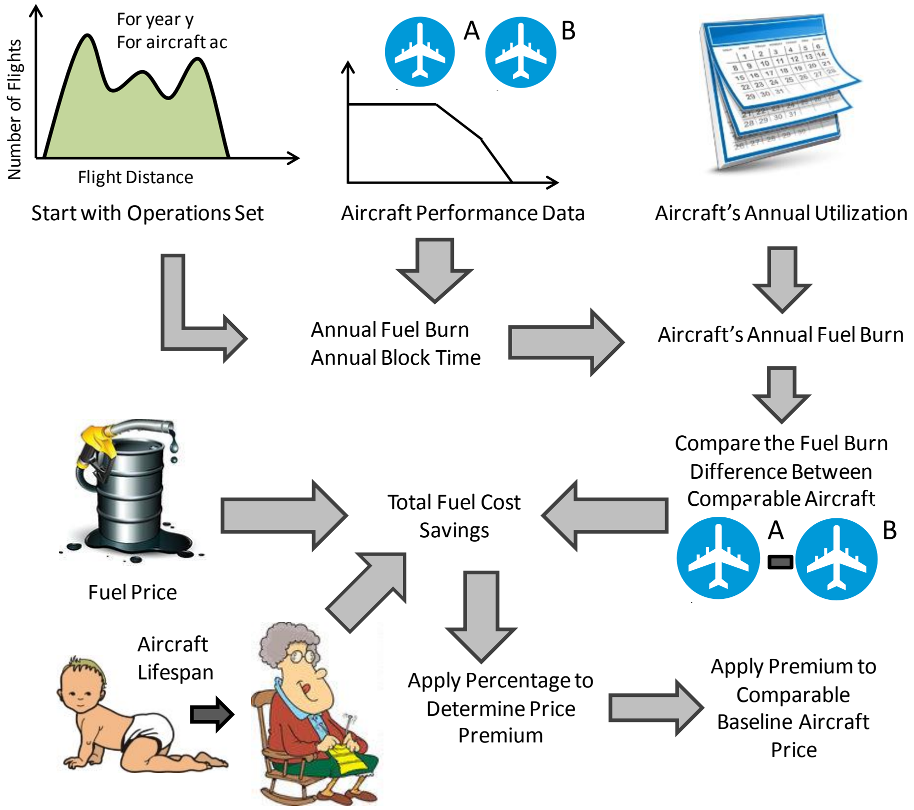


Figure 46. Future Aircraft Price Calculation Approach

BTS data from 2013 was used to get operational information including range and traffic information for all five represented aircraft models.[38] There is a significant amount of information in this data set but the only information that is of particular interest is the flight distance and number of operations. As an example, a small subset of the operations is included in Table 21 and will be used in a demonstration of this approach. The BTS is not as easily grouped as compared to Table 21 as it is predominantly separated by air carrier, payload information, etc.

Table 21. Example Future Technology Price Operations

Flight Distance (nm)	Operations
1947	2892
3953	731
5066	26
4735	449

Given this operational data, the next step is to use aircraft performance information to determine the fuel burn and flight time for each of these flights. One approach could be to run an aircraft performance code to model the performance of the individual flights. Given that surrogates of fuel burn and block time were generated for each aircraft to be used in GREAT, they were additionally used to calculate aircraft performance for this purpose. A comparison of the fuel burn of the two aircraft is in Figure 47 while the flight time is provided in Figure 48. The changes in flight time are not significant enough to be distinguishable such that only the baseline has been provided.

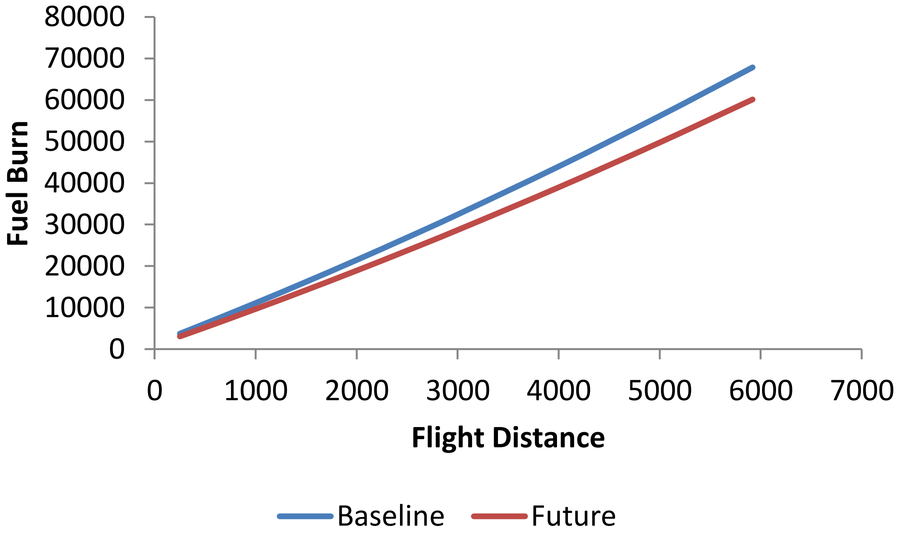


Figure 47. Comparison of the Fuel Burn for Example Aircraft

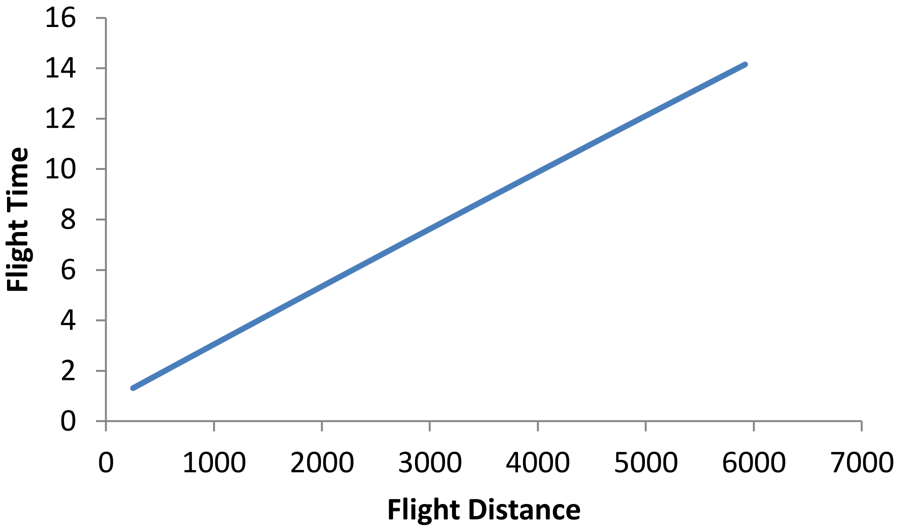


Figure 48. Block Time for Example Aircraft

Using this aircraft performance information, the aircraft level and route total fuel burn block time are calculated and shown in Table 22. Aircraft fuel burn and block time are representative of the performance for a particular route and then the total fuel burn and block time values are for all the operations. Bottom row of Table 22 contains the grand totals for each aircraft for both metrics.

Table 22. Example Future Technology Price Results

Flight Distance	Ops	Baseline				Future			
		Aircraft FB	Aircraft BT	Total FB	Total BT	Aircraft FB	Aircraft BT	Total FB	Total BT
1947	2892	20,910	5.22	6.05E+7	15,107	18,426	5.21	5.33E+7	15,070
3953	731	43,420	9.77	3.17E+7	7,143	38,469	9.75	2.81E+7	7,130
5066	26	56,947	12.26	1.48E+6	318	50,475	12.24	1.31E+6	318
4735	449	52,847	11.52	2.37E+7	5,173	46,838	11.50	2.10E+7	5,164
Grand Total:				1.17E+8	27,743			1.04E+8	27,682

Using the associated utilization assumptions, one can determine the contribution of one aircraft to the total flight time – at this speed, a single aircraft corresponds to 14.8% of the total time. This percentage is then applied to the total fuel burn to calculate an individual aircraft's fuel burn on an annual basis. This is 1.74E+7 kg for the baseline technology M0.76 small twin and 1.54E+7 kg for the future technology vehicle, yielding a difference of 1.99E+6 kg. To calculate the lifespan fuel cost savings of the vehicle, multiply the annual fuel burn by the lifespan and the fuel price. For a fuel price of $3/gal and lifespan of 20 years, the annual fuel savings are $39.1 million.

The additional premium is calculated by applying a fraction of the fuel savings. It was assumed for this work that the value would be half the fuel savings such that the premium for this example is $19.6 million. The baseline M0.76 small twin aisle's price was $180.5 million such that the future aircraft would cost the airlines $200.1 million. Aircraft prices for all aircraft are provided in their respective chapters.

5.2 Intermediate Stops

Given that reduced range aircraft will have a lesser capability, operations will need to be modified to accommodate them to enable their usage on long range flights. In this case, long range flights will have to introduce an intermediate stop to increase adoption of a short range variant. This requires an approach to determine whether a particular route will benefit from an intermediate stop based on airport locations and aircraft performance to ultimately select the final route.

The method used to generate routes utilizing intermediate stops is provided in Figure 49. Generation of intermediate stops requires multiple inputs: a list of airport latitude/longitude locations and corresponding runway length/width data, the origin-destination pairs that are to be considered for intermediate stops, and aircraft performance data for fuel burn and block time to conduct evaluation of prospective routes from an environmental and cost perspective. The corresponding code used for this research is provided in Appendix A. A brief summary of the logic used is provided in this chapter and then trends and observations from the analysis are provided.

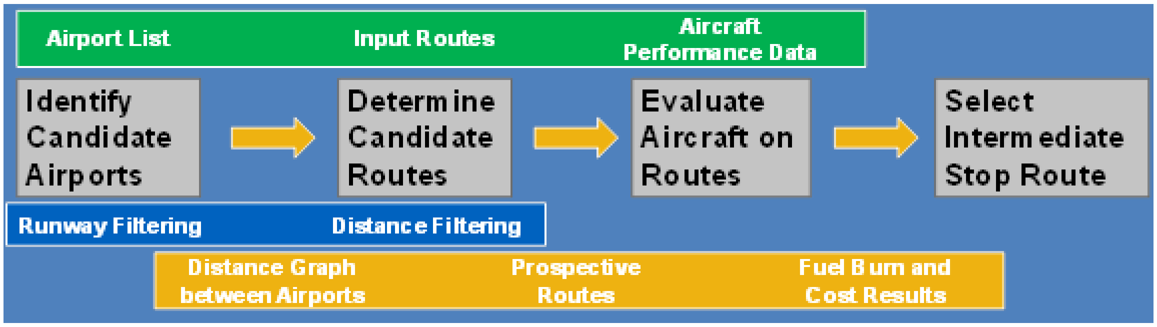


Figure 49. Intermediate Stop Modeling Approach

5.2.1 <u>Intermediate Stop Logic</u>

5.2.1.1 Airports

At the aircraft modeling level, the general assumptions are that the intermediate stop airport lies directly along the original route and at the midpoint of the mission or even thirds in the event that one uses two stops. At the fleet level, intermediate stops cannot just occur at a select point in a long range mission as there may not be an airport available in that location. This requires consideration of airport location with respect to a given route as the driving factor in intermediate stop viability. Additionally, not all airports are capable of operating all types of aircraft – smaller regional airports are primarily used for general aviation aircraft, regional jets, and possibly single aisle aircraft and would be unable to handle larger aircraft traffic. This must be considered when selecting an intermediate stop location as this could be the difference between trying to land a 747 at the original Wichita destination of McConnell Air Force Base vs the much smaller Col. James Jabara Airport and facing significant difficulty departing again.[110]

Therefore, the first step is starting with an initial list of airports that contains latitude/longitude data along with runway length and width information. This information can come from a variety of sources: FAA airport diagrams[111], AirNav[112], or other compiled databases. The data source used for this work was from a database of all ICAO coded airports.

The runway information will be the primary filter to reduce an initial list down to only those relevant airports as this is a fair measure of airport capability. To filter by runway width, the Manual Aerodrome Standards from ICAO should be used to give guidance and relevant data is provided in Table 23[113]. The definitions of code numbers and code letters in Table 23 are provided in Table 24. Both are defined in meters with conversions in feet provided in parentheses. The aircraft being considered for intermediate stop adoption all have takeoff field lengths greater than the 1,800 meters such that code number 4 values will be used. The wing spans for the small twin, large twin, and large quad are 154.8 feet, 199.1 feet, and 208.1 feet respectively such that code D, E, and E will be used. This width requirement will significantly reduce the airport set to a more manageable list.

Table 23. Airport Runway Width Requirements [113]

Code Number	A	B	C	D	E	F
1	18 (60)	18 (60)	23 (75)			
2	23 (75)	23 (75)	30 (98)			
3	30 (98)	30 (98)	30 (98)	45 (147)		
4			45 (147)	45 (147)	45 (147)	60 (197)

Table 24. Translation for the Above Codes [113]

Code element 1			Code element 2		
Code number	Reference field length		Code letter	Wing Span	
1	< 800	(2,625)	A	< 15	(49)
2	800 – 1,200	(2,625 – 3,937)	B	15 – 24	(49 – 79)
3	1,200 – 1,800	(3,937 – 5,905)	C	24 – 36	(79 – 118)
4	> 1,800	(5,905)	D	36 – 52	(118 – 170)
			E	52 – 65	(171 – 213)
			F	> 65	(213)

Runway length is the other filter that is required as it ensures that there is sufficient runway for takeoff. One of the challenges in using runway length is that required runway length is a function of takeoff weight and reduced range aircraft being lighter would in theory have access to a much larger number of airports than their longer range counterparts. However these new airports may also lack sufficient gate infrastructure to handle these new aircraft as accommodating these larger aircraft may have never been in the original plans of the airport owners. To simplify this effort, a comparison of aircraft runway performance within each seat class was used against data available from airport planning documents for the maximum takeoff weight of the aircraft. The datum operations set was also used as a source for runway lower bound limits based on departure airport and similar aircraft information. The final lower bound values for field length used in this work were 7,500 ft for the small twin, 8,500 ft for the large twin, and 10,000 ft for the large quad.

As a part of the airports function, the great circle distance between airports is calculated using the latitude/longitude coordinates. Many functions for this calculation have been developed by others using the Vincenty formula and one by Steve Ratts will be used here.[114] The Vincenty formula is provided as Equation 12 where $\varphi_1\lambda_1$ and $\varphi_2\lambda_2$ represent the longitude and latitude of two points and their central angle is represented by $\Delta\sigma$. To get the great circle distance, $\Delta\sigma$ is multiplied by the Earth's radius.

$$\Delta\sigma = \arctan\left(\frac{\sqrt{(\cos\varphi_2 \sin\Delta\lambda)^2 + (\cos\varphi_1 \sin\varphi_2 - \sin\varphi_1 \cos\varphi_2 \cos\Delta\lambda)^2}}{\sin\varphi_1 \sin\varphi_2 + \cos\varphi_1 \cos\varphi_2 \cos\Delta\lambda}\right) \qquad (12)$$

5.2.1.2 Prospective Routes

Once the candidate airport list has been created, the next step is to determine what the prospective routes would be. This requires origin-destination information from the initial operations set. The routes considered for analysis are input and then all potential route options are analyzed.

Each input airport is modeled as a prospective intermediate stop for each origin-destination pair using the great circle distance data created in the airport step. This would yield a significantly large number of candidate routes in the aircraft evaluation step. However for a large number of airports, many options that would be undesirable due to significant increases in extra flown distance. Additional filtering was added to eliminate the clearly unsuitable routes from future steps.

The primary filter is with regards to the baseline flight distance and the new intermediate stop mission. A ratio is applied to the baseline flight and the new mission total distance is evaluated to check if it is below that value. The default value of the ratio is 1.2, allowing for up to a 20% additional flight distance; although, Langhans' analysis suggests that ratio values exceeding 1.1 will provide fuel burn penalties.[49][50]

The final two filters were determined to be necessary during testing of the algorithms. One filter checks to see if any segment is longer than the initial flight distance and rejects them in the event they are. This can happen where other major cities are close enough to either the origin or destination airport that prospective flights could involve flying past the destination airport or away from the destination to stop and then coming back to the destination. This makes no sense operationally so this filter exists to remove this behavior. An example of this behavior is the blue line in Figure 50 where the flight from Los Angeles stops in Boston and then returns to New York City.

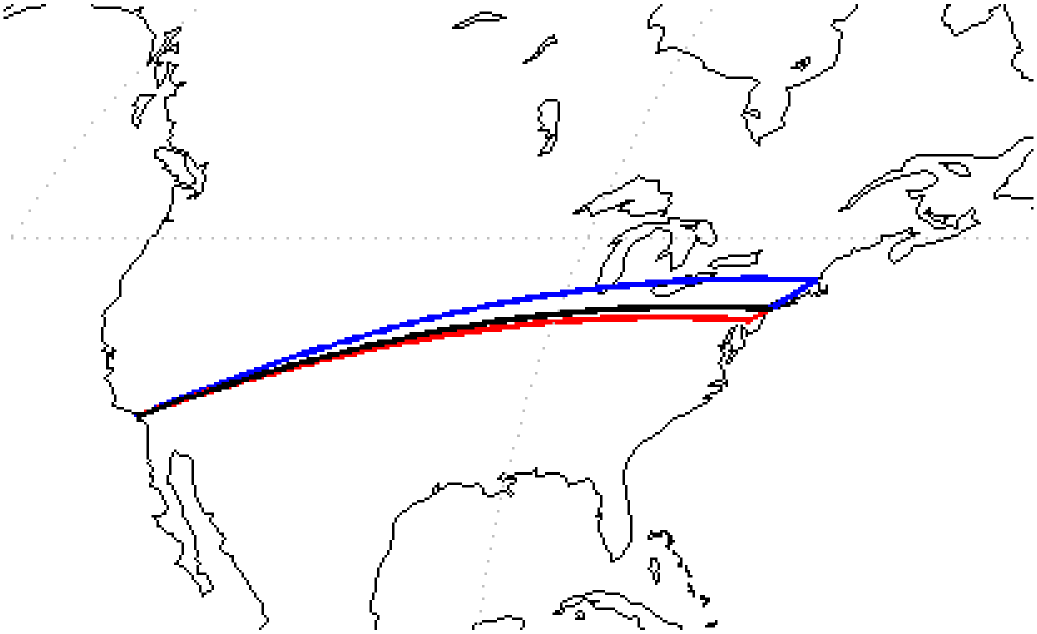


Figure 50. Example of Secondary Range Constraints

The other filter checks to see that the intermediate stop is not too close to either the origin or destination airport. In cities with multiple airports, one route could be to land at another airport in the city and then go to the destination. This also makes no sense operationally so the filter prevents these routes from being evaluated. Implementation is a fraction of the baseline mission flown distance and defaulted at 10% distance. The red line in Figure 50 shows this behavior where the Los Angeles flight to New York City stops in Philadelphia.

The original plan was to model two stops as well as a single stop; however, the vehicle level indicated that both the small twin and large quad aircraft burn more fuel over the one stop strategy on long range flights. The large twin vehicle does show savings from making the transition but they are small over one stop such that the cost of landing would not be made up in fuel savings. Therefore, the code developed here does not account for them. The previously described constraints would remain necessary but require modification based on utilization of a two stop strategy.

5.2.1.3 Route Evaluation

The final step is to evaluate the routes in comparison to the non-stop flight. Aircraft performance information is required for fuel burn and block time if operating cost is of concern. Both are input as 2nd order quadratic functions with flight distance being the only input. Fuel burn analysis is straightforward and the cost evaluations are identical to that described in the previous section.

Once all the candidate routes have been run for all aircraft, the final step is to select the best route. This can be done through fuel burn minimization or operating cost minimization. The introduction of reduced range vehicles will require additional filtering as some prospective routes may not be feasible for a new aircraft with reduced range. This data can be extracted and then processed by the user to select the new route.

5.2.2 Example Problems

To aid in understanding of how the algorithm works, a small example problem has been conducted. For this problem, 50 airports were selected to be considered for intermediate stops on 3 routes for 1 aircraft. The airports used are shown on the map as black dots in Figure 51. Note that a number of these airports are infeasible and this was done intentionally to demonstrate their rejection. The three routes all originate at Los Angeles International and head to Charles de Gaulle in Paris, John F Kennedy in New York City, and Melbourne Airport. These airports are indicated by a blue dot for Los Angeles and red dots for the three destination airports. The aircraft used is a second generation 747. The associated input files for the airports, routes, and aircraft are provided in Appendix A.

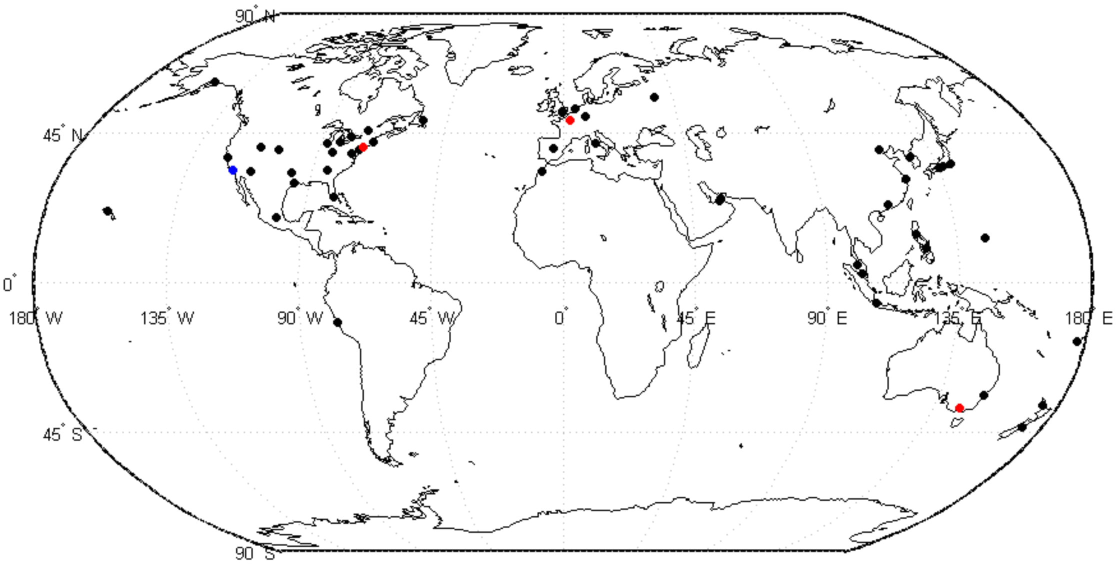


Figure 51. Example Problem Airport Locations

Table 25. Example Problem Airports

City	Country	City	Country
Melbourne	Australia	Moscow	Russia
Sydney	Australia	Seoul	South Korea
Gander	Canada	Madrid	Spain
Montreal	Canada	Abu Dhabi	United Arab Emirates
Toronto	Canada	Dubai	United Arab Emirates
Beijing	China	London Gatwick	United Kingdom
Guangzhou	China	London Heathrow	United Kingdom
Shanghai	China	Anchorage	United States
Nadi	Fiji	Atlanta	United States
Paris	France	Boston	United States
Frankfurt	Germany	Chicago	United States
Guam	Guam	Cincinnati	United States
Jakarta	Indonesia	Dallas	United States
Rome	Italy	Denver	United States
Nagoya	Japan	Detroit	United States
Osaka	Japan	Honolulu	United States
Tokyo	Japan	Houston	United States
Georgetown	Malaysia	Los Angeles	United States
Kuala Lumpur	Malaysia	Miami	United States
Mexico City	Mexico	New York City	United States
Casablanca	Morocco	Newark	United States
Amsterdam	Netherlands	Philadelphia	United States
Auckland	New Zealand	Phoenix	United States
Christchurch	New Zealand	Salt Lake City	United States
Lima	Peru	San Francisco	United States
Mandaue City	Philippines	Washington DC	United States
Manila	Philippines		

5.2.2.1 Paris

The prospective routes are identified on the map in Figure 52 with the baseline path in blue, the minimum fuel and cost route in red, and the other candidate routes are in black. A summary of flight distance, fuel burn, and cost for each route is provided in Table 26 for each of the intermediate airports. There are five routes that provide fuel savings over the direct flight – these are stops in Gander, Montreal, Toronto, Chicago, and Detroit; however, only Gander actually provides cost savings. Given that the fuel savings are not that large (2.1% maximum savings), the cost of the additional stop ends up negating the fuel cost savings for those other four.

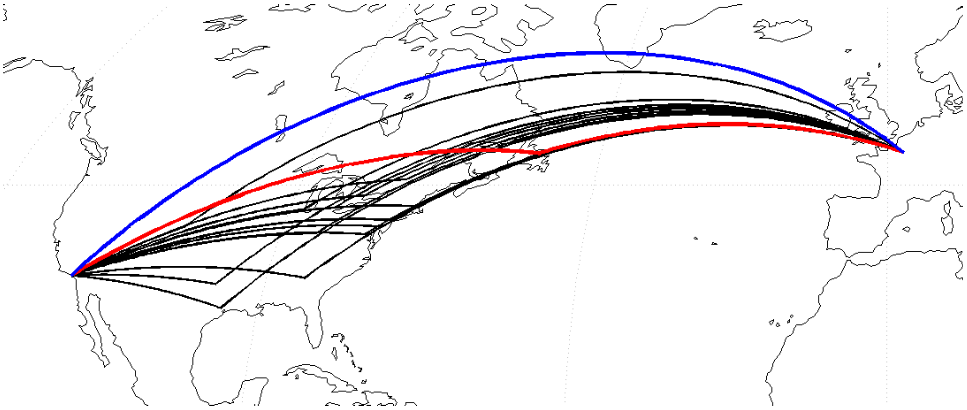


Figure 52. Los Angeles to Paris Routes

Table 26. Los Angeles to Paris Results

Stop Location	Total Distance (nm)	% Change Distance	Distance Split	% Change Fuel Burn	% Change Operating Cost
Gander	5114.3	104.1%	57-43	97.9%	99.8%
Montreal	5119.2	104.2%	42-58	98.1%	100.1%
Toronto	5137.1	104.5%	37-63	99.0%	100.9%
Chicago	5111.3	104.0%	30-70	99.6%	101.4%
Detroit	5149.6	104.8%	33-67	99.7%	101.6%
Baseline	4915.0	100.0%	-	100.0%	100.0%
Boston	5252.4	106.9%	43-57	100.6%	102.5%
Denver	4977.4	101.3%	15-85	100.6%	102.0%
Salt Lake City	4915.0	100.0%	10-90	100.8%	102.0%
Newark	5290.3	107.6%	40-60	101.6%	103.5%
New York City	5295.8	107.7%	40-60	101.7%	103.6%
Cincinnati	5248.7	106.8%	32-68	102.1%	103.8%
Philadelphia	5313.4	108.1%	40-60	102.2%	104.0%
Washington DC	5330.1	108.4%	37-63	102.8%	104.6%
Dallas	5360.3	109.1%	20-80	107.3%	108.6%
Atlanta	5497.6	111.9%	30-70	107.3%	108.9%
Houston	5554.2	113.0%	22-78	111.0%	112.2%

The routes that did not provide savings do so for a variety of reasons. Some routes result in significant excess flight distance that results in greater fuel consumption than the direct route. Examples include Newark, New York City, and Boston. Other routes result in similar flown distance but end up with an intermediate stop further from the ideal midpoint location. Airports like Denver and Salt Lake City are closer to 10-15% into the flight.

5.2.2.2 Melbourne

Los Angeles to Paris offers a significant number of intermediate airports from which to choose. Flying to Melbourne provides a challenge as much of what lies below the aircraft is the Pacific Ocean. This provides only a handful of alternative routes for consideration. Two of these routes provide significant fuel savings compared to the direct flight – Fiji and Honolulu. A third route is Auckland, New Zealand provides a much smaller savings. These routes are shown in Figure 53 with relevant data in Table 27.

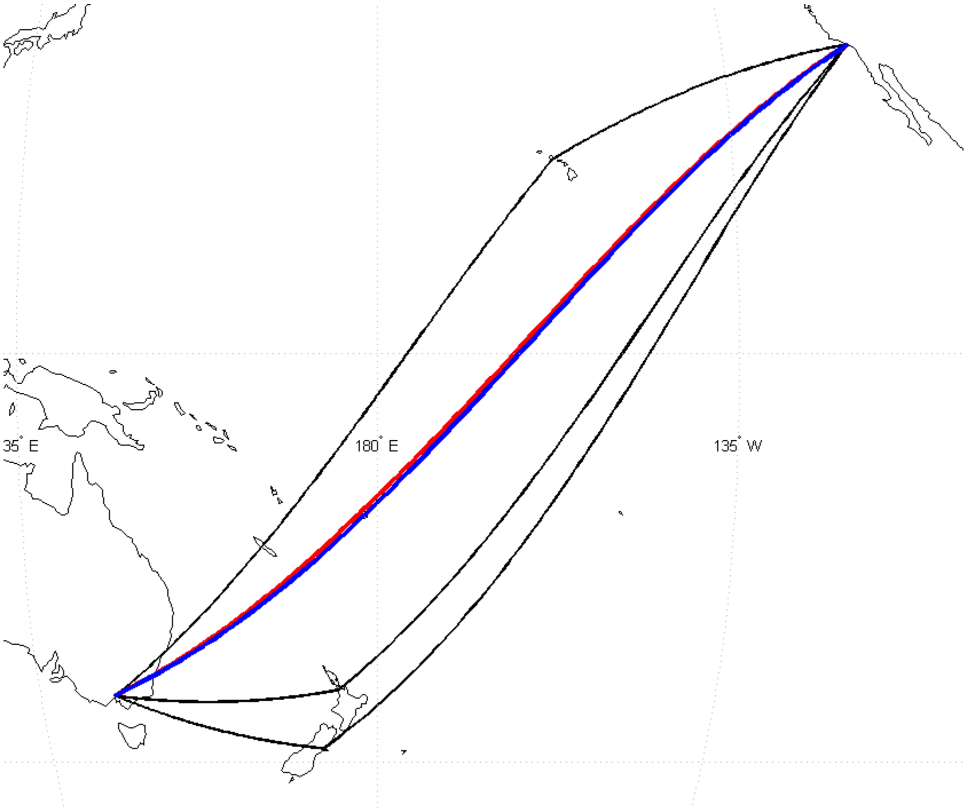


Figure 53. Los Angeles to Melbourne Flights

Table 27. Los Angeles to Melbourne Results

Stop Location	Total Distance (nm)	% Change Distance	Distance Split	% Change Fuel Burn	% Change Operating Cost
Fiji	6889.0	100.0%	70-30	91.0%	93.5%
Honolulu	7010.2	101.8%	32-68	92.5%	94.7%
Auckland	7086.3	102.9%	80-20	97.0%	99.0%
Baseline	6888.7	100.0%	-	100.0%	100.0%
Christchurch	7291.6	105.8%	82-18	101.2%	102.9%

Although the number of routes is somewhat limited, there are significant savings available through introduction of an intermediate stop. One observation though is that these locations will provide significant challenges, particularly with regards to providing sufficient fuel to these island locations. Another would be prospective capacity concerns as land usage is at a premium for these locations. So although fuel savings are available, other limitations may prevent them from being available or fully realized.

5.2.2.3 New York City

Unlike the other two routes, New York City is vastly shorter. This results in the direct flight being the best route for fuel and cost. Short range flights do not benefit from intermediate stops. A map with the prospective routes is provided in Figure 54 and results are provided in Table 28.

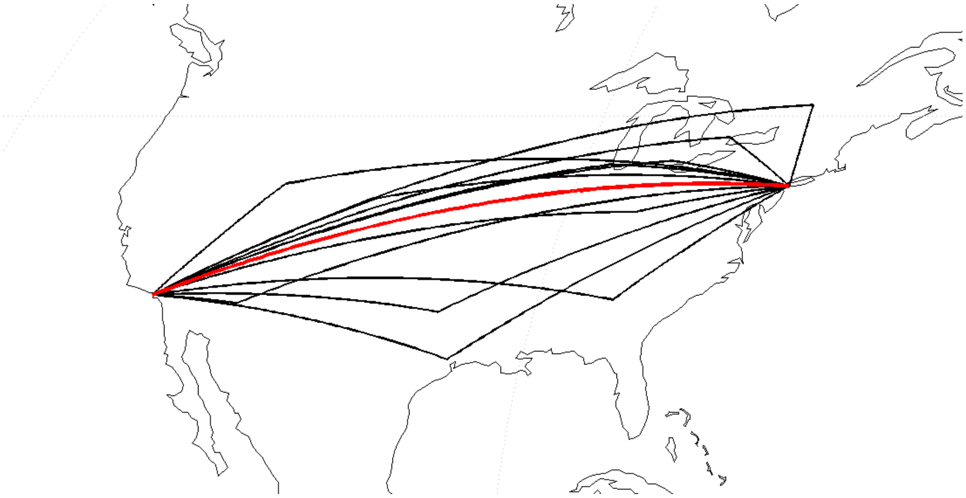


Figure 54. Los Angeles to New York Flights

Table 28. Los Angeles to New York Results

Stop Location	Total Distance (nm)	% Change Distance	Distance Split	% Change Fuel Burn	% Change Operating Cost
Baseline	2145.9	100.0%	-	100.0%	100.0%
Denver	2157.1	100.5%	35-65	108.0%	110.0%
Chicago	2154.4	100.4%	70-30	108.2%	110.2%
Cincinnati	2158.0	100.6%	76-24	109.0%	110.8%
Detroit	2157.0	100.5%	80-20	109.3%	111.1%
Phoenix	2188.2	102.0%	15-85	111.4%	113.1%
Toronto	2204.4	102.7%	86-14	112.2%	113.8%
Salt Lake City	2237.0	104.2%	23-77	112.4%	114.2%
Dallas	2277.6	106.1%	47-53	112.4%	114.5%
Atlanta	2347.7	109.4%	72-28	116.5%	118.3%
Houston	2426.0	113.1%	50-50	118.6%	120.5%
Montreal	2436.1	113.5%	88-12	122.8%	124.0%

One of the consequences of intermediate stops is that more of the flight is spent climbing and descending so for short range flights, this becomes a much greater portion of the total flight distance, penalizing fuel burn. Additional landing costs from adding the stop further penalizes the advantage that intermediate stops might have.

These three routes are here to simply serve as examples of how the intermediate stop modeling algorithms work. An analysis of global traffic will follow based on the initial operations set.

CHAPTER 6

SPEED REDUCTION SAMPLE PROBLEM

This chapter focuses on the impact of speed reduction and is broken into three parts: vehicle impact, fleet impact, and experimental results. The primary objective of the vehicle impact section is to determine whether speed reduction is beneficial to the individual aircraft and if so, how much. The fleet impact section focuses on those aircraft that benefit and measure the impacts to the figures of merit. Also within the fleet impact section in this chapter is the fleet results with no specification changes to provide a reference for the fleet analysis. Finally, the experimental results are discussed using the information gained from the fleet impact analysis.

6.1 Vehicle Design

The first step is to evaluate the respective mission specification change at the vehicle level. Details about how these aircraft were designed are available in Chapter 4.

6.1.1 Bounds of Mission Specification Changes

Speed reduction was conducted in steps of M0.02 from the baseline cruise Mach number, redesigning the aircraft for each speed, until a resulting vehicle design increased in fuel consumption from the previous design. This rise in fuel burn indicates that the minimum fuel burn has been reached and any further reduction in cruise speed will only yield designs with increasing fuel burn for the respective vehicle. Baseline Mach numbers are provided in Table 29 for all five reference vehicles.

Table 29. Speed Reduction Ranges

Seat Class	Minimum Mach Number	Baseline Mach Number
Regional Jet	0.66	0.80
Single Aisle	0.68	0.78
Small Twin Aisle	0.68	0.80
Large Twin Aisle	0.70	0.84
Large Quad	0.73	0.85

Cruise speed reduction also has an impact on engine performance. As the initial engine has been designed to operate at the baseline Mach number, all the reduced speed engines need to be redesigned for optimal performance. This entails increasing the overall pressure ratio of the engines slightly. On the regional jet, this involves changes to the fan and high pressure compressor pressure ratios. The other four vehicles vary only the pressure ratios of the fan and low pressure compressor.

In changing the engine pressure ratios, a couple of engine performance constraints have also been added to maintain technical viability. These constraints include engine temperature limits at the high pressure compressor exit for the engine aerodynamic design point and the engine takeoff at hot day, the combustor exit temperature at aerodynamic design point, and the engine bypass ratio. These limit values change with technology level. For the temperature limits these constraints were not to be exceeded while the bypass ratio was a target objective with small bounds of acceptable deviation, ±0.05.

A comparison of changes to the engine overall pressure ratios (OPR) is available in Figure 55. These results are for the baseline technology aircraft for all five vehicles and all engine OPRs are normalized with respect to the initial engine models. As cruise speed is reduced, the OPRs all increase and this trend is the same for future technology introduction. In some cases, the top of climb thrust had to be varied to maintain climb performance or stay within temperature limits. For the most part, the trends are linear with respect to reduced cruise speed in higher pressure ratios. However, points like M0.66 for the regional jet are an outlier. This is due to variation in lapse rate of the engine to maintain temperature limits.

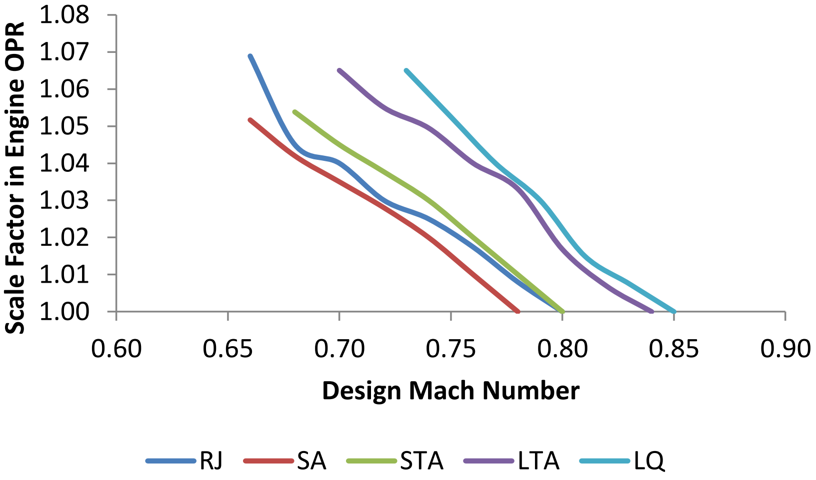


Figure 55. Impact of Speed Reduction on Engine Overall Pressure Ratio

6.1.2 Vehicle Design Results

All aircraft have been evaluated with fuel burn performance against the baseline aircraft. Results will be presented for the regional jet and large twin aisle with the single aisle, small twin aisle, and large quad available in Appendix B.

6.1.2.1 *Regional Jet*

A simplified analysis using first principle analysis will be provided to walk through some of the implications of speed reduction for the regional jet. This analysis will utilize the Breguet range equation and simplified weight and fuel burn build up methods using historical trends from Raymer.[97] The Breguet range equation is detailed in Chapter 2 but provided here as a reminder. The initial weight estimation is provided in Equation 14 where the crew and payload weights are defined in mission requirements, the fuel burn estimation W_f/W_0 is provided in Equation 15, and the empty weight estimation W_e/W_0 is provided in Equation 16. The values in Equation 16 were selected from historical data. Table 30 contains fuel burn estimations for non-cruise portions of the mission profile and Table 31 provides the cruise assumptions used in the analysis. One then needs to iterate on the initial weight guess in Equation 16 with the solution from Equation 14.

$$R = \frac{V}{c_T}\frac{L}{D}\ln\frac{W_i}{W_i - W_f} \tag{13}$$

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - W_f/W_0 - W_e/W_0} \tag{14}$$

$$W_f\!\Big/ W_0 = 1.06 * \left(1 - \prod_{i}^{n}\frac{W_i}{W_{i-1}}\right) \tag{15}$$

$$W_e\!\Big/ W_0 = 1.02 * W_0^{-0.055} \tag{16}$$

Table 30. Fuel Burn Assumptions for Non-Cruise Segments

Segment	Fuel Burn Assumption
Warmup and Takeoff	0.970
Climb	0.975
Landing	0.995

Table 31. Breguet Range Input Assumptions

Mach Number	Cruise Speed (kts)	Thrust Specific Fuel Consumption	Lift to Drag Ratio
0.80	461.1	0.670	16.0
0.78	449.6	0.660	16.4
0.76	438.1	0.651	16.8
0.74	426.6	0.642	17.1
0.72	415.0	0.634	17.4
0.70	403.5	0.625	17.7
0.68	392.0	0.616	17.9
0.66	380.4	0.607	18.1

To size the vehicle, one must first provide an estimate of a number of these parameters. The engine specific fuel consumption and the lift to drag ratio has estimates provided in Raymer while the cruise speeds were assumed for the associated Mach numbers of interest at 35,000.[97] Reductions in cruise speed provides reductions in engine specific fuel consumption while desweeping the wing provides increases in aerodynamic efficiency, providing a higher L/D ratio. These trends are also documented in Raymer.[97] Crew and payload weights were assumed for 4 crew weighing 190 pounds and 86 passengers weighing 210 pounds. Using these numbers and trends, the weight estimates and fuel performance was then solved for iteratively between Equation 14 and Equation 16.

Figure 56 compares the impact that speed reduction has on vehicle performance for the regional jet aircraft (design range 1,980 nm). Overall, there are moderate benefits to fuel consumption due but beyond M0.70, fuel burn begins to be penalized due to increased flight time, even with slightly increased engine and aerodynamic efficiency. The aerodynamics benefits from speed reduction begin to taper off around Mach 0.72 such further reduction results in fewer gains in combination with the slower speeds. This approach does not come without shortcomings. Given that the design range of the aircraft is fixed, the speed reduced aircraft are less sensitive to meeting particular performance constraints; however, they do exist and it does have performance implications. The second is that many of the parameters are assumed constant throughout the mission profile, something that is not reflective of actual mission performance. Although there are a number of techniques that one can take to improve the level of analysis with this approach, tools that are more flexible have been developed.

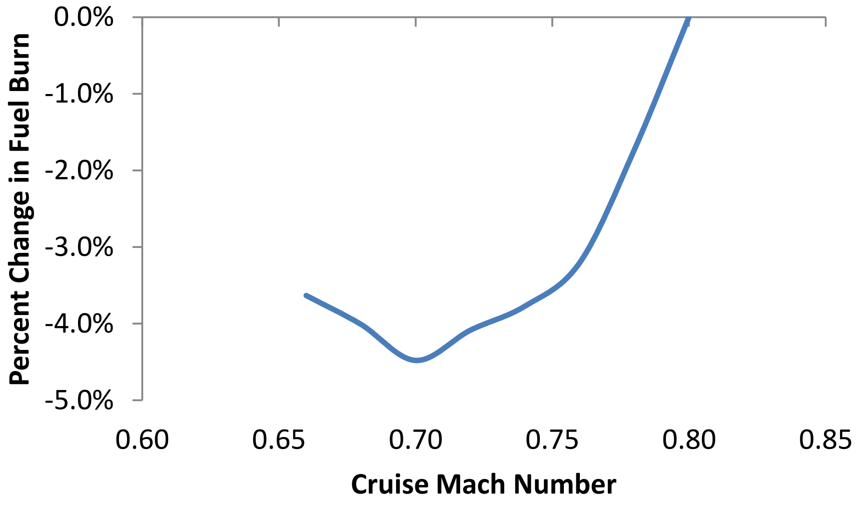


Figure 56. Simplified Fuel Burn Analysis of RJ Speed Reduction

For a more fundamental understanding, a brief analysis will be provided looking at the drag and wing weight changes that occur from speed reduction. A through drag estimation method has been documented by Gur using a number of empirical methods.[115] Equation 17 through Equation 21 are related to the impact that speed reduction has on aerodynamic and wing weight properties of the aircraft. Profile drag is decreased through reduced through wing area reduction but also significantly reduced through wave drag. Induced drag also decreases through increased aspect ratio of the wing from the assumption of holding span constant while decreasing wing area.

The critical elements of determining the wave drag in Equation 18 are the following two equations: Equation 19 relates the critical Mach number to the drag divergence Mach number, M_{DD}, where Equation 20 calculates that value. M_{DD} requires the half sweep angle $\Lambda_{0.5}$ as well as the average wing thickness to chord, section lift coefficient C_l, and the Korn factor κ_A – which is defined as 0.95 for supercritical airfoils. The combination of increasing thickness and decreasing sweep not only raises section C_l but ultimately reduces M_{DD}, lowering M_{crit} and therefore, wave drag.

In the wing weight equation (Equation 21), the wing area S of the aircraft is decreasing as is the vehicle weights (TOGW, ZFW) and the sweep of the load path, Λ_{load}. Average wing thickness to chord ratio increases due to speed reduction while load factor N_{ult}, wing span b, and taper ratio λ are all constant. N_{ult} was assumed to have a value of 3.75, wing span at 75.93’, and taper ratio was 0.281.

$$C_{D_0} = C_{D_{0,w}} + \left(\frac{D}{q}\right)_{body} \frac{1}{S} \tag{17}$$

$$C_{D_w} = 20 * (M - M_{crit})^4 \text{ for } M > M_{crit} \tag{18}$$

$$M_{CR} = M_{DD} - 0.108 \tag{19}$$

$$M_{dd}\cos\Lambda_{0.5} + \frac{C_l}{10*(\cos\Lambda_{0.5})^2} + \frac{t/c}{\cos\Lambda_{0.5}} = \kappa_A,\ \boldsymbol{\kappa}_A\text{=0.95 for supercritical airfoils} \tag{20}$$

$$W_{wing} = 4.22 * S_{wing} + 1.642 * 10^{-6}\frac{N_{ult} * b^3 * \sqrt{TOGW * ZFW} * (1 + 2\lambda)}{(t/c)_{avg} * (\cos\Lambda_{load})^2 * S_{wing}(1 + \lambda)} \tag{21}$$

Results of this analysis are provided in Table 32 for the aerodynamic results and Table 33 for the wing weight results. The predominant impact of speed reduction and desweeping the wing is that the drag divergent Mach number and critical Mach number have both reduced and that has significant implications in terms of wave drag. There are also significant benefits to wing weight but note that the percent changes are with respect to the wing and not total vehicle.

Table 32. Wave Drag Assumptions and Results

Mach Number	**$(t/c)_{average}$**	**$\Lambda_{0.5}$ (deg)**	**C_l**	**M_{DD}**	**M_{crit}**	**C_{dw}**
0.80	0.109	23.8	0.58	0.833	0.725	6.46E-4
0.78	0.113	21.9	0.60	0.818	0.710	4.71E-4
0.76	0.116	20.1	0.62	0.805	0.697	3.07E-4
0.74	0.120	18.2	0.63	0.794	0.686	1.75E-4
0.72	0.124	16.3	0.64	0.783	0.675	8.20E-5
0.70	0.127	14.5	0.66	0.773	0.665	2.92E-5
0.68	0.131	12.7	0.67	0.764	0.656	6.49E-6
0.66	0.134	10.8	0.68	0.756	0.648	4.21E-7

Table 33. Wing Weight Estimation Assumptions and Results

Mach Number	Λ_{load} (deg)	TOGW (lbs)	ZFW (lbs)	W_{wing} (lbs)	Percent Change
0.80	25.75	83,160	64,310	6,788	0%
0.78	23.85	82,483	63,960	6,553	-3%
0.76	21.98	81,908	63,663	6,340	-7%
0.74	20.12	81,687	63,549	6,159	-9%
0.72	18.26	81,564	63,485	5,994	-12%
0.70	16.41	81,411	63,406	5,843	-14%
0.68	14.57	81,595	63,501	5,713	-16%
0.66	12.74	81,742	63,577	5,597	-18%

A more detailed analysis follows, which was conducted using the Environmental Design Space.

Speed reduction provides a moderate benefit to fuel burn for the regional jet at the minimum fuel burn Mach number. The baseline mission is represented in Figure 57 by the blue line and indicates that minimum fuel burn occurs at Mach 0.70, a 0.1 reduction from the baseline cruise speed. These fuel burn benefits max at 4.3% before increasing with further reductions in Mach number. It is also worth noting that a significant portion of the benefits are realized at M0.74 such that penalties from increased flight time may be lessened compared to operating at the minimum.

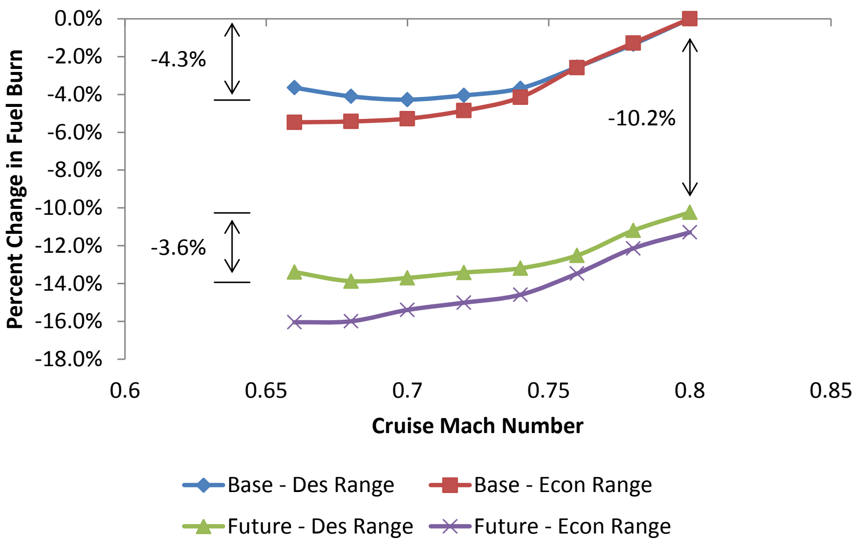


Figure 57. RJ Fuel Burn Impact of Speed Reduction

Technology infusion provides a significant impact to fuel savings – 10.2% for the baseline mission alone. This is indicated back in Figure 57 as well. The green line, representing the design range mission, shows that the benefits of speed reduction are somewhat reduced with the introduction of advanced technology, 3.6% savings vs the base 4.3%. The bucket location shifts from M0.70 to M0.68. The economic mission, the purple line, indicates similar trends to the baseline economic mission where continued speed reduction does not penalize fuel burn.

These benefits are due in part to two things: wing and engine redesign. Wing redesign occurs because the sweep is reduced while the thickness is increased. Less sweep creates a lighter wing and this translates into fuel savings. Engine redesign improves the cruise performance as the lower cruise speed results in less energy in the airflow entering the engine. Given the existing temperature limits of materials, this means that the engine can operate under higher pressure ratios and allows for more efficient combustion. Together these work together to provide fuel savings.

However, these benefits are not constant. Reductions in sweep diminish as cruise speed is reduced such that wing weight savings begin to taper off. Engine benefits are still present but the challenge is that now the aircraft has to flight longer to complete the same mission and the duration of the mission begins to penalize the fuel burn. Eventually, the length becomes significant enough that the aircraft is penalized and requires more fuel to complete the mission than the previous speed.

Back in Figure 57, the 800 nm economic mission shows fuel savings beyond the bucket at Mach 0.70 by the red line. The maximum benefits are also slightly greater than the design range impact by 1%. One of the consequences of speed reduction is that flying long range takes a significantly longer period of time and will eventually result in greater fuel consumption. As this economic range is short, consequences are not felt here.

A comparison of flight times changes between the different speed reduced aircraft is provide in Figure 58. Differences in flight time due to technology changes are minimal such that only the comparisons for the baseline aircraft will be provided. For the design mission, which is indicated by the blue line, each step in Mach number results in approximately a 2% increase in flight time. This means that the baseline mission increases from 5.05 hours at Mach 0.80 to 5.81 hours at Mach 0.66 – an increase of 45 minutes. The economic mission flight time does not increase as significantly as the design mission; however, the time increase is almost 20 minutes (2.47 hours to 2.76 hours).

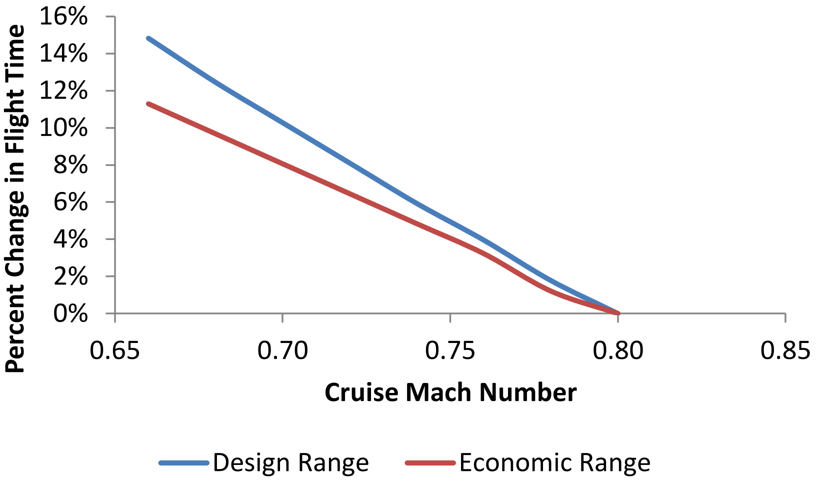


Figure 58. Impact of Speed Reduction on RJ Flight Time

Increases in flight time translate to increases in crew and maintenance costs such that understanding the impact of speed reduction from an airline perspective is important. Given though the fuel burn analysis demonstrated that most of the fuel burn benefits have been realized at M0.74, Figure 59 shows that there is no savings to an airline and at slower speeds, the penalties to the airline are much more significant. Although the future technology aircraft designs show cost savings relative to the baseline, many of the benefits are significantly reduced from the future aircraft. This would indicate that it may not be desirable to even consider speed reduction for this seat class.

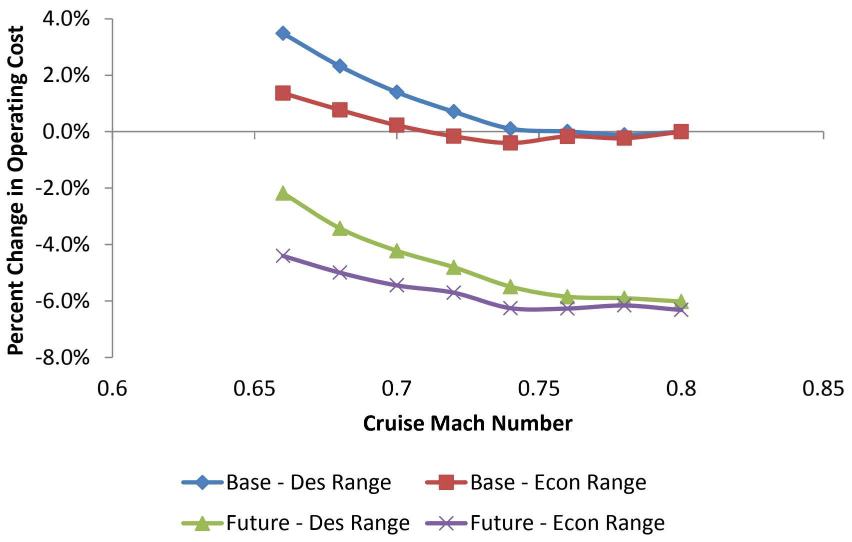


Figure 59. RJ Operating Cost Impact of Speed Reduction

Based on vehicle analysis results, the regional jet should move on to the fleet level for speed reduction. It should be noted that the single aisle trends are quite similar to the regional jet and it also moves on to fleet analysis.

6.1.2.2 Large Twin Aisle

The large twin aisle aircraft initially provides significant benefits in terms of fuel savings. Stepping from Mach 0.84 to 0.82 to 0.80 and then 0.78 provides savings of 2.9%, 5.5%, and 7.3% for the baseline mission. Further reductions can still provide meaningful savings but nowhere near as large at those first three steps. The minimum fuel burn occurs at Mach 0.74 with 8.8% savings. Similar benefits are available for the primary economic mission; however, at Mach 0.70 and 0.72, the fuel savings remain the same or increase. These trends are provided in Figure 60.

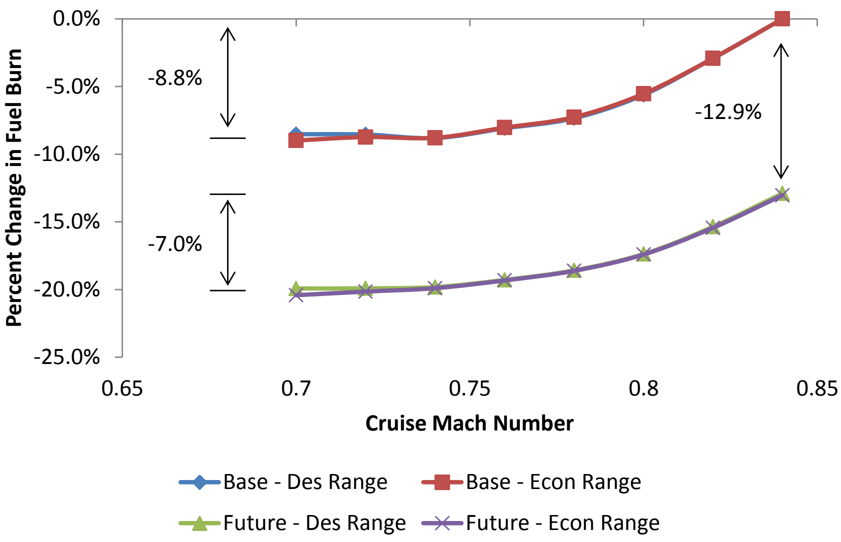


Figure 60. LTA Fuel Burn Impact of Speed Reduction

Technology introduction results in the minimum fuel burn Mach number hitting the minimum bounds but the change from M0.72 to M0.70 is not significant. Fuel savings are 7%, which is less than the 8.8% from the baseline case. The level of impact is close to that of technology on its own – 12.9%. Additionally, the economic mission shows similar fuel burn trends to the design mission, as it did in the baseline technology example.

The causes of fuel savings are similar to that of the regional jet. Speed reduction allows for wing sweep reduction that provides wing weight reductions. Engine redesign allows for a more efficient engine with higher overall pressure ratios. The impact is larger here also because the aircraft itself is larger and flies a much longer range.

Figure 61 contains comparisons of the flight time for both missions. Notice that the trendlines essentially overlap for this aircraft. This is due to the much longer ranges of the design and economic missions for the large twin aircraft. At Mach 0.70, the respective missions have an increase in flight time of 17% and 16.8% - resulting in an increase in flight time of 2.74 hours for the design mission and 1.49 hours for the economic in relation to the baseline times of 16.14 and 8.88 hours respectively.

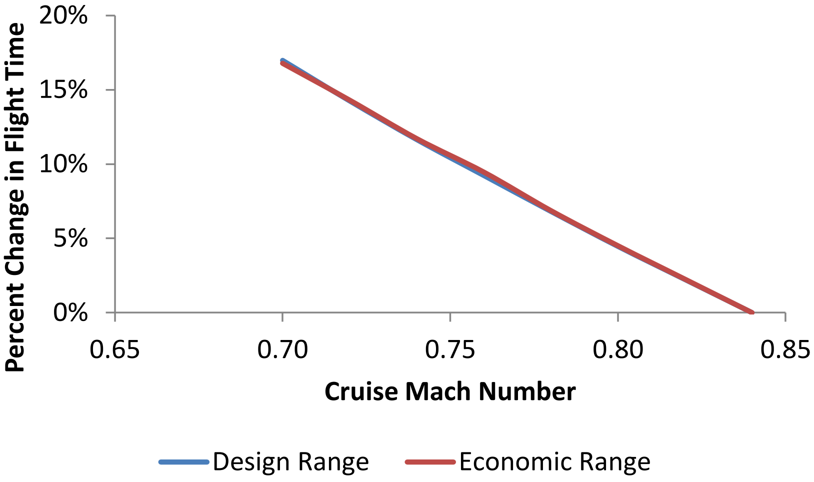


Figure 61. Impact of Speed Reduction on the LTA Flight Times

Like the regional jet, increases in flight time have a significant penalty on crew and maintenance costs. However unlike the previous seat class, the large twin aisle saves far more fuel from speed reduction in comparison to the shorter range regional jet. This ultimately results in cost savings for all speed reduced variants as fuel costs are the largest component of total operating cost.

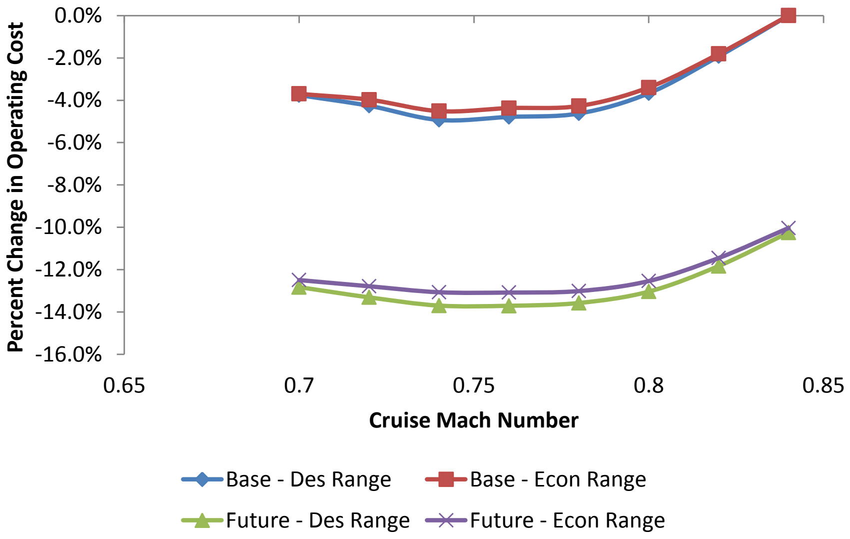


Figure 62. LTA Operating Cost Impact of Speed Reduction

Based on these findings, the large twin aisle will move on to fleet analysis for speed reduction. Trends for the small twin aisle and large quad are more in line with this aircraft but relevant figures are available in Appendix B.

With the design and analysis of the five vehicles complete, the next step is to evaluate the impact that these aircraft will have at the fleet. Since each seat class showed benefit s from cruise speed reduction, all will be carried over to the fleet level.

6.2 Fleet Results

An initial section will discuss the baseline results as well as the future technology results with no specification changes to provide perspective on how future growth impacts metrics. Then the speed results will follow. Finally, the experimental results will end this chapter.

6.2.1 Fleet Forecasting Results

Aviation growth is projected to be significant through under the forecast period of investigation. The objective of this section is to bring perspective to the overall fleet results as the fleet results will be measured by percent difference from their respective technology level baselines. Noise will not be addressed in this section as only 2036 and 2050 are being analyzed.

Figure 63 shows that operations growth is projected to result in 4.5 times the number of the initial 2006 flights at 2050. This growth will have a significant impact throughout the system with respect to all metrics. Note that these results are reflective of the forecast used and the initial operations set.

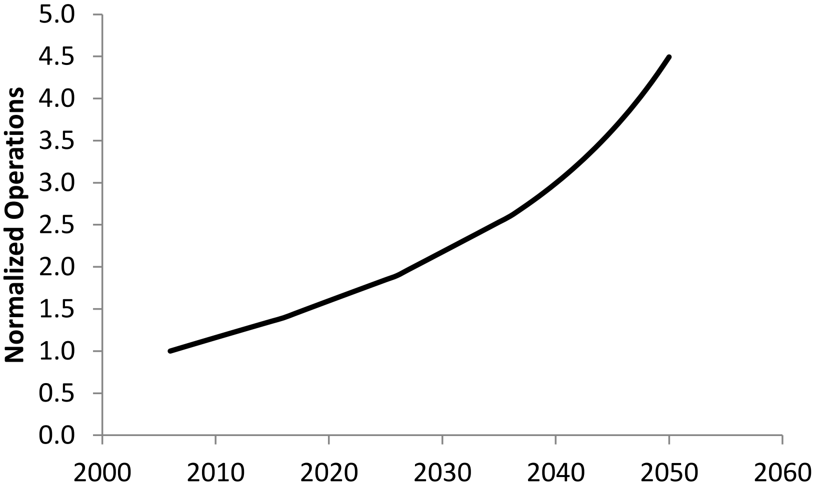


Figure 63. Forecasted Operations Growth from 2006-2050

A further breakdown of operations by individual seat class is provided in Figure 64. These results are normalized with respect to the 2006 total number of operations. The single aisle makes up the significant portion of the datum flights followed by the small regional jet, regional jet, and then the final four by increasing size. When the forecast ends in 2050, the four larger seat classes have all increased significantly as has the regional jet in proportion to the total number of operations. On the other hand, the small regional jet and single aisle have decreased largely due to the significant increase in those classes. Now the small regional jet and very large aircraft will not be modified in this analysis such that approximately 10% of fleet operations at 2050 will not receive technology or mission specification changes. These fleet breakdowns are provided in Table 34.

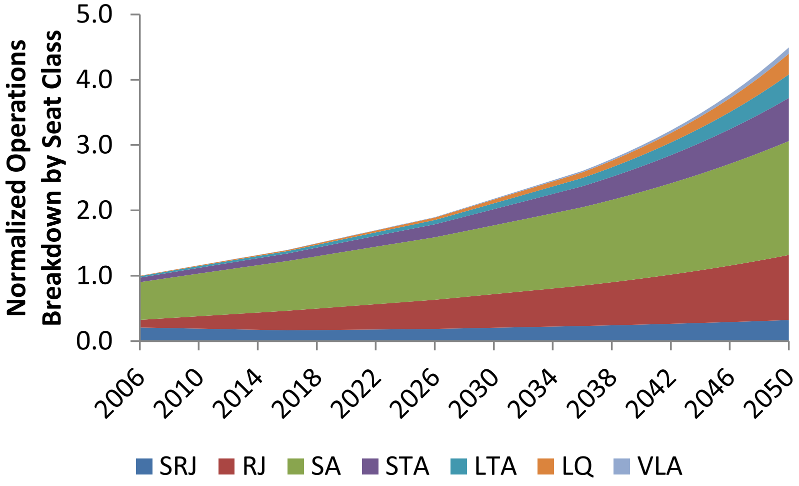


Figure 64. Operations Breakdown by Seat Class

Table 34. Breakdown of Fleet by Seat Class in 2006 and 2050

Seat Class	2006 Percentage	2050 Percentage
SRJ	20.8%	7.2%
RJ	11.7%	22.1%
SA	57.7%	38.8%
STA	6.9%	14.7%
LTA	2.2%	8.0%
LQ	0.6%	7.1%
VLA	0.2%	2.1%

Baseline fuel burn growth is expected to be 6.59 times that of year 2006 in 2050 while the introduction of technology aircraft without mission specification changes reduces it to 5.99 of the initial fleet in 2006. This is a 9.1% reduction in fuel consumption at 2050 and is significant; however, it does come short of carbon neutral goals. This is represented in Figure 65.

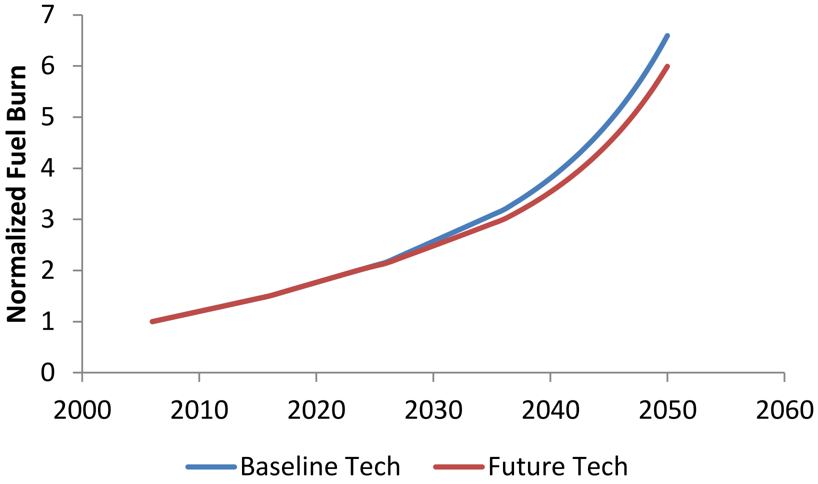


Figure 65. Forecasted Fuel Burn Growth from 2006-2050

For additional reference, Figure 66 contains a breakdown of the total fuel burn with respect to each of the seat classes. This is for the baseline technology level – for future, the components from regional jet through large quad are reduced while the small regional jet and very large aircraft classes are identical to the baseline as they are not receiving technology. This figure largely serves to provide context to the fleet results as even a 10% reduction in one seat class' fuel burn would not correspond to a 10% fleetwide reduction.

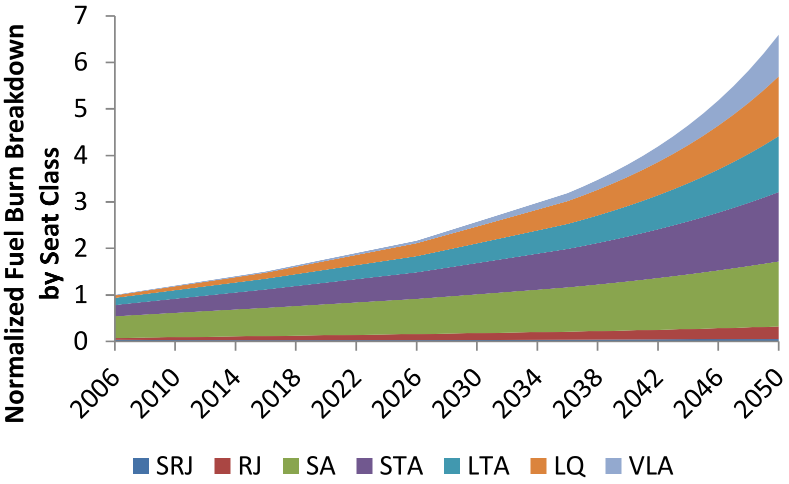


Figure 66. Fuel Burn Breakdown by Seat Class – Baseline Technology

NO_x growth trend is similar to fuel burn although the magnitude of growth is higher – 7.31 for the status quo. Technology infusion is substantial on NO_x growth such that the factor is reduced to 5.68, a 22.4% reduction. Figure 67 shows a comparison of the two NO_x growth trends.

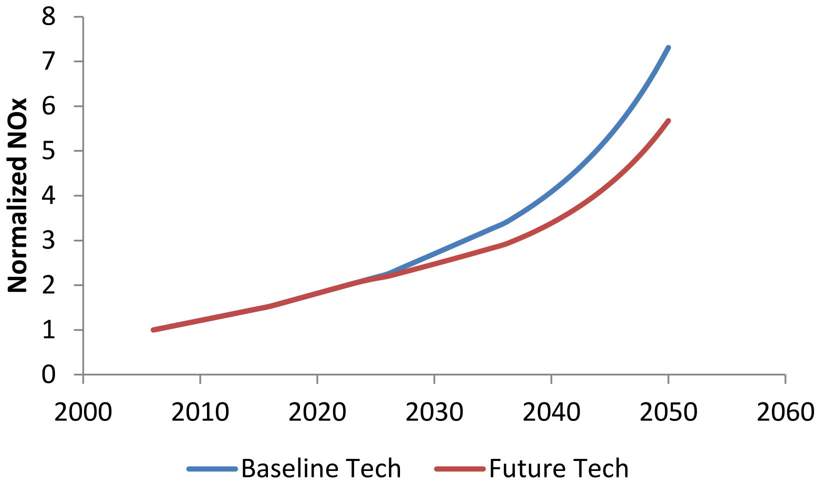


Figure 67. Forecasted NO_x Growth from 2006-2050

Figure 68 compares the impact of growth and technology introduction on the combination of fuel, crew, maintenance, route, and landing fees. Baseline technology results in a 6.23 factor of growth in 2050 over 2006 while technology represents a 5.85 factor. The 6.1% savings is entirely due to fuel savings as the other costs are unchanged since the mission specifications are the same as the baseline aircraft. Figure 69 compares the combination of the operating costs in Figure 68 with changes in capital cost of the replacement aircraft. The margin between the two technology levels is significantly reduced due to the higher prices of the future aircraft. But the future technology total costs are still less than the baseline because of the much larger operating cost savings due to fuel burn reduction.

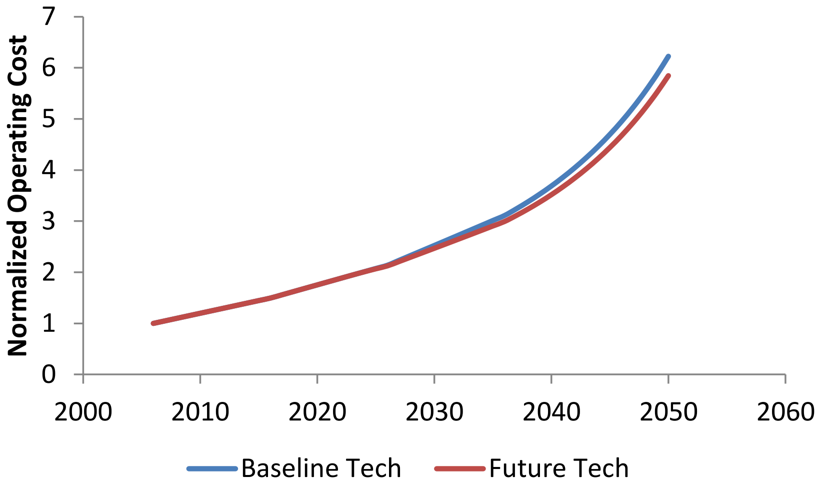


Figure 68. Forecasted Operating Cost Growth from 2006-2050

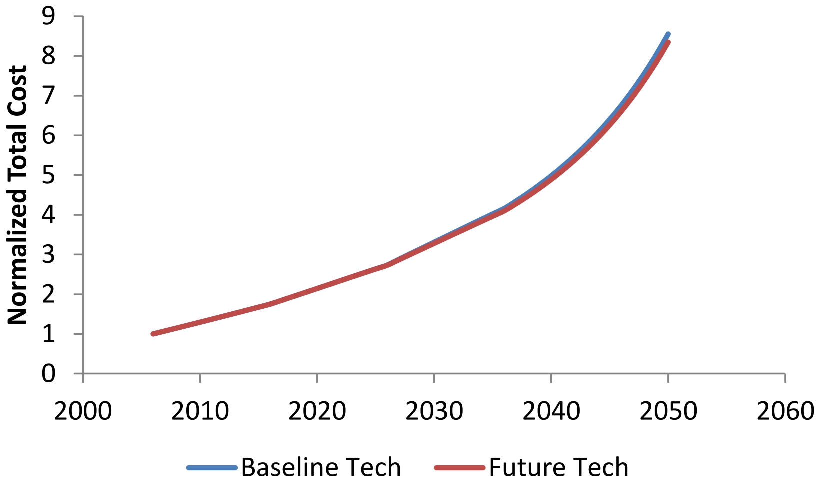


Figure 69. Forecasted Total Cost Growth from 2006-2050

As operations do not change between the two technology levels, safety is constant between the two scenarios. Using accident rates with respect to both operations and flight time, the trends are pretty much the same and in terms of absolute numbers are close as well. They are provided in Figure 70.

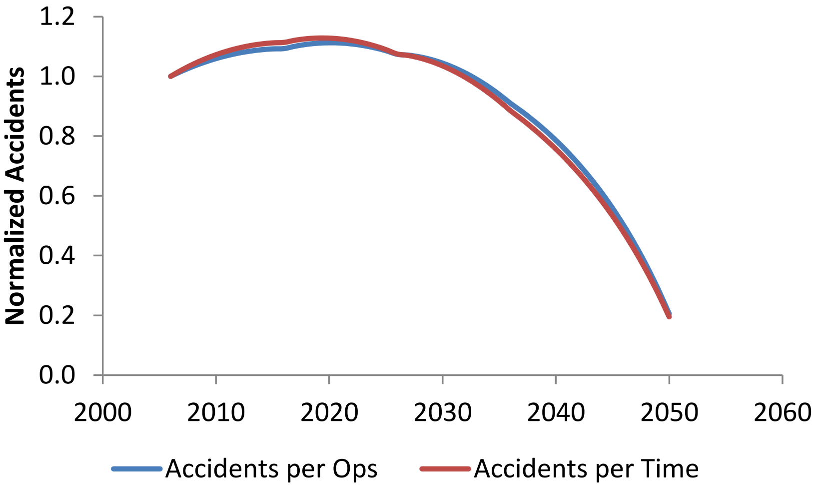


Figure 70. Forecasted Accident Count from 2006-2050

Now that the overall fleet results have been shown, the following section will show the impact that speed reduction has on the fleet.

6.2.2 Fleet Impact of Speed Reduction

The impact of cruise speed reduction will be assessed for both the regional jet and large twin aisle with figures for the other aircraft located in Appendix B. As a reminder, Table 35 contains the bounds of the speed reduction analysis and the minimum fuel burn at the vehicle level for each aircraft.

Table 35. Speed Bounds and Optimum Fuel Burn for Baseline Technology

Seat Class	Minimum Mach Number	Baseline Mach Number	Base Tech Vehicle Optimum	Future Tech Vehicle Optimum
Regional Jet	0.66	0.80	0.70	0.68
Single Aisle	0.68	0.78	0.70	0.74
Small Twin Aisle	0.68	0.80	0.70	0.70
Large Twin Aisle	0.70	0.84	0.74	0.70
Large Quad	0.73	0.85	0.75	0.77

Speed reduction has a significant impact on total number of aircraft required. To better highlight the impact that speed reduction has on other metrics, the total number of required aircraft for each seat class has been separated from cumulative summary figures. These impacts are in Figure 71. Note that 1% represents almost 900 additional required aircraft.

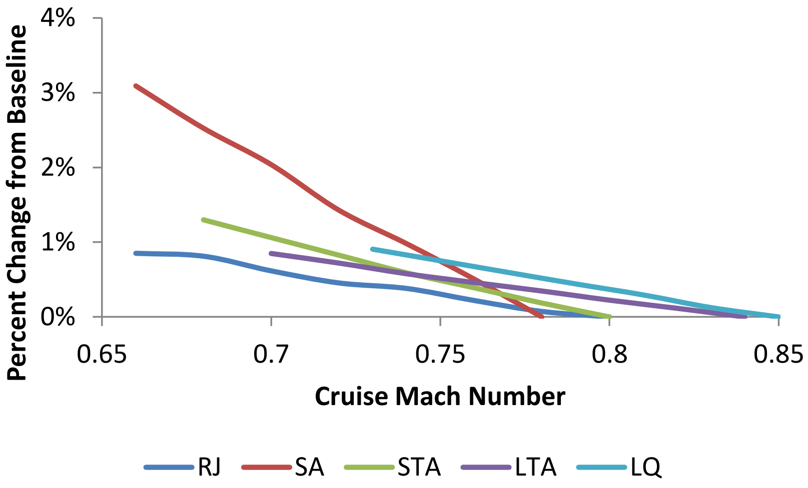


Figure 71. Number of Required Aircraft due to Baseline Speed Reduction

The impact is significant for all seat classes but the single aisle stands out much more noticeably. As shown back in Figure 64, the single aisle contributes to far more operations in the fleet than the other vehicles and therefore is much more sensitive to changes in cruise speed with respect to required number of aircraft. Analysis of the regional jet and large twin aisle aircraft are provided to further understand the fleet level impact of speed reduction on the other metrics.

6.2.2.1 *Regional Jet*

Figure 72 provides a cumulative summary of fuel burn, operating cost, capital cost, total cost, NO_x, and the increase in number of accident due to adoption of speed reduction for the regional jet over the 2006 to 2050 timeframe for the datum set. Fuel burn initially begins to steadily decrease but by M0.72, the benefits begin to significantly diminish. Operating cost minimizes at M0.72 and then the increases in crew and maintenance rates as well as more required aircraft offset the fuel related savings. Capital cost and accident count both steadily increase as cruise speed is reduced. Both are due to the increase in required flight time where the former is due to the increased number of required aircraft, as shown back in Figure 71, while the latter is calculated as a function of flight time. A summary of the cumulative results is provided in Table 36.

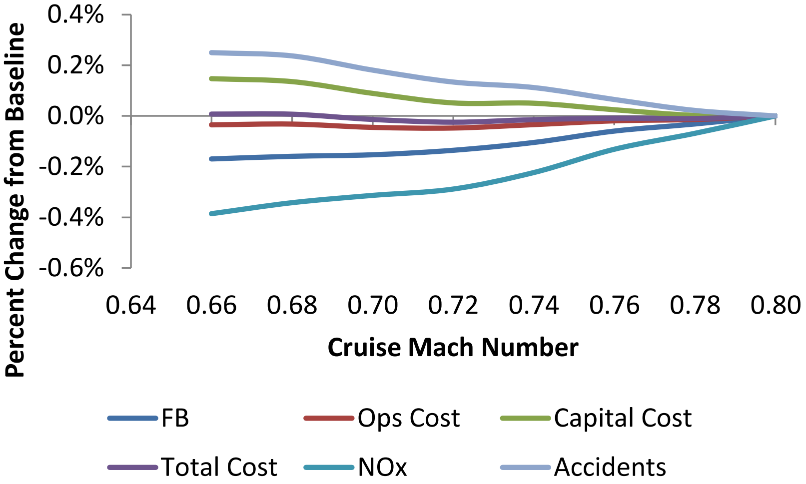
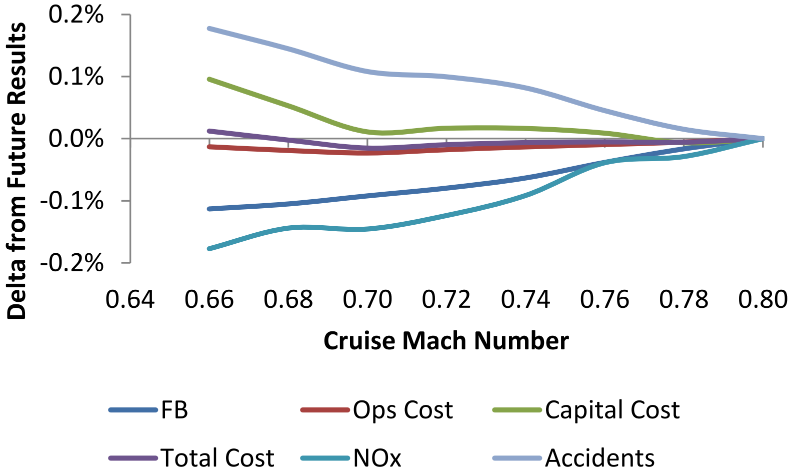


Figure 72. RJ Base Cumulative Speed Reduction Fleet Results

Table 36. RJ Base Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO_x	Number of Aircraft	Accidents
0.80	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.78	-0.03%	-0.01%	0.00%	-0.01%	-0.07%	0.07%	0.02%
0.76	-0.06%	-0.02%	0.02%	-0.01%	-0.13%	0.22%	0.06%
0.74	-0.10%	-0.03%	0.05%	-0.01%	-0.22%	0.38%	0.11%
0.72	-0.14%	-0.05%	0.05%	-0.02%	-0.29%	0.45%	0.13%
0.70	-0.15%	-0.05%	0.09%	-0.01%	-0.31%	0.62%	0.18%
0.68	-0.16%	-0.03%	0.14%	0.01%	-0.34%	0.81%	0.24%
0.66	-0.17%	-0.04%	0.15%	0.01%	-0.39%	0.85%	0.25%

Future technology provides benefits to most of the metrics except for capital cost, which increases due to the higher aircraft prices from its integration into the vehicle, and accidents, which are unaffected by technology introduction. However, the overall sensitivity has greatly lessened for all metrics except for accidents. This is largely due to a significant portion of the fuel burn and NO_x benefits from speed reduction have been reduced. Capital cost on the other hand is reduced simply due to the overall increase in aircraft prices for all seat classes. Figure 73 compares the sensitivity of the metrics to changes in speed reduction with future technology with the corresponding initial values on the right side.



Fuel Burn	-5.13%
Ops Cost	-3.33%
Capital Cost	5.01%
Total Cost	-1.39%
NO_x	-12.74%
Accidents	0.00%

Figure 73. RJ Future Cumulative Speed Reduction Fleet Results

Table 37. RJ Future Cumulative Data

Mach Number	**Fuel Burn**	**Operating Cost**	**Capital Cost**	**Total Cost**	**NO_x**	**Number of Aircraft**	**Accidents**
0.80	-5.13%	-3.33%	5.01%	-1.39%	-12.74%	0.00%	0.00%
0.78	-5.15%	-3.34%	5.00%	-1.40%	-12.77%	0.07%	0.02%
0.76	-5.17%	-3.34%	5.02%	-1.40%	-12.78%	0.20%	0.05%
0.74	-5.20%	-3.35%	5.02%	-1.40%	-12.83%	0.36%	0.08%
0.72	-5.21%	-3.35%	5.02%	-1.40%	-12.86%	0.44%	0.10%
0.70	-5.23%	-3.36%	5.02%	-1.41%	-12.89%	0.47%	0.11%
0.68	-5.24%	-3.35%	5.06%	-1.39%	-12.88%	0.64%	0.14%
0.66	-5.25%	-3.35%	5.10%	-1.38%	-12.92%	0.78%	0.18%

One observation that is that the impact of speed reduction for the regional jet is the benefits at the fleet level are not overwhelmingly large. This is due to a couple of reasons. The first is that the regional jet does not correspond to a significant proportion of the total fleet operations. This is a significant factor in terms of limiting the benefits of the future aircraft. In terms of fuel burn, this margin is even smaller such that the overall fleet impact is even more lessened. Similar trends occur for all other metrics as well. It does ask the question whether speed reduction is even appropriate for this seat class.

6.2.2.2 Large Twin Aisle

The large twin aisle's summary chart is provided in Figure 74. The first major difference between this chart and the regional jet's is that there is a second vertical axis. This is only for the NO_x as the changes are much larger than the other metrics and otherwise, those trends would be less apparent. The fleet minimum fuel burn occurs at Mach 0.70 with savings of 0.78%. Mach 0.72 and Mach 0.74 are both pretty close with benefits of 0.76% each. The vehicle level optimum was at Mach 0.74 for the design mission but the economic mission did indicate additional savings for speeds below the optimum. These fuel savings provide substantial cost savings at Mach 0.74 but total cost savings are maximized at Mach 0.80 such that the significant capital cost increases from greater speed reduction are offset. A summary of the 2050 results is provided in Table 38.

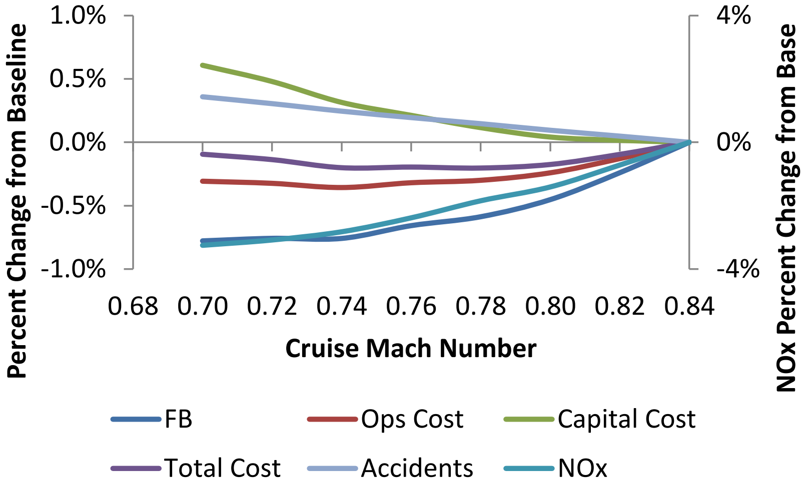
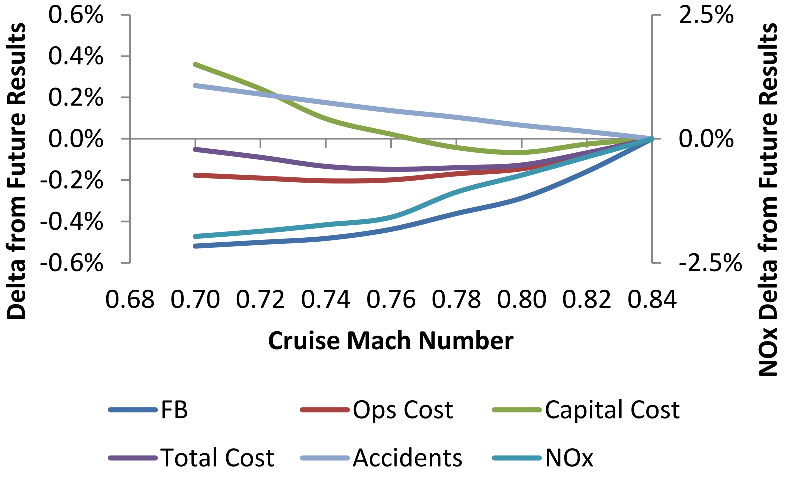


Figure 74. LTA Base Cumulative Speed Reduction Fleet Results

Table 38. LTA Base Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO_x	Number of Aircraft	Safety
0.84	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.82	-0.24%	-0.13%	0.02%	-0.10%	-0.72%	0.12%	0.05%
0.80	-0.45%	-0.24%	0.04%	-0.18%	-1.41%	0.22%	0.09%
0.78	-0.59%	-0.30%	0.12%	-0.20%	-1.85%	0.35%	0.15%
0.76	-0.66%	-0.32%	0.21%	-0.20%	-2.38%	0.46%	0.19%
0.74	-0.76%	-0.36%	0.31%	-0.20%	-2.82%	0.58%	0.25%
0.72	-0.76%	-0.32%	0.48%	-0.14%	-3.08%	0.72%	0.30%
0.70	-0.78%	-0.31%	0.61%	-0.09%	-3.25%	0.85%	0.36%

While future technology provides benefits for the large twin aisle, these benefits are reduced similarly to the regional jet. Much like the other seat class, technology already provides significant savings for all metrics or the penalty, as in the case of capital cost, is lessened due to overall aircraft prices rising. Figure 75 compares the impact of technology on the cumulative results with Table 39 containing the relevant data. Like the baseline technology case, Figure 75 has a secondary axis on the right to be used only for NO_x to aid in making the trends more clear for the other metrics.



Fuel Burn	-5.13%
Ops Cost	-3.33%
Capital Cost	5.01%
Total Cost	-1.39%
NO_x	-12.74%
Accidents	0.00%

Figure 75. LTA Future Cumulative Speed Reduction Fleet Results

Table 39. LTA Future Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO_x	Number of Aircraft	Safety
0.84	-5.13%	-3.33%	5.01%	-1.39%	-12.74%	0.00%	0.00%
0.82	-5.29%	-3.41%	4.98%	-1.46%	-13.11%	0.11%	0.04%
0.80	-5.42%	-3.48%	4.94%	-1.52%	-13.47%	0.20%	0.07%
0.78	-5.49%	-3.50%	4.96%	-1.53%	-13.81%	0.32%	0.10%
0.76	-5.57%	-3.53%	5.03%	-1.54%	-14.32%	0.41%	0.14%
0.74	-5.61%	-3.54%	5.10%	-1.53%	-14.47%	0.53%	0.17%
0.72	-5.63%	-3.52%	5.25%	-1.48%	-14.60%	0.66%	0.22%
0.70	-5.65%	-3.51%	5.37%	-1.44%	-14.71%	0.79%	0.26%

Compared to the regional jet, the large twin benefits are much larger overall. This is not overwhelmingly surprising as although the large twin is a smaller proportion of the overall operations, it is a much larger contributor with respect to fuel burn and other metrics.

6.3 Experimental Results

With the fleet impact of speed reduction completed, the final step is to address the hypotheses and experimental results. This discussion will be in the following order: influence of different fleet metrics of best speeds, comparison of best vehicle to best fleet results, a comparison of replacement strategies, and an evaluation of the influence of technology introduction on the sensitivity of speed reduction.

6.3.1 Influence of Different Fleet Metrics on Best Speeds

Based on the fleet level analysis, the next step was to identify the maximum benefit vehicles for the fleet based on the following metrics: fuel burn, operating cost, and total cost. The corresponding speeds for the minimum results of each metric are in Table 40.

Table 40. Comparison of Cruise Speeds Corresponding to Different Metrics

Seat Class	Baseline Technology			Future Technology		
	Min Fuel	Min Ops Cost	Min Total Cost	Min Fuel	Min Ops Cost	Min Total Cost
Regional Jet	0.66	0.72	0.72	0.66	0.70	0.70
Single Aisle	0.70	0.72	0.78	0.68	0.74	0.74
Small Twin Aisle	0.70	0.72	0.74	0.68	0.74	0.76
Large Twin Aisle	0.70	0.74	0.78	0.70	0.74	0.76
Large Quad	0.75	0.75	0.81	0.75	0.77	0.77

The predominant trend is that the speeds for minimum fuel burn and the two costs are not the same. In some cases, the two costs are the same and when there is a difference, it is due to the change in capital and crew/maintenance costs increasing faster than the fuel savings. The baseline technology single aisle is such a large outlier because of the impact it has over such a larger number of operations and its lesser fuel savings compared to other aircraft.

So while there is a best speed for fleet fuel burn, it does not necessarily represent the minimum cost and depending on perspective, might not be the most ideal outcome. Any organization interested in reducing the environmental impact of aviation would strongly prefer an outcome with the greatest reduction in fuel burn. On the other hand, airlines will be far more interested in minimizing their costs such that minimum operating cost or total cost is the more relevant outcome.

This debate in which metric one should use will have significant implications on the manufacturers as it is in their best interests to develop aircraft and engines that are capable meeting any future regulatory changes as well as being attractive to the operators and leasing companies that purchase them. Historically, the typical consideration is that a system or operating scheme has to buy its way onto the aircraft.

One pertinent question is the impact that shifting selection metric has among the other fleet metrics. Figure 76 compares all three strategies on fuel burn, NO_x, operating cost and total cost. With respect to fuel burn, minimum operating cost is not that much less in terms of savings as fuel costs contribute significantly to fleet costs but total cost is a percent less such that the influence of capital cost is more significant. NO_x essentially follows fuel burn. Looking at operating cost, there is very little variation between the three strategies but that 0.1% difference between minimum fuel and minimum operating cost represents $3.4B cumulatively from 2006-2050 with the datum six week set. Meanwhile, the 0.4% difference in total cost for the minimum fuel burn and minimum total cost scenarios represents $15.3B over the same timeframe.

Technology introduction shows a lot of the same trends. All three strategies provide greater savings than no action except for total cost with the minimum fuel burn approach – slightly increasing cost.

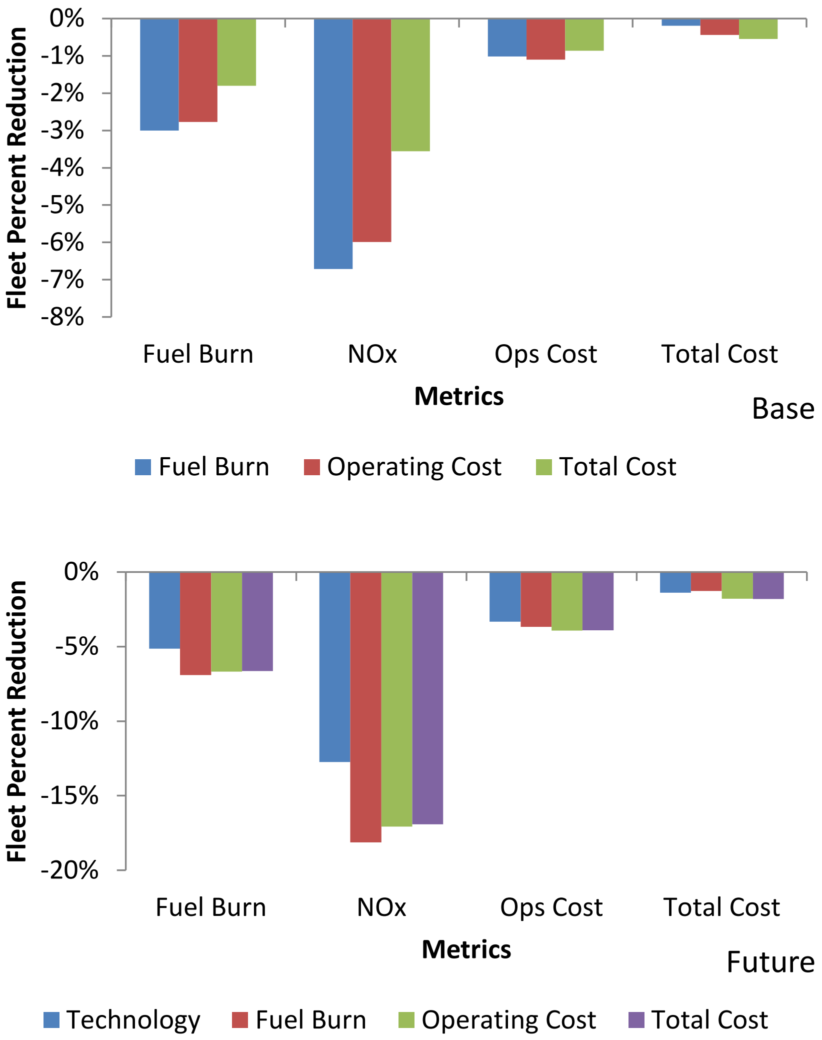


Figure 76. Fleet Performance Based on Metric Minimization

Noise analysis will be limited to the minimum fuel burn variants as variation within speed reduction does not result in significantly different noise contours and given that the certification numbers are all within small variation. Figure 77 compares the 55 dB contour area summations for the representative airports defined in Chapter 4 over both technology levels. Overall, noise exposure is relatively constant among all of the airport groupings. There are small increases in the high and medium traffic airports but this should be considered within an acceptable margin and indicate that speed reduction has little impact on airport noise. The increases are due to reductions in climb out thrust from the vehicle optimization, resulting in the aircraft spending slightly more time in the terminal area and generating more noise.

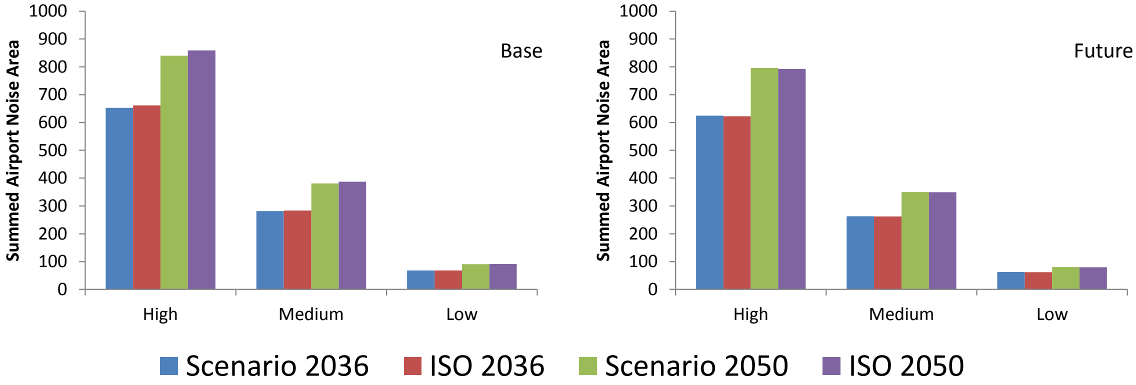


Figure 77. Noise Impact Comparison from Speed Reduction – 55 dB

6.3.2 Comparison of Best Vehicle to Best Fleet Results

As a significant portion of literature has been focused on the vehicle level benefits of mission specification changes, it follows that a comparison of the vehicle best results should be compared to the fleet level results. Given that vehicle optimization was focused on minimizing fuel burn at each speed, fleet comparisons will focus on the minimum fuel burn results. This data is available in Table 41.

Table 41. Cruise Speed Comparison for Minimum Fuel Burn

Seat Class	Baseline Technology		Future Technology	
	Vehicle Optimum	Fleet Optimum	Vehicle Optimum	Fleet Optimum
Regional Jet	0.70	0.66	0.68	0.66
Single Aisle	0.70	0.70	0.74	0.68
Small Twin Aisle	0.70	0.70	0.70	0.68
Large Twin Aisle	0.74	0.70	0.70	0.70
Large Quad	0.75	0.75	0.77	0.75

At the baseline technology level, the regional jet and large twin aisle both have fleet optimum speeds that are slower than their vehicle level counterpart. This trend occurs when a significant number of operations are further from the design range. It can also be seen in the vehicle operating range trends such that their minimum fuel points are slower than the design curves. Future technology levels result in the same behavior for all vehicles except the large twin aisle, whose speeds are the same – the minimum bounds.

Similarly, a comparison of the operating cost results was conducted. For many of the seat classes, the vehicle optimum is much faster than the fleet outcome, only two cases differ. This again highlights the importance of conducting fleet level assessment rather than looking only at the design mission outcomes. Secondary assessment at the vehicle level through economic mission would address this somewhat but ultimately, even one or two flight distances is not enough to fully capture the fleet level impact.

Table 42. Cruise Speed Comparison for Minimum Operating Cost

Seat Class	**Baseline Technology**		**Future Technology**	
	Vehicle Optimum	**Fleet Optimum**	**Vehicle Optimum**	**Fleet Optimum**
Regional Jet	0.78	0.72	0.80	0.70
Single Aisle	0.76	0.72	0.76	0.74
Small Twin Aisle	0.74	0.72	0.74	0.74
Large Twin Aisle	0.74	0.74	0.76	0.74
Large Quad	0.77	0.75	0.77	0.77

Ultimately, both technology levels indicate the importance of looking at fleet level analysis when conducting changes in mission specifications, providing evidence that supports Hypothesis 2.

6.3.3 Comparison of Replacement Strategies on Future Operations

The minimum fleet fuel burn results will be used to evaluate the impact that immediate replacement (the current approach in assessing fleet level impact of mission specifications) has in comparison to fleet evolution that is used in this research. If one used either cost scenario, there would be variation in the outcomes of the metrics but the observations would still be similar.

Figure 78 demonstrates the cumulative impact that immediate replacement of vehicles has on the fleet in comparison to the impact of fleet evolution for fuel burn, NO_x, operating cost, and total cost. The solid lines represent fleet evolution while the dashed lines are immediate replacement of all respective vehicles. These results are with respect to the baseline technology fleet with no specification changes.

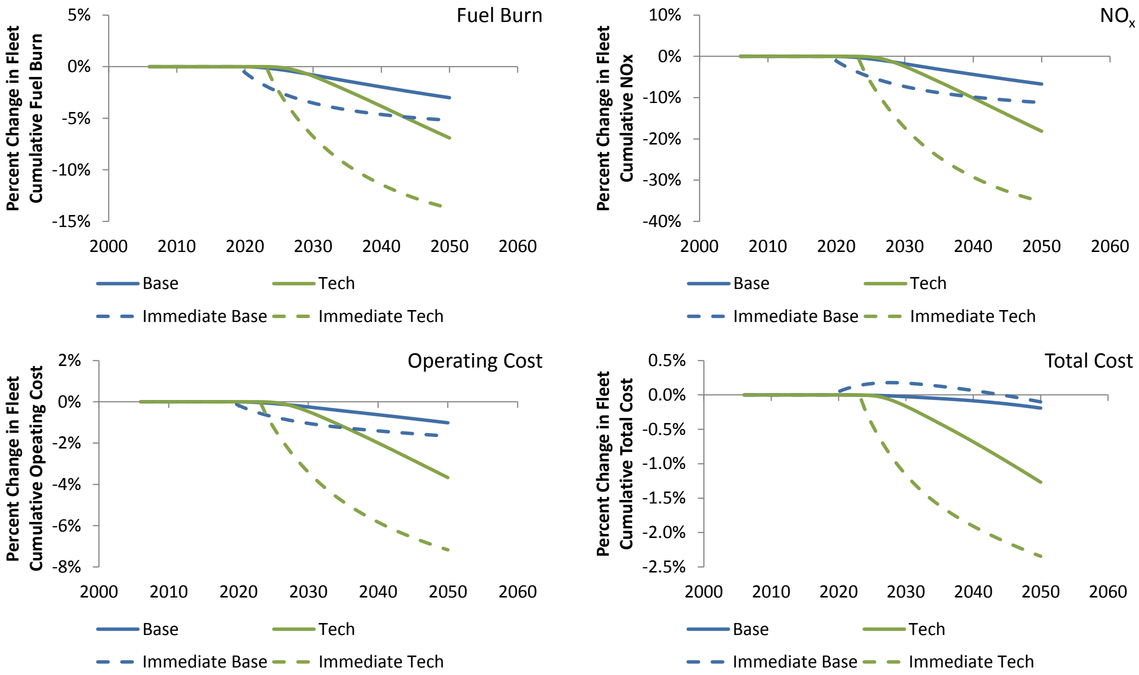


Figure 78. Cumulative Comparison of Replacement Strategies – Speed

Fuel burn benefits are greatly overestimated through immediate replacement over phased in replacement. For the current state of the art, the fuel savings are an additional 2.2% over the 44 year period for immediate replacement. Future technology is almost an additional 7% savings. The increase in the gap between the two strategies is solely due to technology introduction as the gains from only speed reduction are not that large in comparison to the overall benefits of technology.

NO_x impacts are much greater for the same reasons. An additional source is that within the initial operations set, there are aircraft that are used in multiple seat classes – an example is the Boeing 777 that is flown in seat classes 6 through 9. This trend is less obvious in the fuel burn data and much more so here as the additional NO_x savings are much higher than the fuel savings: 4.5% for the baseline and 17.0% with the future aircraft. Benefits are overwhelmingly large in the future because much of the fleet has now been replaced with aircraft utilizing advanced combustors that significantly reduce NO_x production.

Figure 78 indicates that operating cost trends are very similar to fuel burn and NO_x except that the overall benefits from immediate replacement continue to decrease more aggressively than the fuel burn or NO_x results based on the significant leveling out of the slow in the baseline case. Future technology does not see this trend as the fuel savings are much more significant overall. Additional savings are 0.7% for the base aircraft and 3.5% for future.

On the other hand, the total cost is negatively impacted with respect to the baseline technology results. Speed reduction immediately adds a number of aircraft into the fleet and requires a significant investment early but the differences in the two approaches have nearly reconciled by 2050; however, it is not enough to offset them completely and it pays a 0.1% penalty here. Future technology results drop by 1% as the gap in price between speed reduced aircraft is larger than for the baseline technology level. Additionally, the operating cost savings from technology provide a significant both to overall performance.

One shortcoming in this analysis is that all the aircraft operating the year before will likely not have been fully paid off. In one case, the operators would have to continue paying the capital costs associated with ownership of these unused aircraft, resulting in higher total cost in the years post-entry. Or the annual capital cost would have increased to make up for the future loss of revenue, resulting in higher total in the years leading up to the entry year. Either way, the total capital cost penalty has not been fully captured.

From an environmental perspective, complete replacement of respective vehicles looks like an appealing strategy. However, there are significant capital cost penalties that should be fully quantified to understand the impact. It should be noted that any evaluation with entire replacement of the associated vehicles in the fleet indicate that benefits represent a theoretical maximum and not something completely realizable.

6.3.4 Impact of Technology on Cruise Speed Reduction Effectiveness

Additionally, the minimum fuel results will be used to explore the impact that technology has on the impact of mission specifications. Much of the existing literature has focused on a fixed technology level that is the current state of the art. The need exists to understand how significant an influence that technology integration will have on the sensitivity of mission specification changes.

As the entry into service dates are different between the two technology levels, both will be given the same entry into service date to evaluate whether the cruise speed reduction is less effective on the next generation of aircraft. The future technology entry year was transitioned to be consistent with the baseline entry year (2020) and results are in Figure 79 for fuel burn, NO_x, operating cost, and total cost and a cumulative summary of results in Table 43. These numbers are with respect to the baseline fleet results.

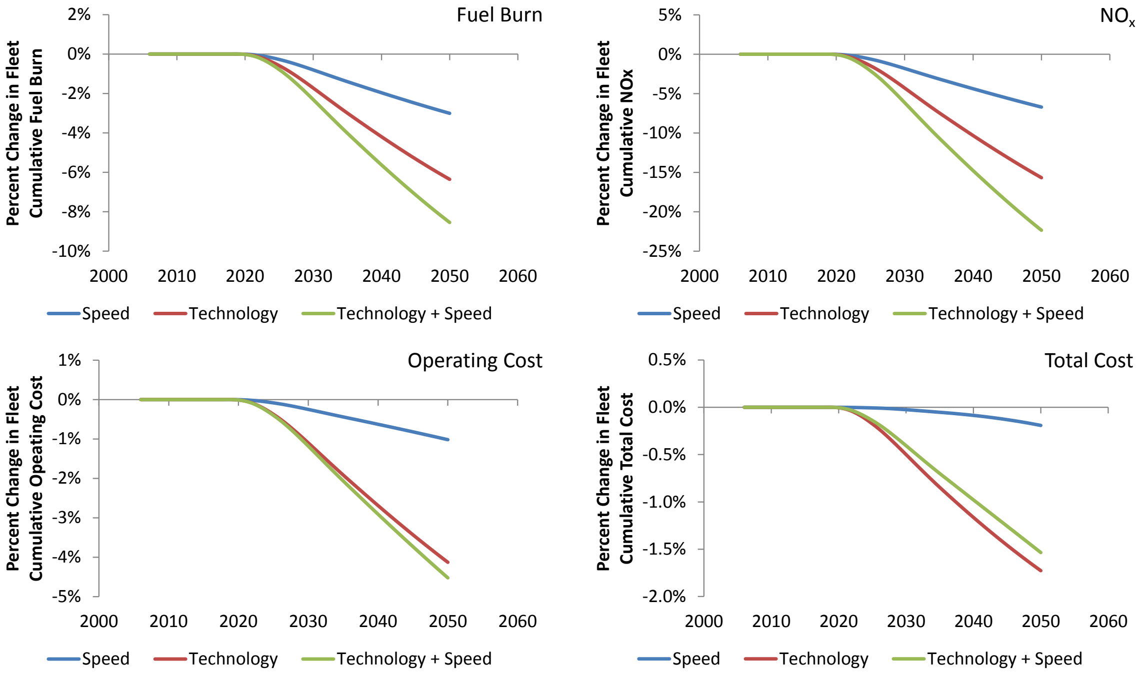


Figure 79. Comparison of Technology Impact on Speed Reduction Effectiveness

Table 43. Technology Impact on Cruise Speed Reduction Effectiveness

Scenario	Fuel Burn	NO_x	Operating Cost	Total Cost
Speed Reduction	-3.01%	-6.71%	-1.02%	-0.19%
Technology	-6.36%	-15.67%	-4.13%	-1.73%
Technology + Speed	-8.54% (-2.19%)	-22.33% (-6.67%)	-4.52% (-0.39%)	-1.53% (0.19%)

For the technology and speed reduction results, the percentage in the parentheses represents the difference between that case and technology alone. For all four metrics, the impact of technology has reduced the impact that speed reduction has on the fleet results. For fuel burn and operating cost, the impact is around 1.0% and 0.6% respectively. The impact of NO_x is negligible. Total cost's impact is a penalty of 0.4%.

6.4 Summary

This chapter has been focused on the impact that speed reduction has at both the vehicle and fleet levels. The representative aircraft were designed with minimizing fuel burn subject to a number of performance constraints. These results were then analyzed to determine suitability as to whether each aircraft should be considered at the fleet level. As all aircraft provided fuel burn savings, it was determined that they would all advance.

After a brief discussion of the baseline fleet forecasting results, speed reduction was assessed at the fleet level over multiple metrics – fuel burn, operating cost, and total cost (a combination of operating and capital cost). This analysis yielded insights into the importance of cruise speed variation on these metrics. An additional comparison was made with the vehicle optimal results to the fleet fuel burn optimal results to compare and assess their differences.

Further analysis was conducted to determine the importance of vehicle integration whether it be through fleet evolution where retirement of existing aircraft is considered and new aircraft are phased in over time in comparison to the practice of conducting a complete fleet replacement of the associated vehicles in a given year. Using the optimal fuel burn vehicles, it showed a pretty significant discrepancy on fuel burn if the complete replacement results are forecasted out.

Finally, an analysis was conducted to compare the impact that technology introduction has on speed reduction effectiveness. This required both technology levels to have the same entry into service years. Data clearly showed that the impact of speed reduction was reduced when future technology was applied. While the benefits are still significant with respect to fuel burn, it is worth noting that the operating cost savings are significantly lessened.

Based on this analysis, speed reduction is a viable fleet level strategy for reducing the environmental impact of aviation going forward. It does come at a price with respect to capital cost, as more aircraft will be required just to meet the projected growth and it offsets the cost savings from fuel savings. However, speed reduction will not be enough to reach carbon neutral growth on its own or with the aid of technology as demonstrated in Figure 80.

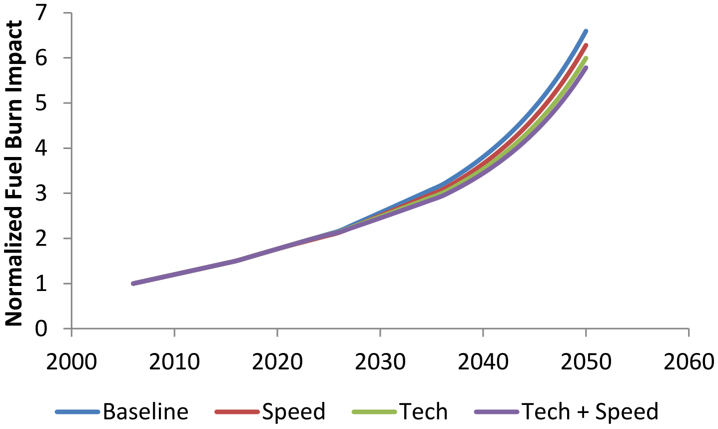


Figure 80. Normalized Impact of Speed Reduction on Fuel Burn

CHAPTER 7

RANGE REDUCTION SAMPLE PROBLEM

This chapter focuses on the impact of range reduction and is broken into four parts: vehicle impact, intermediate stop feasibility, fleet impact, and experimental results. The primary objective of the vehicle design section is to determine whether range reduction is beneficial to the respective seat classes and if so, how much. Intermediate stop feasibility is focused on understanding what ranges that intermediate stops should be used on in comparison to direct operations for aircraft going to the fleet analysis. The fleet impact section focuses on those aircraft that receive benefits and measures the impact to figures of merit. Within the fleet impact section is an assessment of the impact that ISO has on the fleet. Finally, the experimental results are discussed using the information gained from the fleet impact analysis.

7.1 Vehicle Design

The first step is to evaluate the respective mission specification change at the vehicle level.

7.1.1 Bounds of Mission Specification Changes

Range reduction was conducted in 5% steps from 100% design flight distance to 35% of the baseline design value to allow for one intermediate stop evaluation for ranges up to 50% and two intermediate stops down to 35%. Engine optimization was not necessary as the cruise speed was held constant and airflow was simply scaled. Bounds for range reduction are provided in Table 44. Initially, the plan was to include the regional jet and single aisle down to 35%; however neither showed benefits with just one stop such that analysis ended at 50% range reduction. As a reminder, the economic ranges for all aircraft are also included. The secondary economic range for the two larger aircraft is required as the short range variants will eventually be unable to fly those ranges.

Table 44. Range Reductions Boundaries and Economic Mission Values

Seat Class	Minimum Design Range (nm)	Baseline Design Range (nm)	Economic Range 1 (nm)	Economic Range 2 (nm)
Regional Jet	990.0	1,980	800	-
Single Aisle	1,480.0	2,960	900	-
Small Twin Aisle	2,072.0	5,920	1,800	-
Large Twin Aisle	2,635.5	7,530	4,000	2,500
Large Quad	2,471.0	7,060	4,400	2,400

7.1.2 Vehicle Design Results

All aircraft have been evaluated with fuel burn performance against the baseline aircraft. As the direct flight is no longer feasible due to design range reduction, the introduction of intermediate stops was modeled. If one stop shows significant benefit, then a second stop was also considered. Stops were assumed to be at the midpoint of the baseline design range for one stop and at a third of the baseline range for two stops with no excess distance flown. This means that for the large twin aisle, baseline mission performance comparison will be the fuel burn of two 3,765 nm flights for all aircraft variants to model one stop. For two stops, analysis would be the combined fuel burn of three 2,510 nm flights.

As with Chapter 6, discussion here will be limited to the regional jet and large twin aisle with the relevant information for the other seat classes in Appendix C.

7.1.2.1 Regional Jet

A simplified analysis using first principle analysis will be provided to walk through some of the implications of range reduction for the regional jet. This analysis will utilize the Breguet range equation and simplified weight and fuel burn build up methods using historical trends from Raymer.[97] The Breguet range equation is detailed in Chapter 2 but provided here as a reminder. The initial weight estimation is provided in Equation 23 where the crew and payload weights are defined in mission requirements, the fuel burn estimation W_f/W_0 is provided through Equation 24, and the empty weight estimation W_e/W_0 is provided in Equation 25. Table 45 contains fuel burn estimations for non-cruise portions of the mission profile.

$$R = \frac{V}{c_T}\frac{L}{D}\ln\frac{W_i}{W_i - W_f} \tag{22}$$

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - W_f/W_0 - W_e/W_0} \tag{23}$$

$$W_f/W_0 = 1.06 * \left(1 - \prod_{i}^{n}\frac{W_i}{W_{i-1}}\right) \tag{24}$$

$$W_e/W_0 = 1.02 * W_0^{-0.055} \tag{25}$$

Table 45. Fuel Burn Assumptions for Non-Cruise Segments

Segment	Fuel Burn Assumption
Warmup and Takeoff	0.970
Climb	0.975
Landing	0.995

Table 46. Breguet Range Input Assumptions

Design Range (nm)	Cruise Mach	Cruise Speed (kts)	Thrust Specific Fuel Consumption	Lift to Drag Ratio
1,980	0.80	461.1	0.670	16.0

For the range reduced aircraft, the cruise speed, engine thrust to weight ratio, and wing sweep and thickness parameters are all similar among designs such that those values in the Breguet range equation can be assumed constant. Additionally, this means that all the aerodynamic considerations presented in Chapter 6 are not necessary for this analysis and all benefits are due to wing weight changes. In Equation 26 all of the terms can be assumed constant as the cruise speed is fixed except for the wing area and vehicle weights. The second term is much more sensitive to changes in the vehicle design due to range reduction and results in a lighter wing.

$$W_{wing} = 4.22 * S_{wing} + 1.642 * 10^{-6} \frac{N_{ult} * b^3 * \sqrt{TOGW * ZFW} * (1 + 2\lambda)}{(t/c)_{avg} * (\cos \Lambda_{load})^2 * S_{wing}(1 + \lambda)} \tag{26}$$

Table 47. Wing Weight Estimation Assumptions and Results

Design Range (nm)	Λ_{load} (deg)	TOGW (lbs)	ZFW (lbs)	W_{wing} (lbs)	Percent Change
1,980	25.75	83,160	64,310	6,788	0%
1,881	25.75	80,785	63,082	6,702	-1%
1,782	25.75	78,515	61,906	6,620	-2%
1,683	25.75	76,345	60,779	6,542	-4%
1,584	25.75	74,267	59,699	6,466	-5%
1,485	25.75	72,277	58,663	6,393	-6%
1,386	25.75	70,369	57,669	6,322	-7%
1,287	25.75	68,539	56,713	6,254	-8%
1,188	25.75	66,782	55,794	6,189	-9%
1,089	25.75	65,094	54,911	6,126	-10%
990	25.75	63,472	54,060	6,064	-11%

The only variables are the cruise range, which is known, and the weight estimation results. After sizing the vehicle, then one can go back and determine the fuel burn for the one stop mission using the weights of the crew, payload, empty weight (determined from the previous sizing), and fuel burn (determined in the mission analysis for the one stop mission) to calculate the impact of intermediate stops in comparison to the direct mission. The gross weight guess used to calculate the fuel burn is then iterated on until the difference from the calculated weight and the guess is negligible.

Figure 81 compares the impact of range reduction and intermediate stops on fuel burn performance for the regional jet using this method. Note that overall, there are significant penalties to applying intermediate stops at the longer ranges while for the shortest range, there is a slight savings in fuel burn. This is due to the addition of another climb segment for what is a very short design mission. Increased efficiency at cruise is not enough to offset the penalty to fuel burn that is from climb performance. However, this method does have a number of shortcomings. The first is the lack of general performance constraints such as approach speed, takeoff field length, and other thrust requirements. This ultimately neglects some of the design constraints like a larger wing area being required to meet an approach speed. The second is that many of the parameters are assumed constant throughout the mission profile, something that is not reflective of actual mission performance. Although there are a number of techniques that one can take to improve the level of analysis with this approach, tools that are more flexible have been developed.

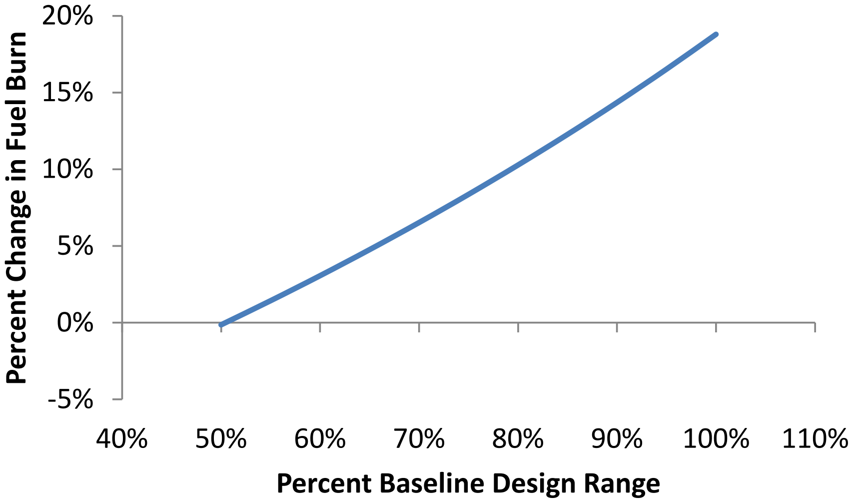


Figure 81. Simplified Fuel Burn Analysis of RJ Range Reduction

A more detailed analysis follows, which was conducted using the Environmental Design Space.

Range reduction provided no benefits to fuel burn for the baseline technology aircraft and the corresponding variants. Even though the variants become lighter with reductions in wing area and more efficient with increases of wing aspect ratio, these changes are not sufficient to provide any fuel savings for this seat class. This is demonstrated in Figure 82 by the blue line.

The penalties from intermediate stops are due to a significantly increased portion of the mission being operated in the climb phase of the mission. Climb is the least efficient part of the mission and given the baseline design range of the regional jet, the savings provided in cruise are not sufficient to offset the penalties from the additional climbs. This penalty occurs for all variants equally. Given that one stop did not provide any benefits, analysis was stopped at the 50% range variant and two stops analysis was not conducted.

The introduction of technology does provide fuel savings over the baseline regional jet's performance for the design mission. For the future technology aircraft with 100% range, the fuel savings from intermediate stops are 4.5% of the baseline aircraft. However, the same aircraft flying directly saves 10.2% of fuel in comparison (represented by the black dot). So although there is no penalty from using intermediate stops in comparison to the baseline aircraft performance, they do not provide any benefits when compared to direct operation of the aircraft. Additionally, the sensitivity of the future technology variants to range is less than that of the baseline aircraft – 1.7% savings between the 100% and 50% variants compared to the base's 2.5% savings.

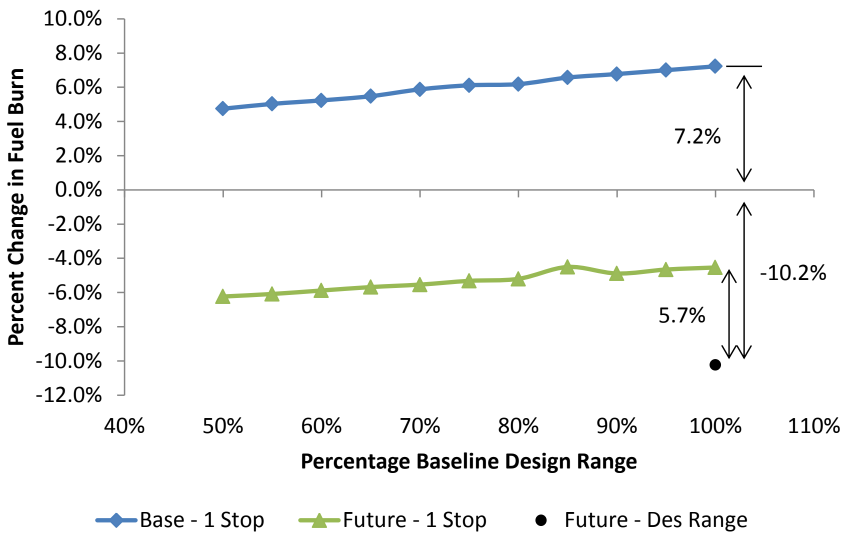


Figure 82. RJ Fuel Burn Impact of Range Reduction

In addition to fuel burn, an analysis of operating cost was conducted and results are in Figure 83. For both technology levels, intermediate stops penalize operating cost significantly in comparison to the baseline mission. Technology introduction does reduce the penalty but this is due only to the fuel savings. The landing fee from the additional cost is much more significant than those savings and ultimately penalizes this strategy. Assumptions for costs were operation in North America, $3/gallon fuel price, and crew costs during the stop were neglected, which would only increase the lack of cost desirability for this seat class.

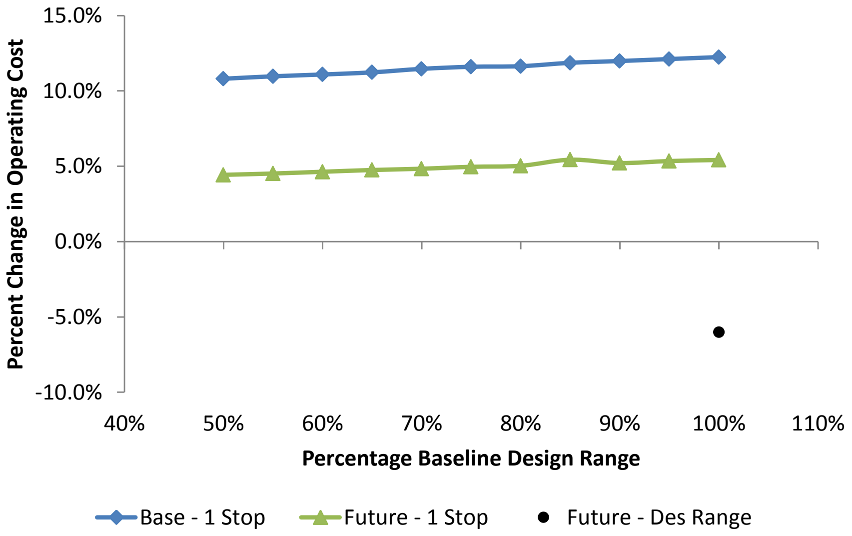


Figure 83. RJ Operating Cost Impact of Range Reduction

For the 800 nm economic mission, all of the range reduced designs show improvements but overall, the benefits are fairly small. This is shown by the red line in Figure 84. With respect to future technology, the meager benefits of the economic mission are slightly reduced. Operating cost trends are fairly similar with lesser savings due to fuel costs being only part of the operating costs.

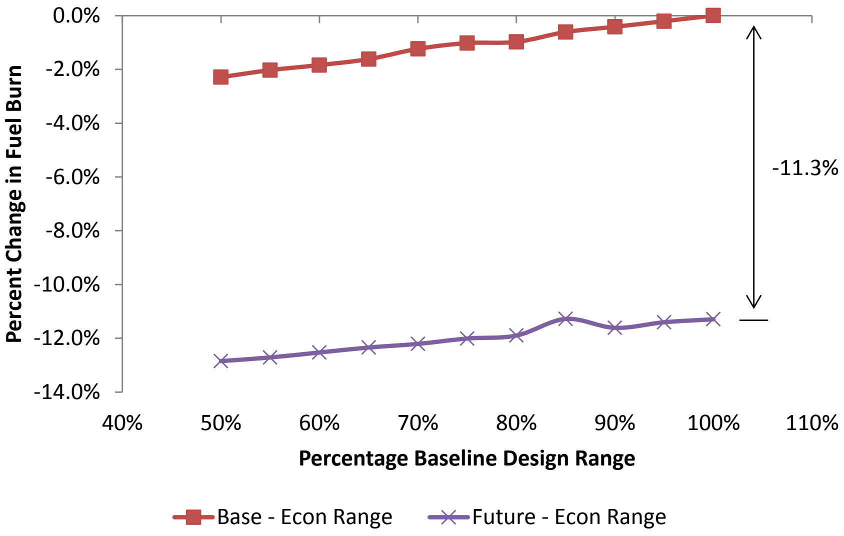


Figure 84. RJ Fuel Burn Impact of Range Reduction on Economic Missions

Based on these findings, the regional jet should not consider design range reduction and will not move on to the fleet analysis. These trends are consistent with the single aisle as well such that it will also not move on to fleet level analysis.

7.1.2.2 Large Twin Aisle

In comparison, the large twin aisle sees significant fuel burn benefits from the introduction of intermediate stops and range reduction. Figure 85 shows that one and two stops (blue and red respectively) are almost identical in terms of providing fuel savings for the design mission. Initially introducing intermediate stops provides 7.4% and 7.6% reductions for one and two stops. Continued reduction in design range provides significant benefits – 21.1% for 50% range with one stop and 23.4% for 35% range for two. The significance of the two strategies lying almost equally on top of each other indicates that there are additional cruise benefits towards utilizing two stops; however, the fuel burn penalties from the additional climb offsets those saving such that they are nearly identical to the one stop strategy. If the design range of the large twin aisle was significantly increased, this would likely result in two stops clearly outperforming one stop. Conversely, there is a clear separation between one and two stops for the small twin aisle, which has a much lower design range.

Vehicle design trends are largely the same as observed for the regional jet – wing area and thrust are reduced while wing aspect ratio rises. Even though the climb phases of the mission are inefficient, the legs for both the one and two stop strategies are significantly long enough to save enough fuel to offset the penalties from climb. This is true for both technology levels.

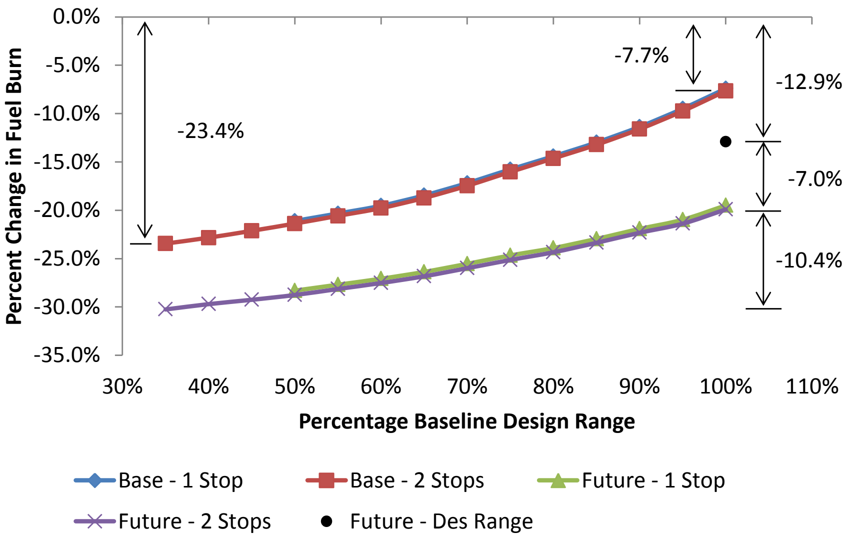


Figure 85. LTA Fuel Burn Impact of Range Reduction

Technology introduction provides a similar benefit to the baseline initially but it tapers off as the design range is reduced. This is demonstrated in Figure 85 for one stop in green and two stops in purple. It is worth noting that technology introduction results increases the fuel savings due to moving from one stop to two but the overall benefit from intermediate stops is reduced from technology infusion.

As seen with the regional jet, technology introduction also reduces the sensitivity of this seat class to range reduction. One stop provides 13.7% additional benefits as range is reduced for the baseline technology while the future aircraft gain only 8.8% savings. Two stops is reduced from 15.8% to 10.4% for the technology shift.

Given the significant fuel savings provided from intermediate stops, it is not a surprise to find that the operating costs are reduced for all range variants, even with the additional landing fees for both strategies. Figure 86 demonstrates that although two stops was slightly more beneficial with respect to fuel burn, the fee associated with the additional stop ultimately penalizes it such that one stop is clearly preferable. Technology introduction does not result in any changes to preference in intermediate stop cost effectiveness as both strategies provide cost savings. But similar to fuel burn, the operating cost sensitivities are reduced with technology being introduced.

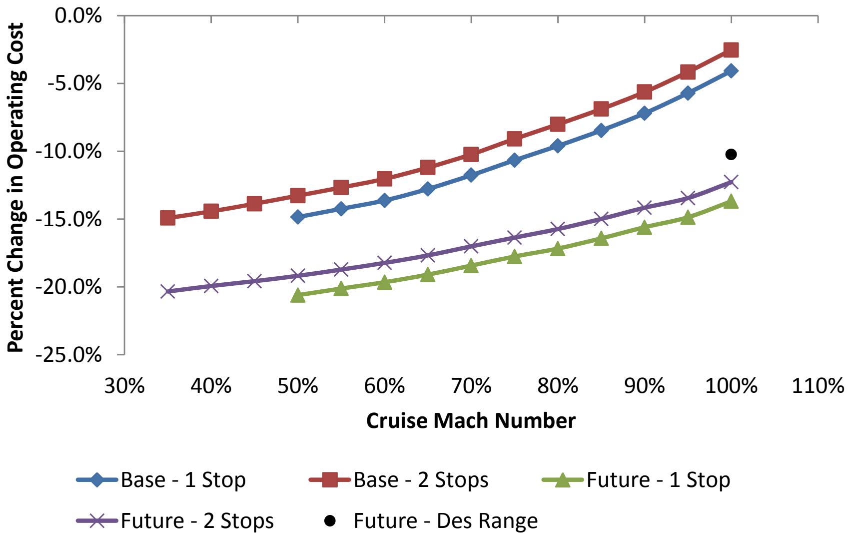


Figure 86. LTA Operating Cost Impact of Range Reduction

The large twin aircraft has two economic missions as the 4,000 nm mission would not be feasible for the 50% range and below variants. One observation is that the savings from range reduction impacts to both the 4,000 nm mission and the 2,500 nm are essentially the same. The long range economic mission is represented by the blue and green lines in Figure 87 for the baseline and future levels respectively. The short range economic mission is represented by the red and purple lines.

Operating cost trends look very similar to these results. The 4,000 nm economic mission maxes out at 10.6% savings for the baseline technology mission while the 2,500 nm economic mission maxes out at 12.7%. Future technology provides 10% savings to both missions for the initial design range and savings of 167% and 18.3% for the respective missions.

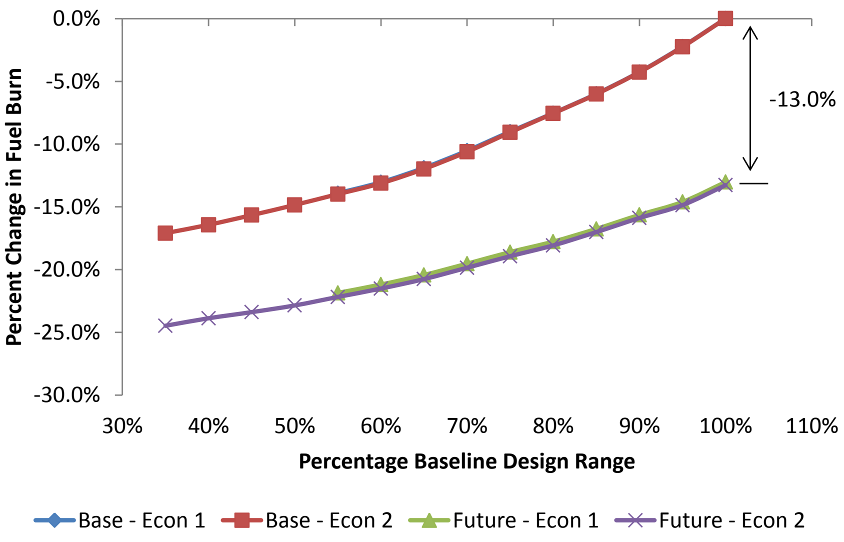


Figure 87. LTA Fuel Burn Impact of Range Reduction on Economic Missions

Given that range reduction has shown benefit, large twin moves on to fleet level analysis. The small twin and large quad aircraft show trends similar to the large twin and also move on to fleet level analysis. Recall that the regional jet and single aisle do not. The next step is to identify prospective mission ranges where the aircraft should fly a direct route as opposed to fly one or two intermediate stops.

7.2 Intermediate Stop Feasibility

With the small twin aisle, large twin aisle, and the large quad aircraft having been identified as benefiting from the usage of intermediate stops, the next step is to investigate under what flight distances each aircraft should be flown for a direct route, one stop, or two stops. Each design was evaluated at full passenger payload. An analysis for each aircraft design will be presented in a format similar to Figure 88. All percent change results are with respect to fuel burn for the 100% design range aircraft for the baseline technology level.

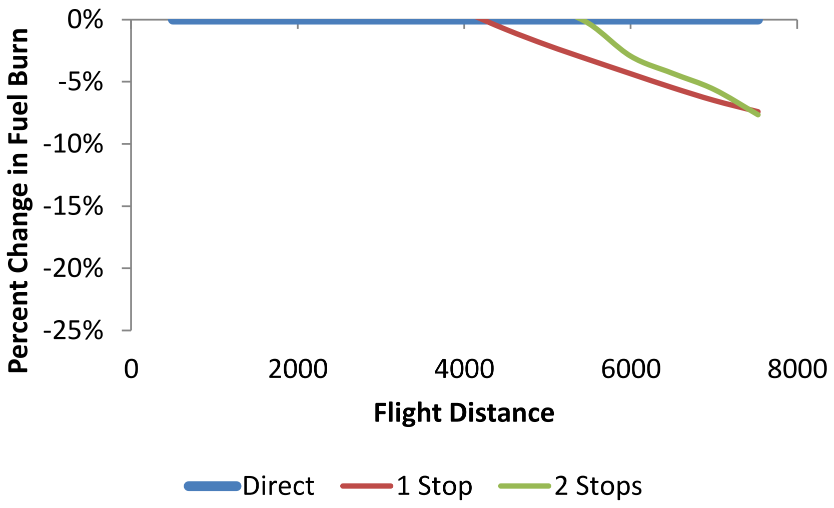


Figure 88. LTA Base 100% Intermediate Stop Feasibility Diagram

Figure 88 is for the 100% range large twin at the baseline technology such that the direct flight results are the reference condition and represented by the blue line. The red line represents the impact that introducing one stop halfway through the mission and the green line is for two stops, splitting the mission into thirds. In Figure 88, direct flights are advantageous for any operation below almost 4,200 nm as the one stop and two stop strategies result in increases in fuel burn over the direct mission. Any flight beyond this range saves fuel with the introduction of a single stop at the midpoint. At approximately 5,400 nm, two intermediate stops start to provide savings and eventually overtake one stop at around 7,200 nm. However, the savings are not that large – under 0.5%.

To provide additional comparison, the 35% range variant for the large twin is provided in Figure 89. Here, the direct flight provides significant benefits over the 100% range aircraft for applicable ranges. The one stop strategy does provide fuel savings in this region but not nearly as significantly as the direct flight. However once the maximum range is reached, the one stop strategy is required. There is a significant gap between the direct flight and one stop such that although fuel savings are still available over the reference condition, a significant amount of savings is lost due to the design range. This behavior also occurs in transition from one stop to two stops.

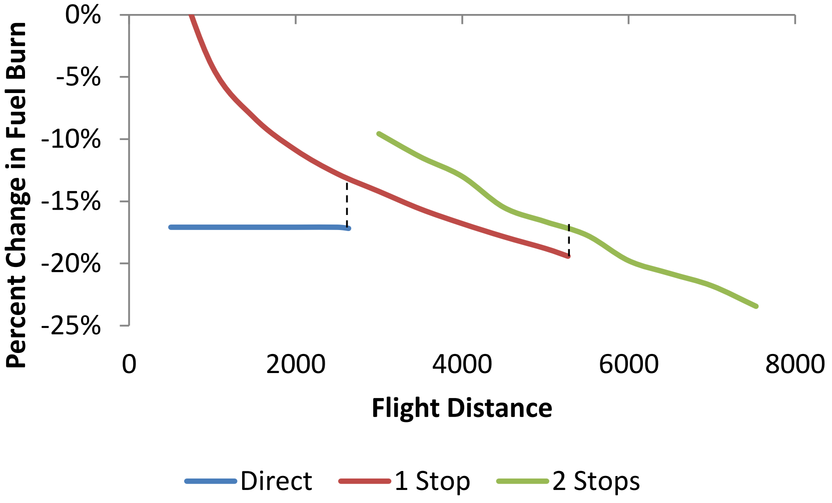


Figure 89. LTA Base 35% Intermediate Stop Feasibility Diagram

The remainder of this section is dedicated to exploring the impacts of the large twin aisle over each technology level. Trends for the small twin and large quad are similar and relevant figures are provided in Appendix C.

With respect to direct flights, range reduction provides benefits as it continues to be reduced; however, these benefits are marginally diminished for continued range reduction as shown in Table 48 for the 2,500 nm flight distance.

Table 48. Impact of Range Reduction on LTA at 2,500 nm

Range	Baseline Technology		Future Technology	
	Fuel Savings	**Marginal Savings**	**Fuel Savings**	**Marginal Savings**
100%	0.0%	-	-13.3%	-
95%	-2.2%	2.2%	-14.9%	1.6%
90%	-4.3%	2.0%	-15.9%	1.0%
85%	-6.0%	1.7%	-17.0%	1.1%
80%	-7.5%	1.5%	-18.1%	1.1%
75%	-9.1%	1.5%	-18.9%	0.9%
70%	-10.6%	1.5%	-19.8%	0.9%
65%	-12.0%	1.4%	-20.8%	0.9%
60%	-13.1%	1.1%	-21.5%	0.7%
55%	-13.9%	0.8%	-22.2%	0.7%
50%	-14.8%	0.9%	-22.8%	0.7%
45%	-15.7%	0.8%	-23.4%	0.5%
40%	-16.4%	0.8%	-23.9%	0.5%
35%	-17.1%	0.7%	-24.5%	0.6%

Figure 90 demonstrates that transition to one stop from direct flights remains fairly constant through the 55% design range aircraft. This distance is approximately 4,100 nm and just over half of the baseline design range. Further reduction result in a discontinuity between the direct flight and one stop operations as the two no longer intersect. This occurs due to reductions in range being more significant than the fuel savings from operating in ISO. It is preferable that one designs an aircraft that does not have these discontinuities as it provides smooth fuel consumption within operating ranges. Otherwise, the result is penalty to fuel burn due to design range reduction. Although the gap at 50% range is not that large, the gap for the 35-45% aircraft increases fuel burn by 4-5% and this suggests that these aircraft would also be disruptive to an airline.

The biggest difference overall though is the viability of two stop operations in comparison to a single stop. Unfortunately, the two stop strategy is only really viable for the design range for all aircraft of 50% range or higher but the fuel savings are 0.1-0.2%, which isn’t going to be enough to truly justify this type of operations. For the 35-45% aircraft, two stops is the only viable strategy for the only range flights. The savings from a two stop 35% aircraft vs a one stop 50% is 23.4% to 21.1% fuel burn savings. The 2.3% difference is pretty significant but this is also only for the 7,530 design range. At 6,000 nm, the difference between the two is 19.8% vs 18.5% resulting in a much smaller gap. Additionally, the operating costs of two stops suggest that one stop is still a preferable strategy.

Technology reduces both the impact of range reduction as well as the transition point for one stop operations in Figure 91. This is due to technology ultimately improving efficiency throughout the mission, including climb. Viability of two stops is not significantly changed. Based on this analysis, it would indicate that aircraft designed for less than 50% of the baseline range are not worth pursuing as well as a two stop strategy not providing enough benefits over the flight regime for this aircraft.

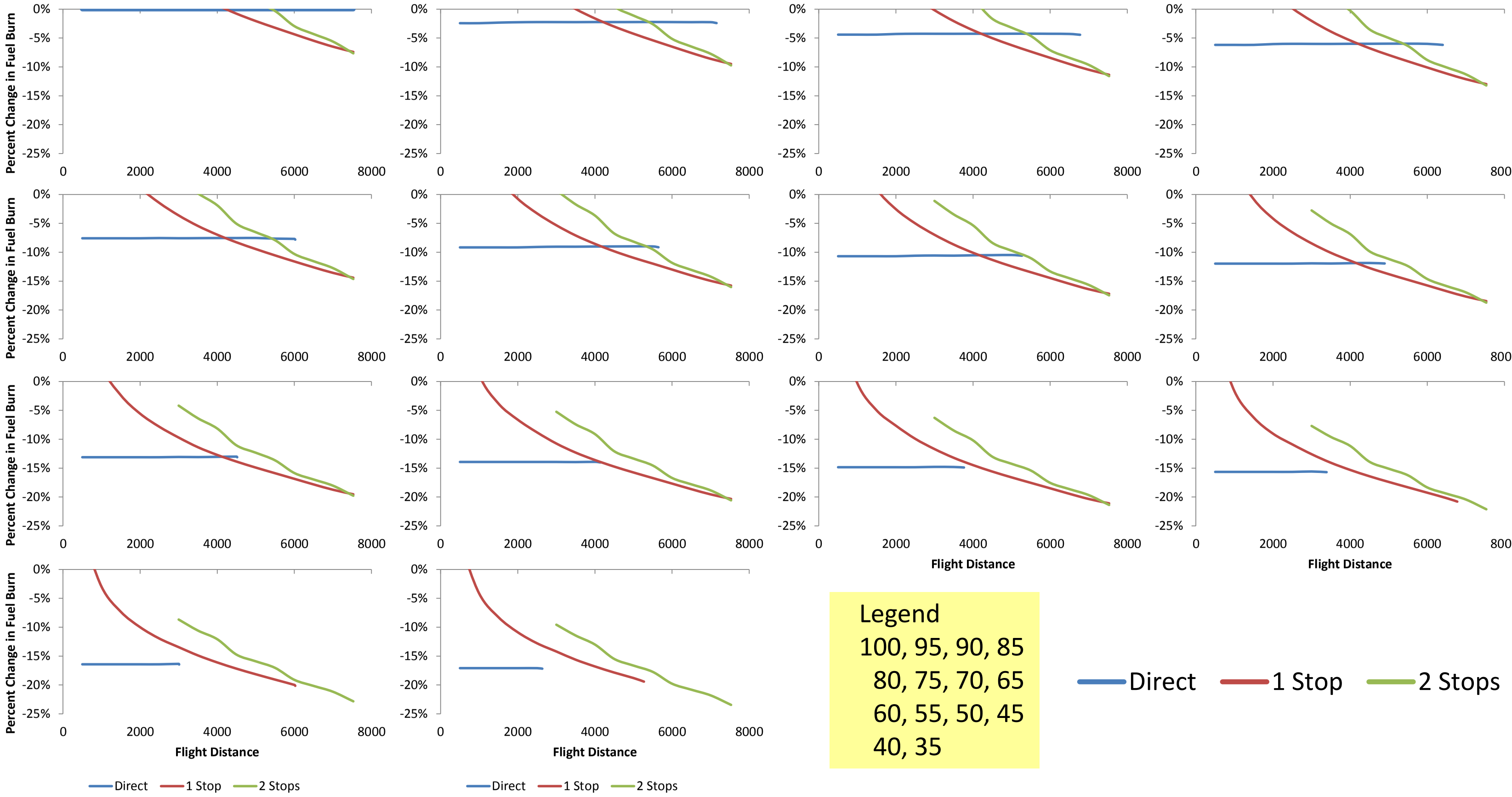


Figure 90. Intermediate Stop Feasibility for LTA Baseline Technology

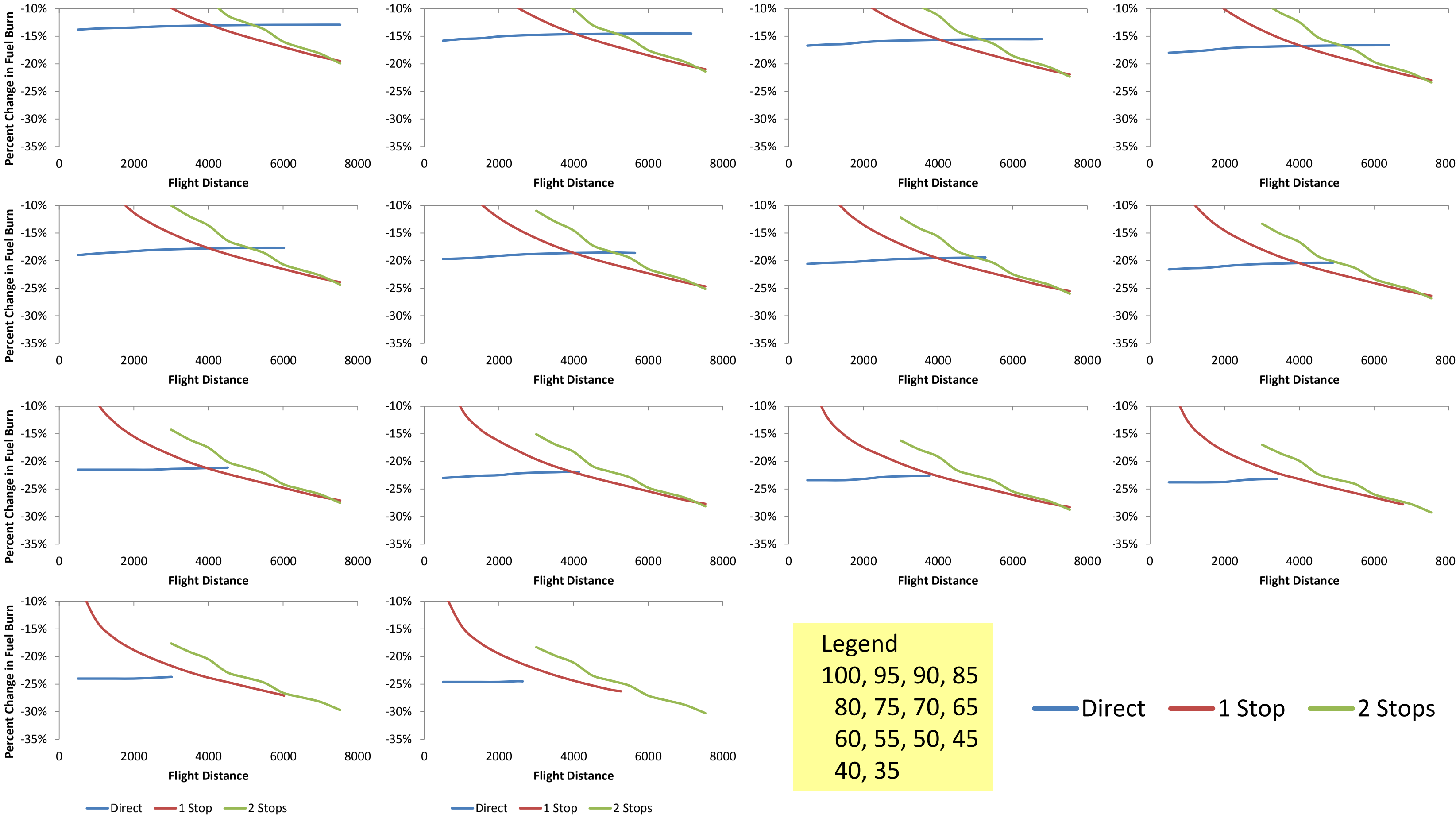


Figure 91. Intermediate Stop Feasibility for LTA Future Technology

7.3 Fleet Analysis of Range Reduction

The impact of range reduction will need to first be measured with respect to the introduction of intermediate stops to isolate their impact on the fleet against the impact that the reduced range variants will have on the fleet in conjunction with intermediate stops. The general fleet growth results are in Chapter 6. This section will first address the impacts that intermediate stops have and then look at the reduced range variants for the large twin aisle.

7.3.1 Impacts of Intermediate Stops

The only way to model intermediate stops is to modify the initial operations set. This will result in their introduction at the initial year of 2006 as opposed to the planned entry years of 2020 for the baseline technology level and 2024 for the future. Therefore, the approach will be to use results from no action up to each respective entry year and then use the intermediate stop results from that year to 2050. This will result in a sudden change for all metrics. Noise will also only be addressed in the final results.

7.3.1.1 Baseline

The initial focus here will be on the change in number of operations as intermediate stops effectively double the number of operations for the flights adopting this strategy. The percent change in number of total fleet operations for all three aircraft is provided in Figure 92. While 0.5% or 1.5% might not sound like a big deal, it corresponds to approximately 74,700, 27,000, and 17,700 operations for the small twin, large twin, and large quad respectively in year 2020. Forecasted forward, the smaller two aircraft operation percentage decreases but this is due the growth in other seat classes. In 2050, the total increase in operations from 2020-2050 due to intermediate stops is approximately 314,000, 137,500, and 185,800 for the respective aircraft. These annual numbers are from the datum six weeks such that 52 week numbers can be scaled up.

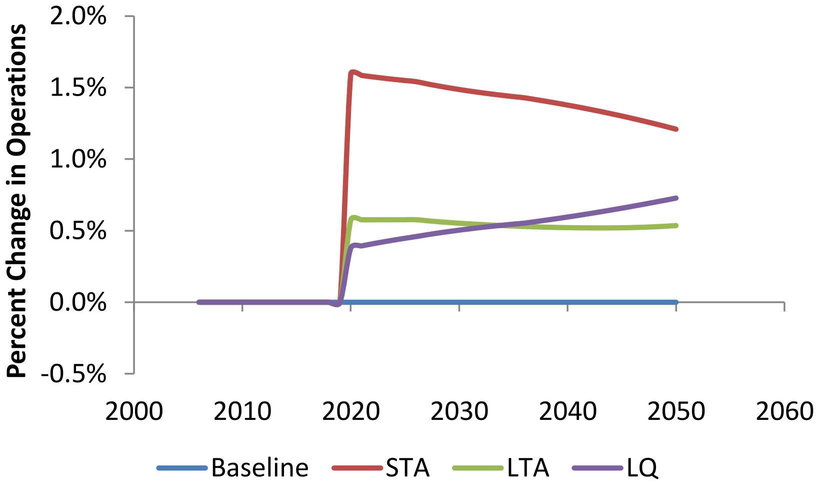


Figure 92. Impact of Intermediate Stops on Operations

With respect to safety, the increase in accidents that occur due to intermediate stops are identical to that of the increase in operations if one uses the safety approach that is based on the rate per million operations. When using the rate that is based on flight hours, the impact of intermediate stops become somewhat smaller and is provided in Figure 93. With this method, the large quad grows significantly and eventually outpaces the small twin results due its significantly longer flight times.

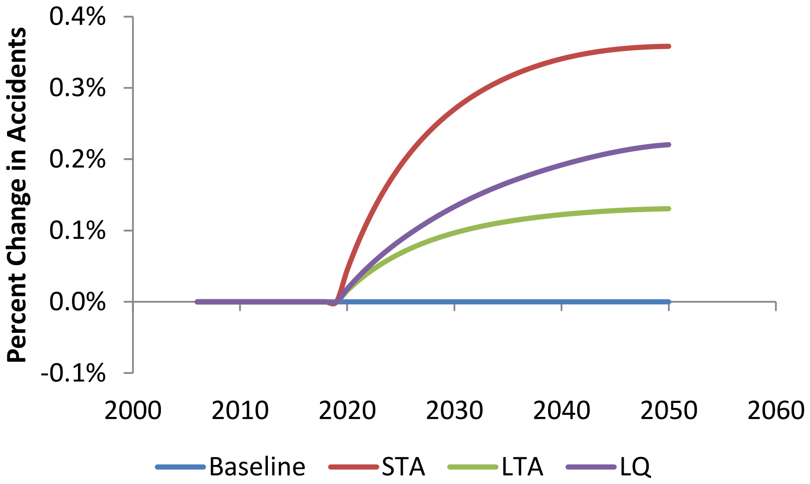


Figure 93. Impact of Intermediate Stops on Accidents

Regarding fuel consumption, intermediate stops alone are not overwhelming significant in terms of cumulative savings – 0.22%, 0.09%, and 0.22% overall. This is not substantially large overall but intermediate stops impact only a portion of an individual seat class' operations such that the overall margin is lower. Additionally, the total number of flights would also drive how significant the benefits are overall. A comparison of the percentages to totals is included in Table 49.

Table 49. Fuel Burn Impacts from Intermediate Stops – Baseline

Seat Class	Cumulative Fuel Savings (kg)
Small Twin	4.9B
Large Twin	1.9B
Large Quad	4.8B

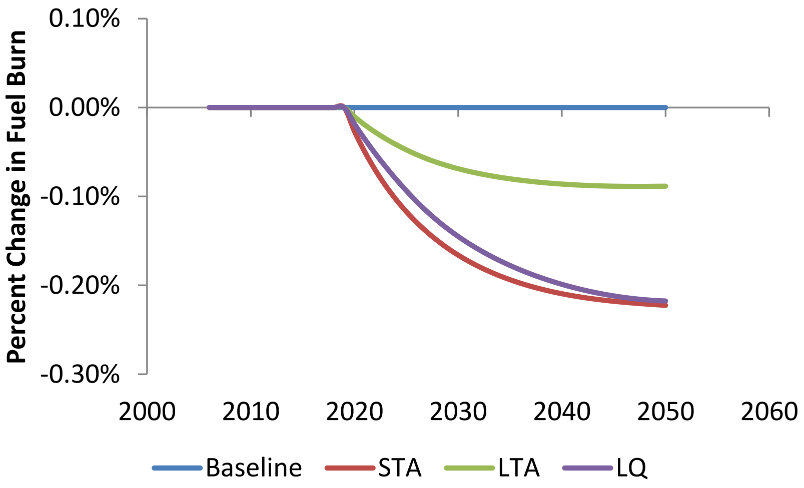


Figure 94. Impact of Intermediate Stops on Baseline Fuel Burn

The NO_x impact is overly similar to fuel burn with the only real difference being that all three aircraft provide similar levels of reduction. Given that NO_x production is also tied to fuel burn, this outcome is not surprising.

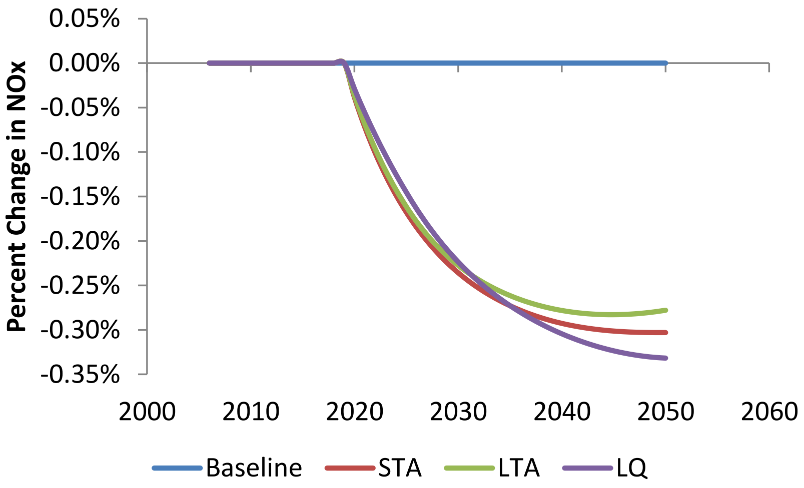


Figure 95. Impact of Intermediate Stops on Baseline NO_x

The introduction of intermediate stops has a significant impact on both the number of aircraft and the operating costs in the fleet. As some of the intermediate stop locations do not lie along the direct flight path, there will be the introduction of excess flight distance, which requires more flight time and increases the number of aircraft required. This impact is shown in Figure 96. Like the operations impact, the percent change is not that significant but it corresponds to an additional 95 small twin, 34 large twin, and 82 large quad aircraft for each seat class in 2020. This also clearly shows where the largest driver in fleet growth is as the large quad shows significant exponential growth in the replacement aircraft total by 2050 – 269 STA, 117 LTA, and 485 LQ.

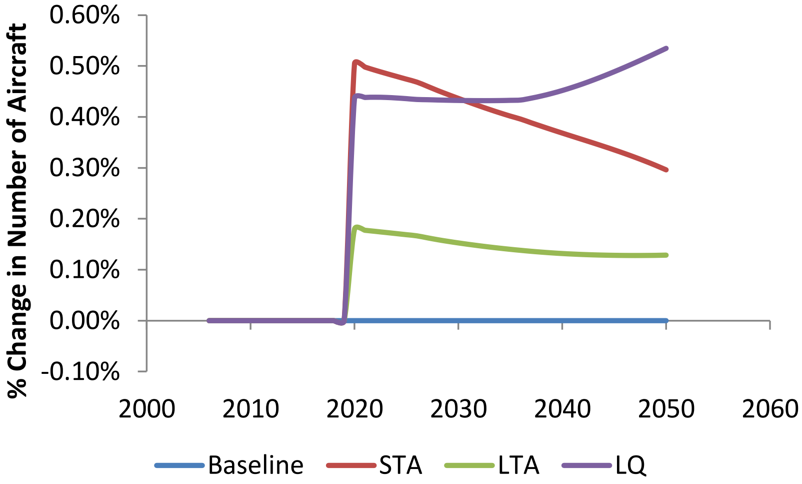


Figure 96. Impact of Intermediate Stops on Baseline Number of Aircraft

These extra aircraft impact the capital costs of the fleet and this impact is in Figure 97. The biggest impact is to the large quad but impacts of the small twin and large twin are not insignificant. The cumulative increase in capital cost at 2050 is $4.9B, $2.6B, and $10.3B for each seat class respectively. Keep in mind that these numbers are representative of the datum six weeks of operations and not the entire year.

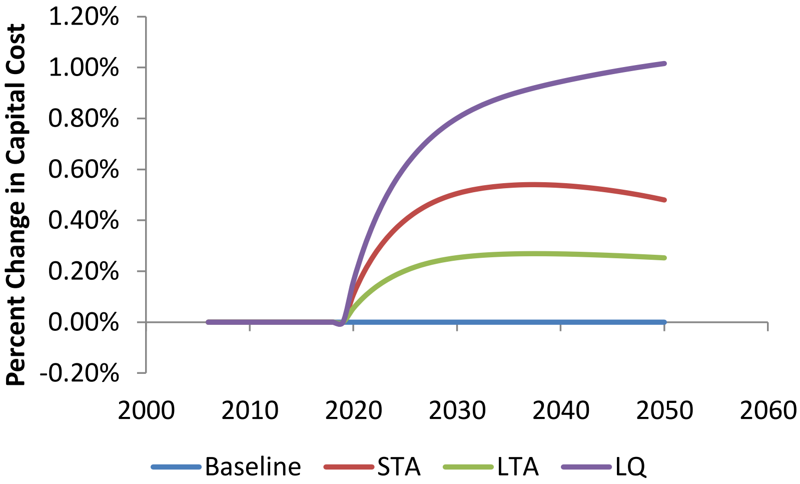


Figure 97. Impact of Intermediate Stops on Baseline Capital Cost

As previously mentioned, additional flight time is incurred from using intermediate stops. This has a direct impact on crew and maintenance costs as they are charged in hourly rates by flight hours. The excess distance will have an impact on the routing fees. And the intermediate stop will come with landing fees for each airport. So although there is fuel savings by operating in this fashion, Figure 98 demonstrates the other costs will ultimately offset the fuel cost savings. By 2050, this means a total increase of $4.8B, $2.4B, and $1.9B for each seat class. Again, this is over the datum six weeks.

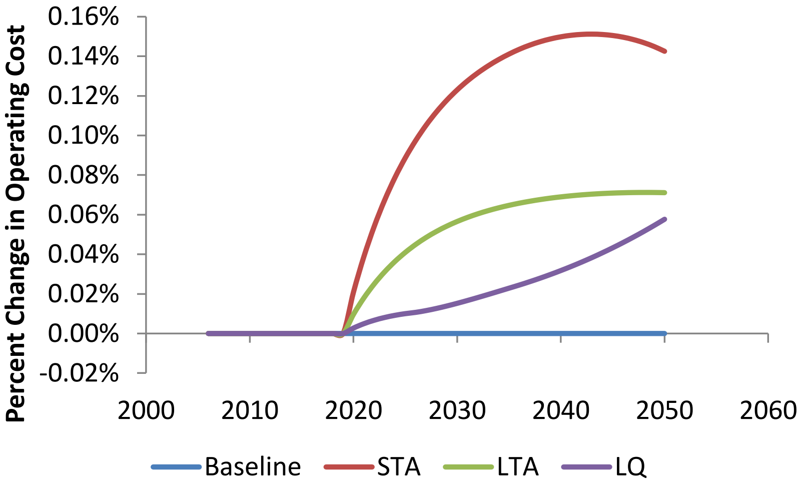


Figure 98. Impact of Intermediate Stops on Baseline Operating Cost

The fleet total operating costs are included in Figure 99, combining the results of the previous two figures. While the trends of the small and large twin aircraft are generally the same, their magnitudes have increased from the operating costs chart in Figure 98. The large quad shows a significant change in trend and this is from the significant increase in capital costs due to introducing intermediate stops.

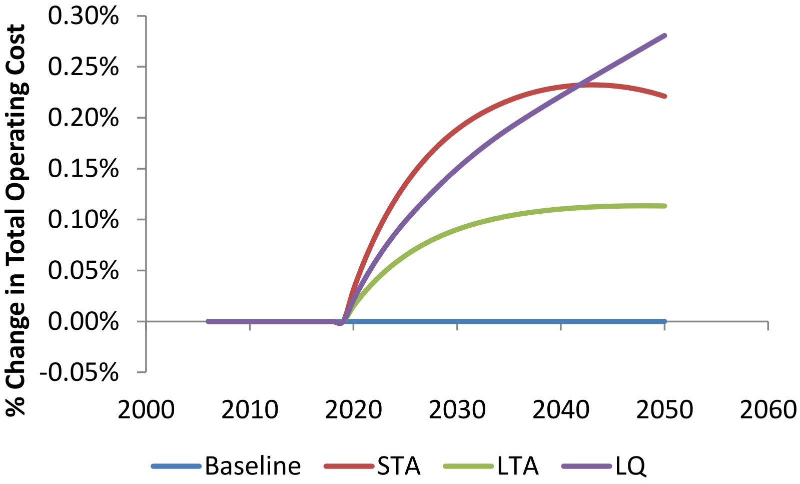


Figure 99. Impact of Intermediate Stops on Baseline Total Cost

7.3.1.2 Future

Operations growth is identical even with the introduction of the technology package as operations growth is dependent on the forecast used, not the aircraft technology level. The only change from Figure 92 is that intermediate stops begin in 2024 instead of 2020. Therefore, this figure will not be provided. The remaining figures for this section are with respect to the future technology baseline results.

Fuel burn trends are similar to that of the no action future technology results. The overall cumulative benefits aren’t that large and pretty hard to distinguish in Figure 100. Table 50 compares the impact of future technology to the intermediate stop results for each seat class. Note that the overall impact is quite small when compared to the benefits of future technology and the savings are smaller than those shown in Table 49.

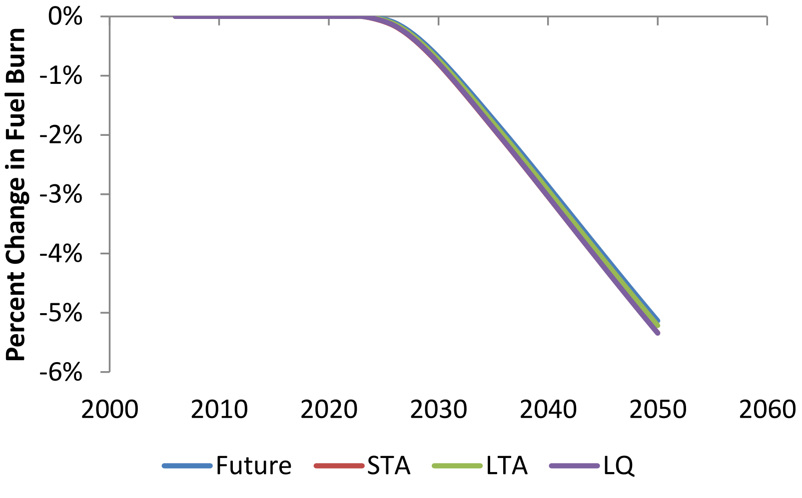


Figure 100. Impact of Intermediate Stops on Future Fuel Burn

Table 50. Fuel Burn Impacts from Intermediate Stops – Future

Seat Class	Cumulative Fuel Savings (kg)	Delta from Future (kg)
Small Twin	117.8B	4.5B
Large Twin	115.0B	1.8B
Large Quad	117.8B	4.6B

NO_x doesn't perform similar to fuel burn here but that is due to the introduction of technology significantly reducing NO_x for most seat classes.

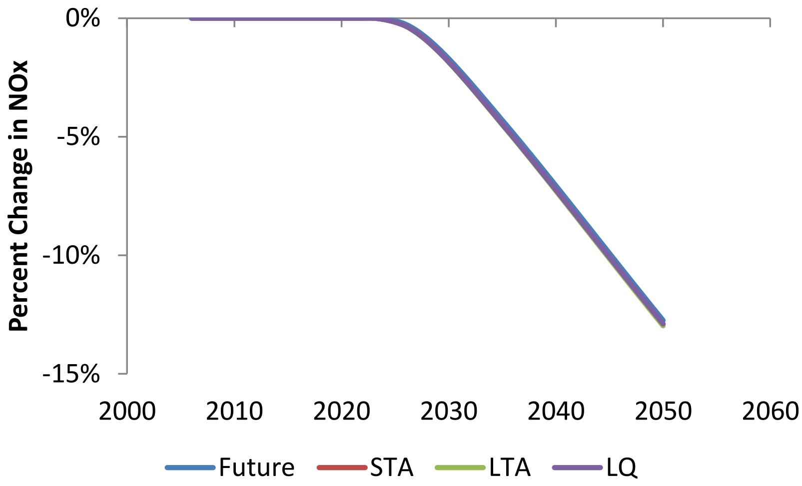


Figure 101. Impact of Intermediate Stops on Future NO_x

As the cruise speed is fixed, technology changes do not impact the number of aircraft required. Therefore, the impact is the same as the baseline except for the 2024 entry into service changes. Results are identical to Figure 96 except for the 2024 entry into service date.

Capital cost trends are fairly similar even with the significant increase in aircraft price from technology introduction, which adds $51.8B to total capital costs over the timeframe. The large quad continues to provide substantial increases in costs. The breakdown over the three aircraft is an additional \$4.7B, \$2.5B, and \$10.4B by 2050. Again, remember that all four capital cost values are for the datum six weeks summed over the timeframe.

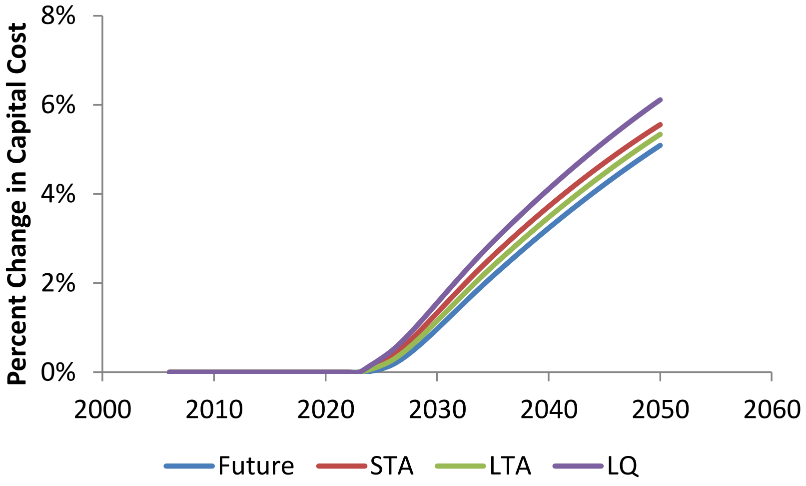


Figure 102. Impact of Intermediate Stops on Future Capital Cost

Operating cost is generally unaffected as technology introduction does not change four of the five components: crew rates, maintenance rates, route fees, and landing fees. While fuel savings occur, fuel costs are also not as significant a part of these costs because technology introduction reduces overall fleet fuel burn significantly. Cumulative benefits of technology make up \$111.4B while intermediate stops represent a penalty to that number of \$4.3B, \$2.2B, and \$1.8B for each seat class respectively.

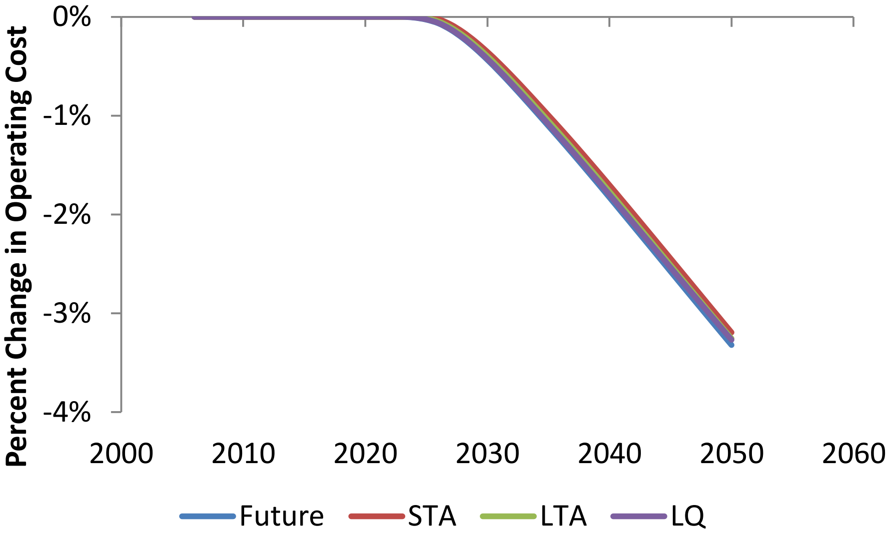


Figure 103. Impact of Intermediate Stops on Future Operating Cost

The combined cost displays similar trends to the prior case as well. This is not surprising since the operating cost and capital cost elements showed similar trends to their baseline technology counterparts. While utilizing intermediate stops with future technology still provides cost savings, there is a penalty in comparison to no action.

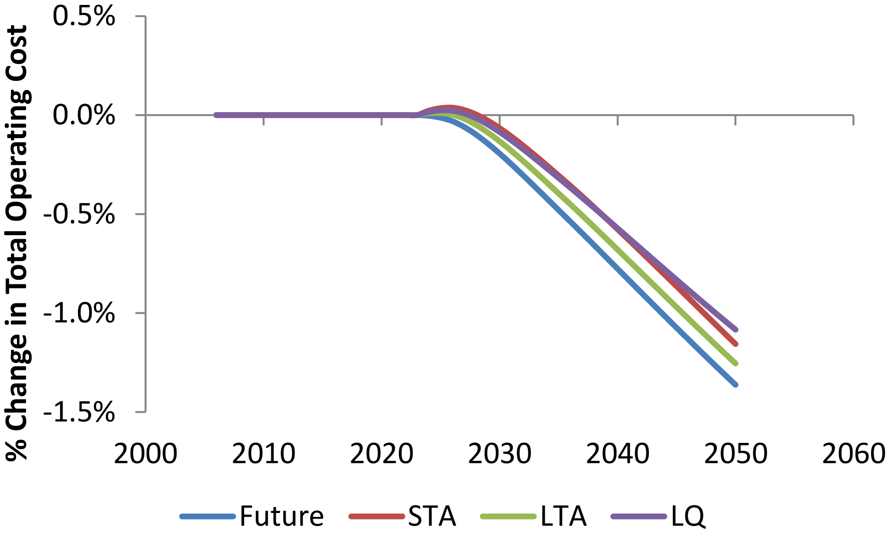


Figure 104. Impact of Intermediate Stops on Future Total Cost

7.3.2 Impact of Reduced Range Variants

Results in this section will focus on the large twin aisle and those for the small twin and large quad can be found in Appendix C. In the following figures, the yellow dot represents the current approach of having one fixed range aircraft while the green dot represents the variant that minimizes the metric of interest. Contours are presented as variations in design range and short range variant distribution. The latter was varied from a 50%-50% split to 100%-0% in 10% increments of the variants below the range threshold being the short range aircraft or the long range aircraft. For operations beyond the threshold, they were only the long range variant.

The impact range reduction has on the fleet for the large twin is quite significant at both technology levels. Figure 105 demonstrates that the reducing range to the 60% variant has a 1.1% reduction in cumulative fuel burn at baseline technology levels over the fixed variant results with intermediate stops. Future technology results are reduced to 0.6% fuel savings for the same variant. This is not particularly surprising as technology adoption takes away some level of the overall potential benefits, which was also observed at the vehicle level.

Range reduction is a much greater driver in terms of overall fleet results but as the variant moves towards shorter range variants, the impact begins to lessen. This is caused by the range threshold of these variants encountering the largest chunk of operations and it becomes a trade of increased fuel savings for fewer overall operations. For ranges like 90% and 80%, this is not as big a deal as the contour is quite steep in those regions but this behavior really begins to appear in the 60% and 70% aircraft. This behavior is also more pronounced at the more equitable SR variant distribution levels such as 70%-30% and lower.

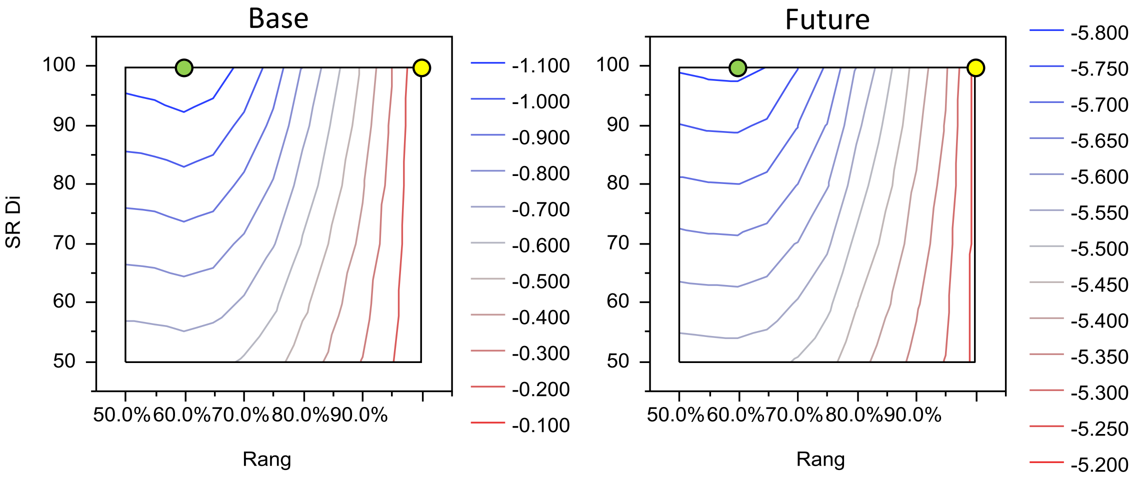


Figure 105. Fuel Burn Sensitivity for the LTA under Range Reduction

NO_x trends are different from fuel burn as continued reduction in range provides increased savings. Minimum NO_x occurs at the 50% range variant for both technology levels but the magnitude is significantly different. At the baseline level, the savings attributed to range reduction are 0.9% while future technology benefits are 0.3%. This is due to the significant improvements that have already occurred due to technology infusion and range reduction has much less influence.

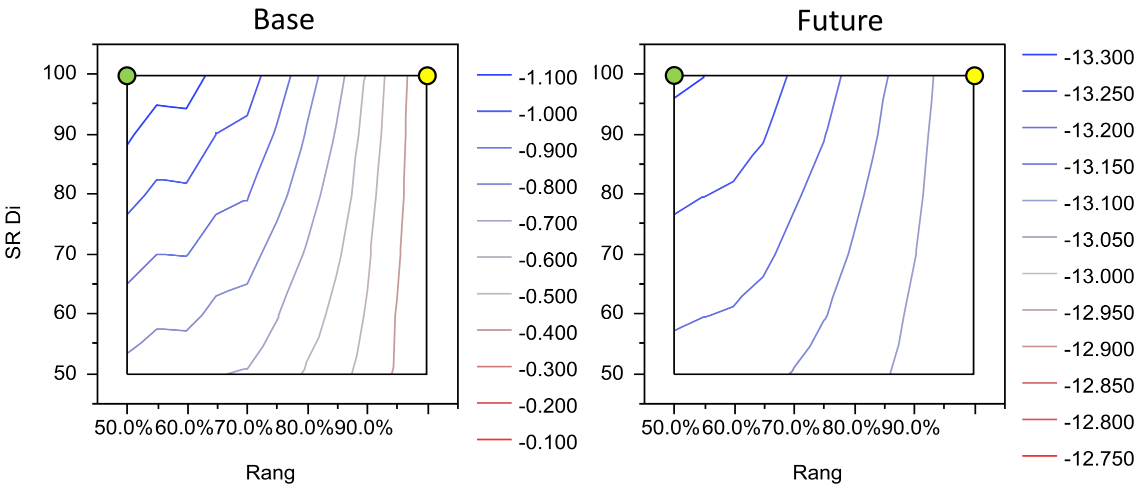


Figure 106. NO_x Sensitivity for the LTA under Range Reduction

Operating cost trends are similar to the fuel burn such that the variants with the minimum values are the same. This is due to operating cost components like crew, maintenance, landing, and route fees being constant among all the variants such that fuel burn is the only means to provide any influence. At baseline technology levels, there are 0.70% savings over one long range aircraft while savings of 0.40% are possible for future technology. This behavior was also observed at the vehicle level. Variant distribution has a significant influence here as well as more short range variants provide greater overall fuel savings and therefore operating cost savings.

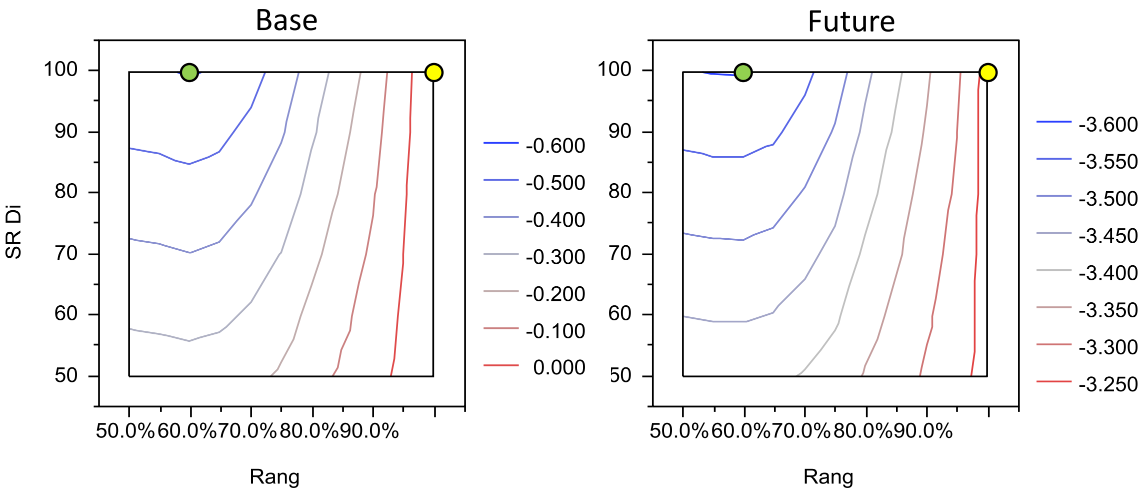


Figure 107. Operating Cost Sensitivity for the LTA under Range Reduction

Capital cost for the baseline case is minimized for the 50% design range variant. This is not particularly surprising as aircraft price is a function of vehicle weight and the vehicle weight is minimized at the lowest design range. With the addition of future technology, the overall capital cost for the fleet significantly increases with respect to the baseline but capital cost is minimized at the 55% range aircraft. This difference is attributed to differences in the range threshold for the short range variant as this value will determine the number of operations that are viable for that aircraft. Variant distribution has a significant influence here as well as more short range variants provide greater overall capital cost savings.

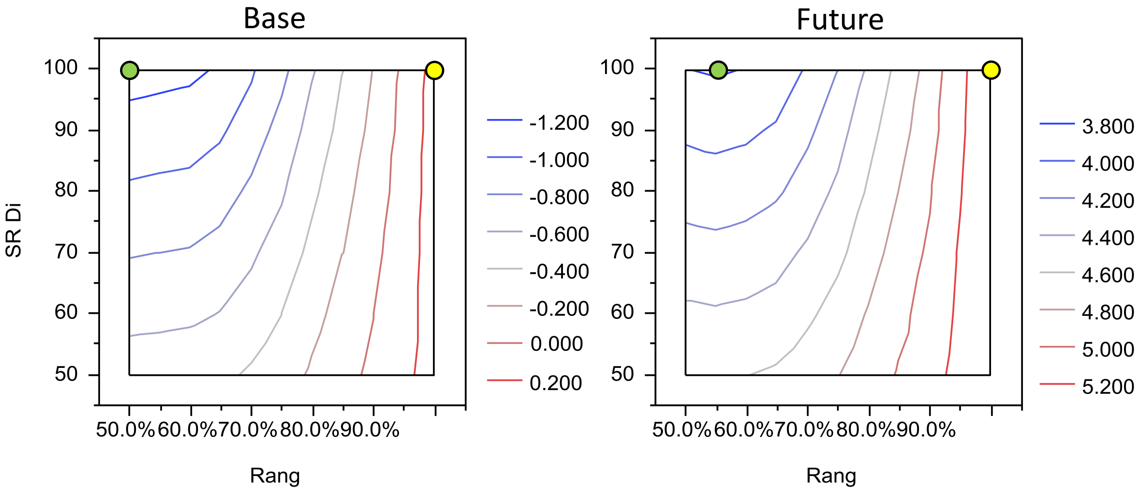


Figure 108. Capital Cost Sensitivity for the LTA under Range Reduction

Total cost minimum location is not influenced by the capital cost trends under the baseline technology level such that it remains at the same 60% variant. The overall fuel burn savings are larger than the capital cost savings; however, the 50% and 55% range aircraft are very close in terms of performance. Future technology shifts to the 55% variant as the fuel savings from greater range reduction are not enough to offset the capital costs from shorter range aircraft. But again, the nearby variants are also incredibly close as well. The sensitivity to variant distribution is carried over as well as both operating and capital costs are sensitive to its influence.

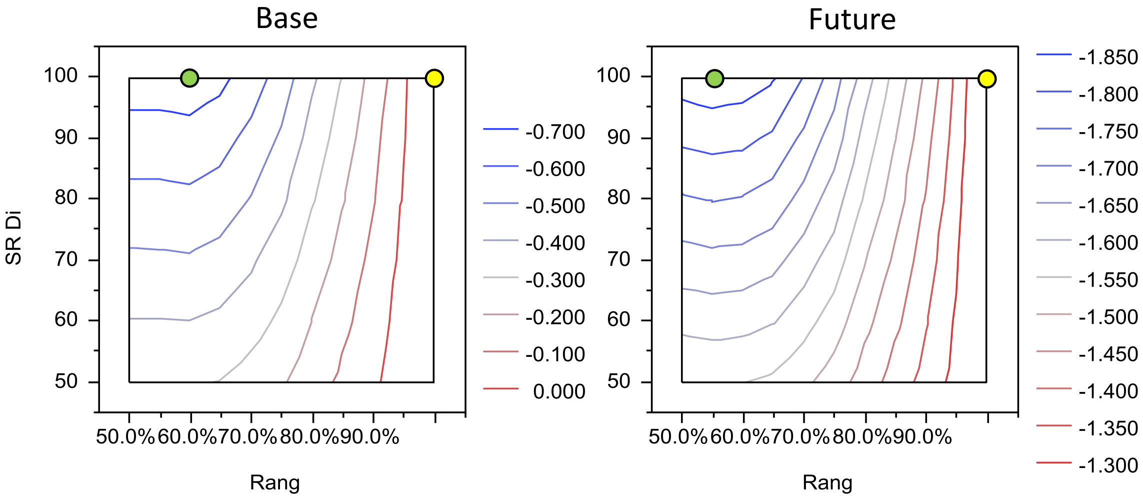


Figure 109. Total Cost Sensitivity for the LTA under Range Reduction

With the fleet impact of range reduction completed, the final step is to address the hypotheses and experimental results.

7.4 Experimental Results

This discussion will be in order as presented in Chapter 6: influence of metrics on optimal variants, comparisons of vehicle and fleet level optimal variants, the influence of replacement strategies, and impact technology has on the sensitivity of range reduction.

7.4.1 Influence of Different Fleet Metrics on Best Ranges

Fleet analysis results have identified which range reduced variants minimize fuel burn, operating cost, and total cost and these are located in Table 51. It is worth noting that the 100%-0% SR-LR variant distribution always resulted in the fleet total minimum therefore the 70%-30% distribution is also provided to represent more realistic fleet distribution if range reduction was adopted.

Table 51. Comparison of SR Variants Corresponding to Different Metrics

SR-LR Dist	**Seat Class**	**Baseline Technology**			**Future Technology**		
		Min Fuel	**Min Ops Cost**	**Min Total Cost**	**Min Fuel**	**Min Ops Cost**	**Min Total Cost**
100%-0%	Small Twin Aisle	55%	55%	55%	55%	55%	55%
	Large Twin Aisle	60%	60%	60%	60%	60%	55%
	Large Quad	50%	50%	50%	50%	50%	50%
70%-30%	Small Twin Aisle	55%	55%	55%	55%	55%	55%
	Large Twin Aisle	60%	60%	60%	60%	60%	55%
	Large Quad	50%	50%	50%	50%	50%	50%

The first observation is that for the small twin and large quad, changing metrics provides no impact to what the associated optimal aircraft is. The large twin only experiences a change in selected aircraft when considering capital cost as a part of total cost for future technology only. At first, this was surprising as there was an expectation that different metrics should still yield different vehicles. However in thinking about each of the metrics, the explanation is fairly simple.

When considering operating cost, range reduction does not impact crew or maintenance costs as the cruise speed is fixed so it only impacts fuel burn, route fees, and landing fees. Intermediate stops provides a fuel savings on its own while slightly penalizing the other cost elements but the addition of the range reduced aircraft provides significant fuel savings compared to the now fixed crew, maintenance, route, and landing fees with intermediate stops.

With the additional of capital cost, the optimal aircraft for total cost was largely unchanged except for the large twin with future technology and even then it was a single step reduction. Even though the minimum capital cost results always favor the 50% range variant aircraft, the fuel savings from the larger variants is large enough to offset the capital cost increases from utilizing a longer range variant.

For comparison purposes, the cumulative impact of range reduction with respect to the different metrics is provided in Figure 110 for both technology levels. Results are with respect to the baseline results. Intermediate stops have also been included to compare their impacts with respect to the scenarios and the baseline. These results are not as interesting as their speed reduction counterparts as the minimum aircraft is the same for two of the three scenarios. And with respect to total cost, the difference lies in the hundredths of percent for both technology levels.

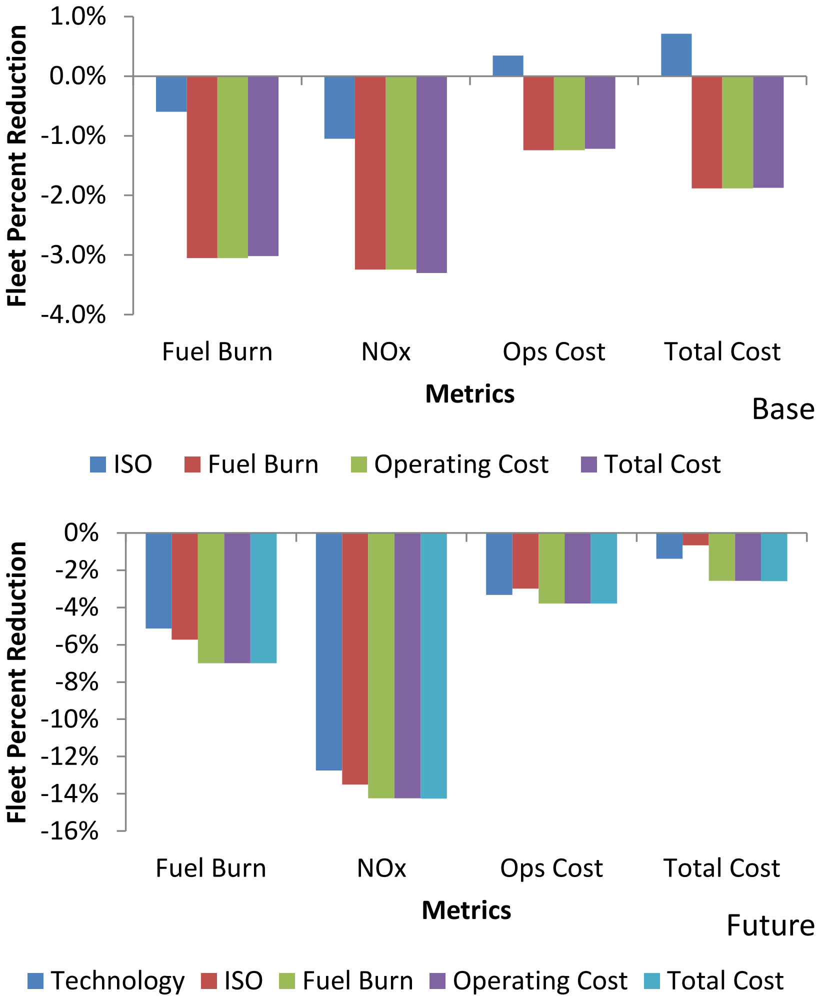


Figure 110. Fleet Performance Based on Metric Minimization

As in the speed reduction results, the impact of the range reduced variants doesn't provide overwhelmingly significant changes to the noise counters for the representative airports in the high, medium, and low categories. This is not remotely true for the intermediate stop airports. Figure 111 illustrates that for these five airports, the 2036 55 dB results are 13.4 times larger than the original operating set results and the 2050 results are 12.7 times larger. Similar magnitudes of growth occur for the future technology results. This is a significant change from what the original forecasted operations would expect.

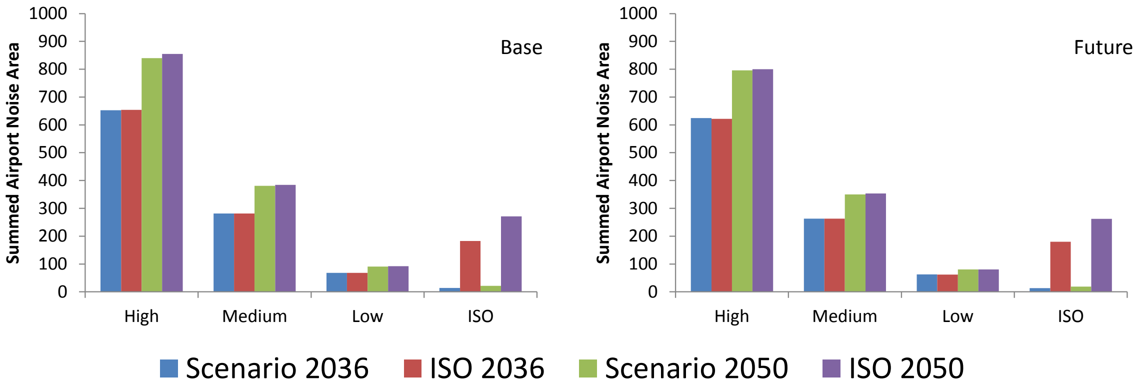


Figure 111. Noise Impact Comparison from Range Reduction – 55 dB

Although population concerns were not accounted for in this work, it is incredibly likely that the surrounding communities will be negatively affected. 65 dB figures are in Appendix C. Even though the sensitivity of range reduction to the other metrics was stagnant, quantifying and understanding the impact of noise is the critical component for this sample problem. Given that Chicago O'Hare has received $565 million to date for noise abatement, the number of impacted airports for intermediate stops is going to be significant as will the costs of increasing capacity.[7]

7.4.2 Comparison of Best Vehicle to Best Fleet Results

Given literature's predominant focus on the vehicle level, the fleet minimum should be compared to the vehicle minimum. The focus here is again on fuel burn with comparisons in Table 52. For two of the three seat classes, the results are different, thus indicating the critical element of operational distribution in determining the total optimum aircraft.

Table 52. SR Variant Comparison for Minimum Fuel Burn

Seat Class	Baseline Technology		Future Technology	
	Vehicle Optimum	Fleet Optimum	Vehicle Optimum	Fleet Optimum
Small Twin Aisle	50%	55%	50%	55%
Large Twin Aisle	50%	60%	50%	60%
Large Quad	50%	50%	50%	50%

From an operating cost perspective, results are identical between the vehicle and fleet levels, presented in Table 53. Based on the analysis from the previous section, this outcome is not surprising since minimum fuel burn, operating cost, and total cost aircraft are all largely insensitive to range reduction.

Table 53. SR Variant Comparison for Minimum Operating Cost

Seat Class	Baseline Technology		Future Technology	
	Vehicle Optimum	Fleet Optimum	Vehicle Optimum	Fleet Optimum
Small Twin Aisle	50%	55%	50%	55%
Large Twin Aisle	50%	60%	50%	60%
Large Quad	50%	50%	50%	50%

Based on the analysis conducted in this chapter, it indicates that Hypothesis 2 is partially supported but not entirely. The large quad aircraft disproves the theory that vehicle and fleet results will be different while the other two vehicle results do support it. It is not likely that this hypothesis is something that should be considered on a seat class by seat class basis and instead conclude that the fleet level results are largely dependent on the initial operations set, in particular where the aircraft are specifically flying. An operations set that operates predominantly over land mass will have a much easier time utilizing intermediate stops and providing suitable airports for feasibility. Additionally, the small twin aisle has far more prospective airports given its smaller size than the large twin and large quad due to the shorter takeoff field length and runway widths required.

7.4.3 Comparison of Replacement Strategies on Future Operations

As previously conducted, the minimum fuel burn results will be used to evaluate the impact of immediate replacement of aircraft as opposed to fleet evolution. Figure 112 demonstrates the impact that immediate replacement of vehicles has on the fleet in comparison to the impact of fleet evolution for fuel burn, NO_x, operating cost, and total cost. The solid lines represent fleet evolution while the dashed lines are immediate replacement of all respective vehicles. These results are with respect to the fleet where the replacement vehicles are the current baseline aircraft.

Similar to the speed reduction results, the fuel burn benefits are overpredicted through immediate replacement compared to the phased in evolution. At baseline technology levels, this impact is an additional 1.4% cumulative while future technology is much greater with 5.6% savings more. The additional benefits are so much greater in this case in part because the regional jet and single aisle are both receiving technology packages and are also assumed to have immediate replacement. Even then, the cumulative savings from range reduction are quite significant.

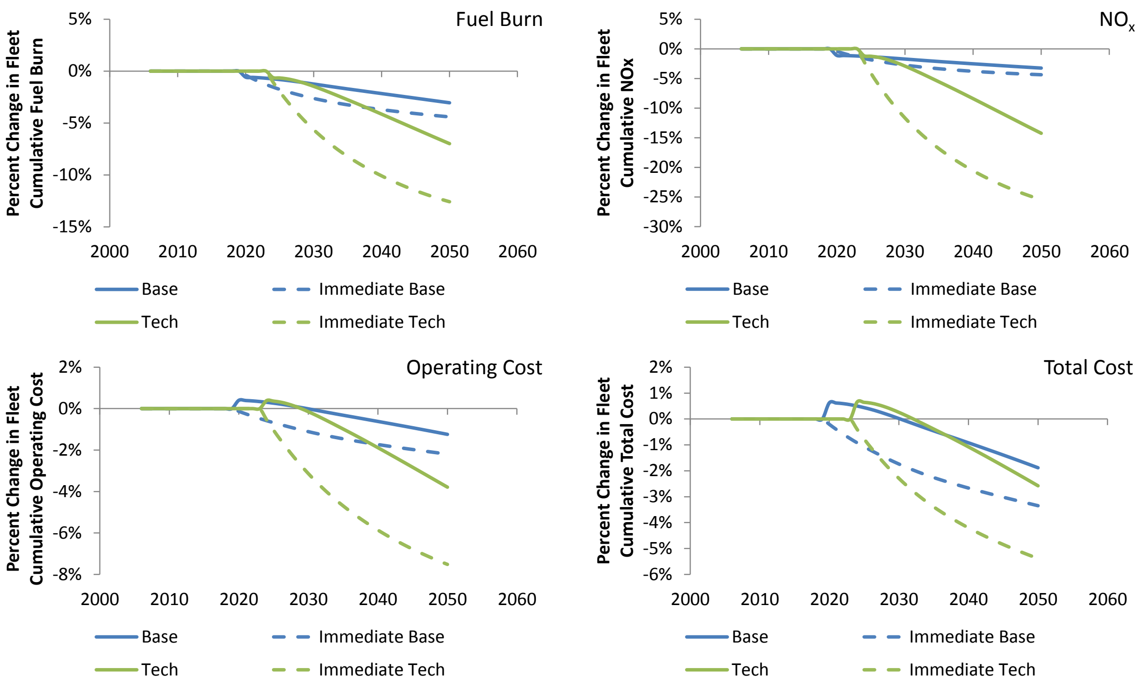


Figure 112. Cumulative Comparison of Replacement Strategies – Range

NO$_x$ impacts are largely similar for the same reasons. NO$_x$ savings are much higher for the future results due to the aircraft utilization mentioned in the previous chapter. There are aircraft that are used in multiple seat classes – an example is the Boeing 777 that is flown in seat classes 6 through 9. Replacing a large twin in the small twin seat class with a small twin aircraft will provide significant NO$_x$ reductions on its own. That, in combination with advanced combustors, is the cause of the significant reduction in NO$_x$. Additional savings are 1.2% and 11.2% for the two technology levels respectively.

Operating cost trends are similar to fuel burn overall. Note that there is an initial bump in 2020 and 2024 due to the transition from direct flights to intermediate stops. This bump does not occur for the immediate replacements as the fuel savings are ubiquitous throughout the fleet as opposed to having to be phased in over time. As range reduced aircraft are introduced to the fleet, these costs continue to drop from both perspectives as the fuel savings continue to increase. Differences between approaches are 1% for the baseline results and 3.7% for the future.

Total cost faces a larger initial bump due to the inclusion of capital costs for the evolution approach but this is again due to the transition from direct to intermediate stop flights. Unlike the speed reduction results, there is no bump for the immediate replacement as the range reduced variants that are immediately adopted cost much less than their long range counterparts. In addition with the fuel savings, the rise in costs disappears. Overall, the cumulative difference is 1.5% and 2.8% respectively.

One could then argue that their introduction would be a boon to the airlines as a lower capital cost improves profitability. But like the speed reduction discussion mentions, the immediate approach is underestimating the costs of replacing all the aircraft in the fleet. Those unused aircraft that were previously in operation have no customer to sell them to other than for scrap such that it will result in a pretty hefty loss for either the airlines or leasing companies. Or the annual capital cost would have increased to make up for the future loss of revenue, resulting in higher total in the years leading up to the entry year. Additionally, as tail tracking is not done, it could mean that even more aircraft are required due to potential scheduling issues regarding planned flights and also leaves airlines with less fleet flexibility. Regardless, the total capital cost penalty has not been fully captured.

7.4.4 Impact of Technology on Range Reduction Effectiveness

The minimum fuel results will be used to explore the impact that technology has on the impact of mission specifications. Much of the existing literature has focused on a fixed technology level that is the current state of the art. The need exists to understand how significant an influence that technology integration will have on the fleet sensitivity of mission specification changes.

As the entry into service dates are different between the two technology levels, both will be given the same entry into service date to evaluate whether range reduction is less effective on next generation of aircraft. The future technology entry year was transitioned to be consistent with the baseline entry year (2020) and results are in Figure 113 for fuel burn, NO_x, operating cost, and total cost and a summary of the cumulative numbers in Table 54. These numbers are with respect to the baseline fleet results. Note that the technology results are with respect to the baseline operations while results with range reduction include intermediate stops.

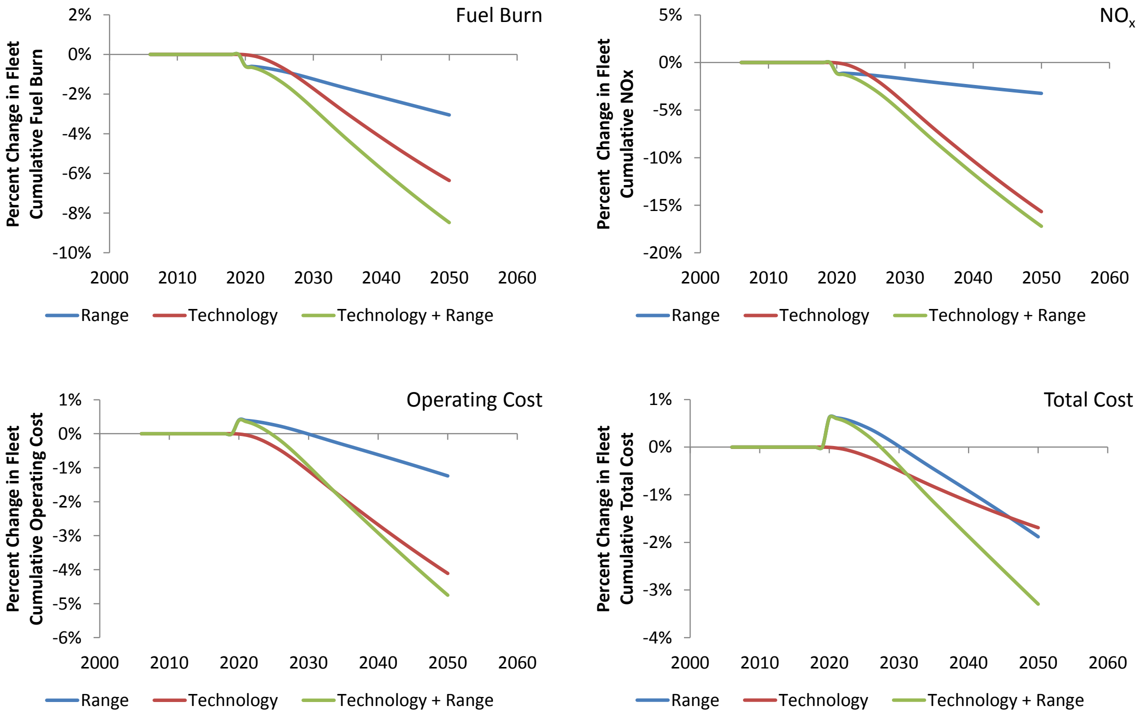


Figure 113. Comparison of Technology Impact on Range Reduction Effectiveness

Table 54. Technology Impact on Range Reduction Effectiveness

Scenario	Fuel Burn	NO$_x$	Operating Cost	Total Cost
Range Reduction	-3.05%	-3.24%	-1.24%	-1.88%
Technology	-6.36%	-15.67%	-4.11%	-1.69%
Technology + Range	-8.48% (-2.12%)	-17.21% (-1.54%)	-4.75% (-0.64%)	-3.30% (-1.60%)

For the technology and speed reduction results, the percentage in the parentheses represents the difference between that case and technology alone. For all four metrics, technology introduction has reduced the impact that range reduction has on the fleet results. For fuel burn, it is reduced by a third while NO$_x$ is cut by over half. Operating cost is approximately halved while total cost the impact is less than a quarter of percent reduction.

7.5 Summary

This chapter has focused on the impact that range reduction has at both the vehicle and fleet levels. The representative aircraft were designed with minimizing fuel burn subject to a number of performance constraints. These results were then analyzed to determine suitability as to whether each aircraft should be considered at the fleet level. This involved utilization of intermediate stops such that the design range was broken into two or three (if two stops was beneficial) flights to use less fuel. Not all aircraft realized fuel savings. The regional jet and single aisle seat classes showed increases in fuel or trivial benefits such that adoption for those aircraft was deemed unnecessary. This was due to the increases in climb fuel being a much greater penalty than the savings in the more efficient cruise portion of flight.

The three larger seat classes all indicated that there were significant savings by utilizing one or two stops at the design range such that the next step was to evaluate what ranges each strategy was optimal. All though the large twin aisle under both technology levels and the future large quad preferred two stops at the design range, the benefits overall were not significant enough to merit their usage such that one stop was deemed the better operational strategy. This also considered other implications of two stops such as landing fees and viability within total fleet operations.

This then required the evaluation of operations from the initial set to determine which direct flights would be updated to use intermediate stops. This is documented in Chapter 5. A brief discussion of the impact of intermediate stops at the fleet level is provided for each seat class. Following that, the impact of range reduction over the metrics of fuel burn, operating cost, and total cost (a combination of operating and capital cost) was conducted. This analysis indicated that the impact of range reduction is quite uniform over these three metrics. An additional comparison was provided with respect to a different replacement strategy over the short ranges but resulted in no changes in outcome.

Further analysis was conducted to determine the importance of vehicle integration whether it is through fleet evolution where retirement of existing aircraft is considered and new aircraft are phased in over time in comparison to the practice of conducting a complete fleet replacement of the associated vehicles. Using the optimal fuel burn vehicles, it showed a pretty significant discrepancy on fuel burn if the complete replacement results are forecasted out.

Finally an analysis was conducted to compare the impact that technology had on the effectiveness of range reduction. This required both technology levels to have the same entry into service years. Data clearly showed that the impact of speed reduction was reduced when future technology was applied. While the benefits are still significant with respect to fuel burn, it is worth noting that the operating cost savings are significantly lessened.

Based on this analysis, range reduction is a viable fleet level strategy for reducing the environmental impact of aviation going forward. It does have significant consequences with respect to noise for intermediate airports that will need to be considered if one was to move forward. Additionally, intermediate stops do increase the potential for accidents whether one uses the rate per operations or flight time such that it could be a cause for concern. However, range reduction will not be enough to reach carbon neutral growth on its own or with the aid of technology demonstrated in Figure 114.

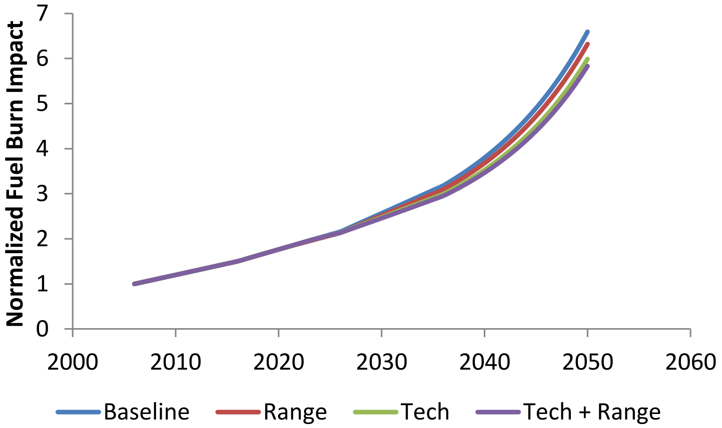


Figure 114. Normalized Impact of Range Reduction on Fuel Burn

CHAPTER 8

SPEED AND RANGE REDUCTION SAMPLE PROBLEM

Based on the finding from the previous two chapters, the small twin, large twin, and large quad aircraft benefited from both speed and range reductions. Therefore, all three aircraft will be assessed jointly. The large twin results will be presented here while the figures from the other two aircraft will be in Appendix D.

8.1 Vehicle Design Results

At a given speed, the engine assumptions were consistent with what was presented in Chapter 6. For variations in range at a speed, only the airflow was varied. Similarly, assumptions used for average wing thickness and wing sweep were treated in a similar fashion. As this chapter focuses on both speed and range reduction, contour plots of fuel burn performance will be provided in lieu of single axis charts. Yellow dots represent the baseline design while green dots represent the optimal resulting aircraft.

Figure 115 compares the impact of joint reduction over both one and two stops for both technology levels. Regardless of technology level or number of stops, the optimal vehicle for fuel burn is always the M0.70, 50% range variant. Two stops are still slightly more preferable for this aircraft but the difference between the two operating schemes is only marginal. Also of note is that technology introduction has significantly reduced the impact of joint reduction.

The initial impact of intermediate stops is around 7.5% fuel savings for the M0.84, 100% range aircraft and the benefits at M0.70, 50% range is approximately 30.5%. With the introduction of technology, the results are 19.5% for the initial aircraft down to 36.6% for the optimum. Although the savings from joint reduction are still fairly large, technology infusion has significantly reduced their overall benefits. Weight savings from range reduction provide additional benefits that result in the speed fuel burn bucket disappearing for this seat class.

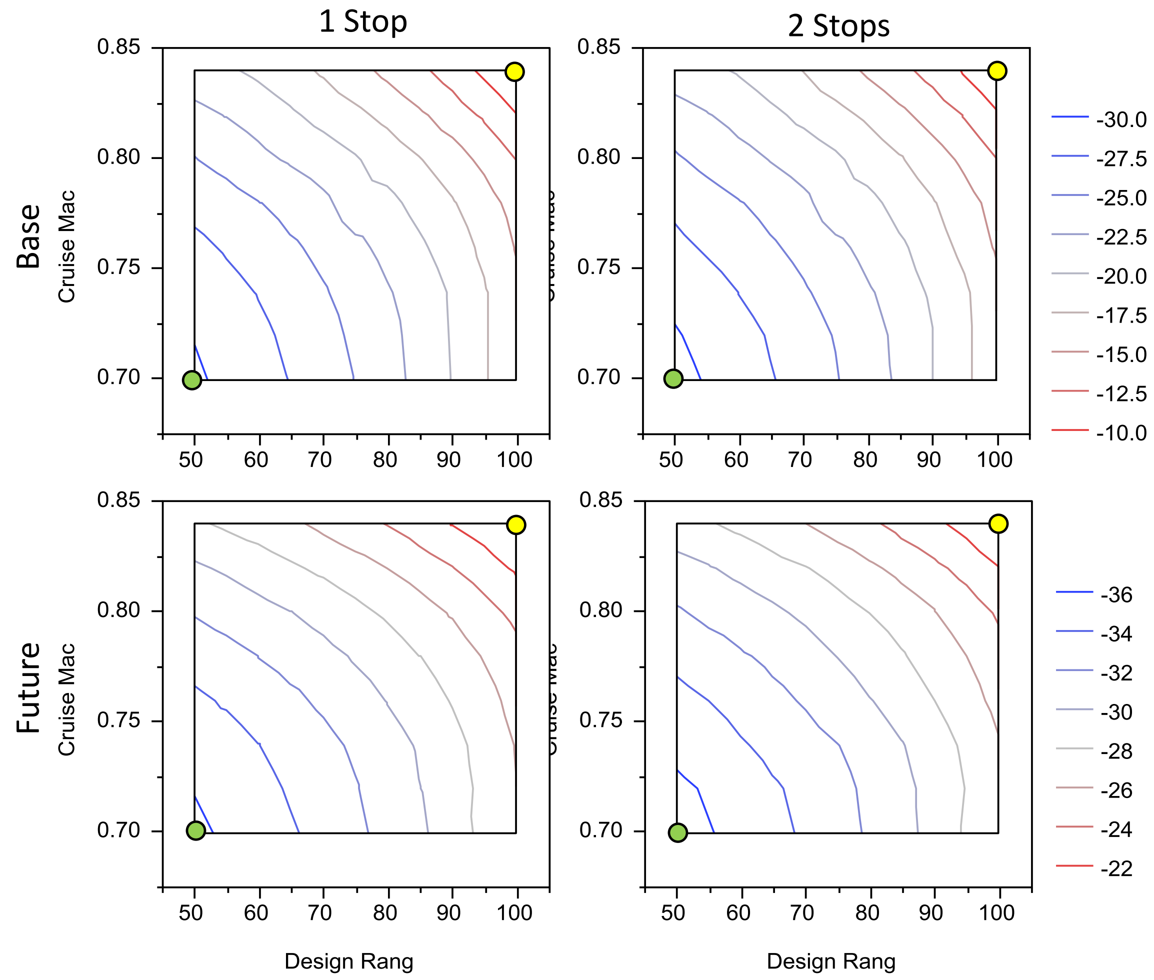


Figure 115. LTA Joint Design Mission Fuel Burn Performance

Similar trends for operating cost are observed in Figure 116. While the two stop strategy is slightly more beneficial from a fuel consumption standpoint, the cost penalty from the extra stop results in two stops falling out of favor economically. Additionally, the impact of speed reduction is felt here as well, generating a cost bucket. The minimum operating cost results are for the M0.72, 50% variants instead of the M0.70 aircraft.

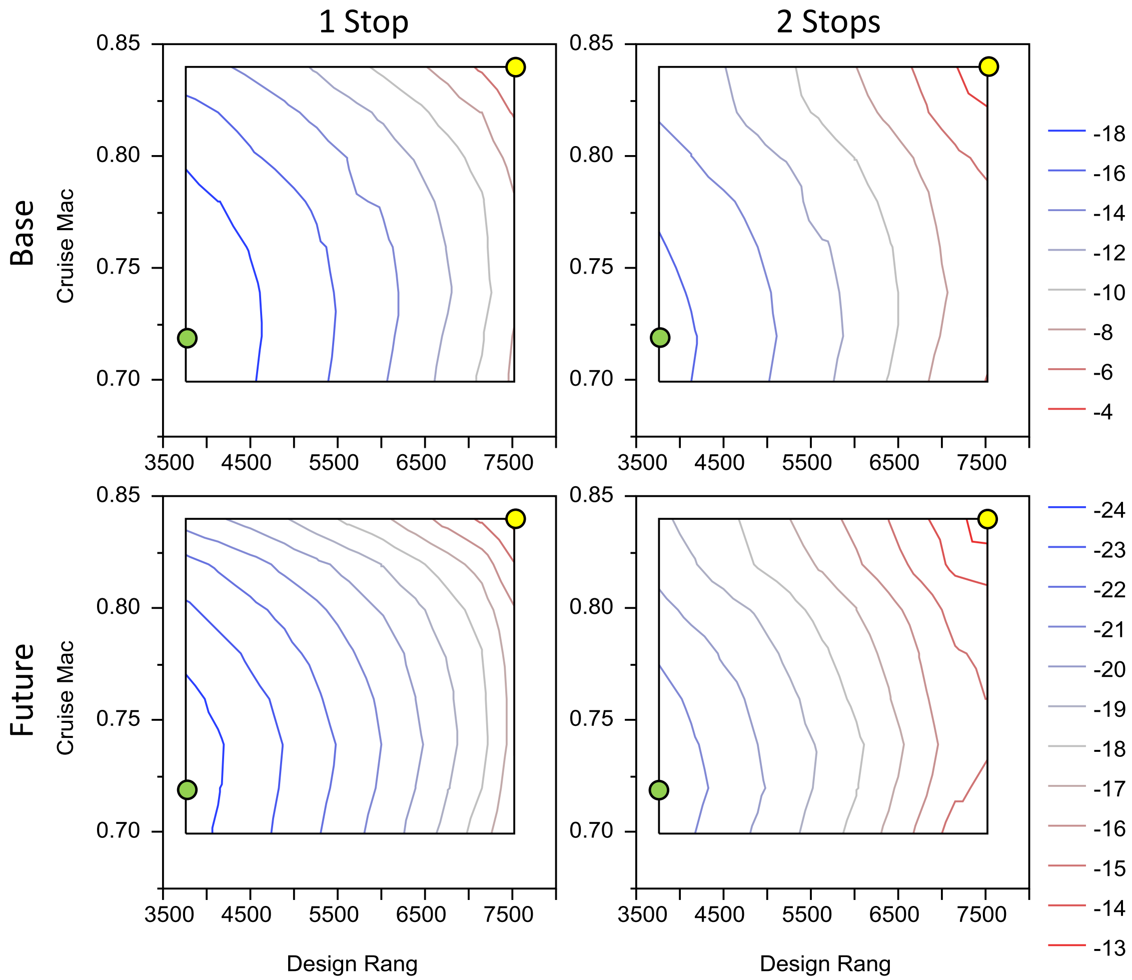


Figure 116. LTA Joint Design Mission Operating Cost Performance

The economic mission compares fuel burn performance for the respective minimum variants in Figure 117. The 4,000 nm mission is the 55% variant at M0.70

while the 2,500 nm mission is the M0.70, 50% aircraft. These results are consistent with the design mission.

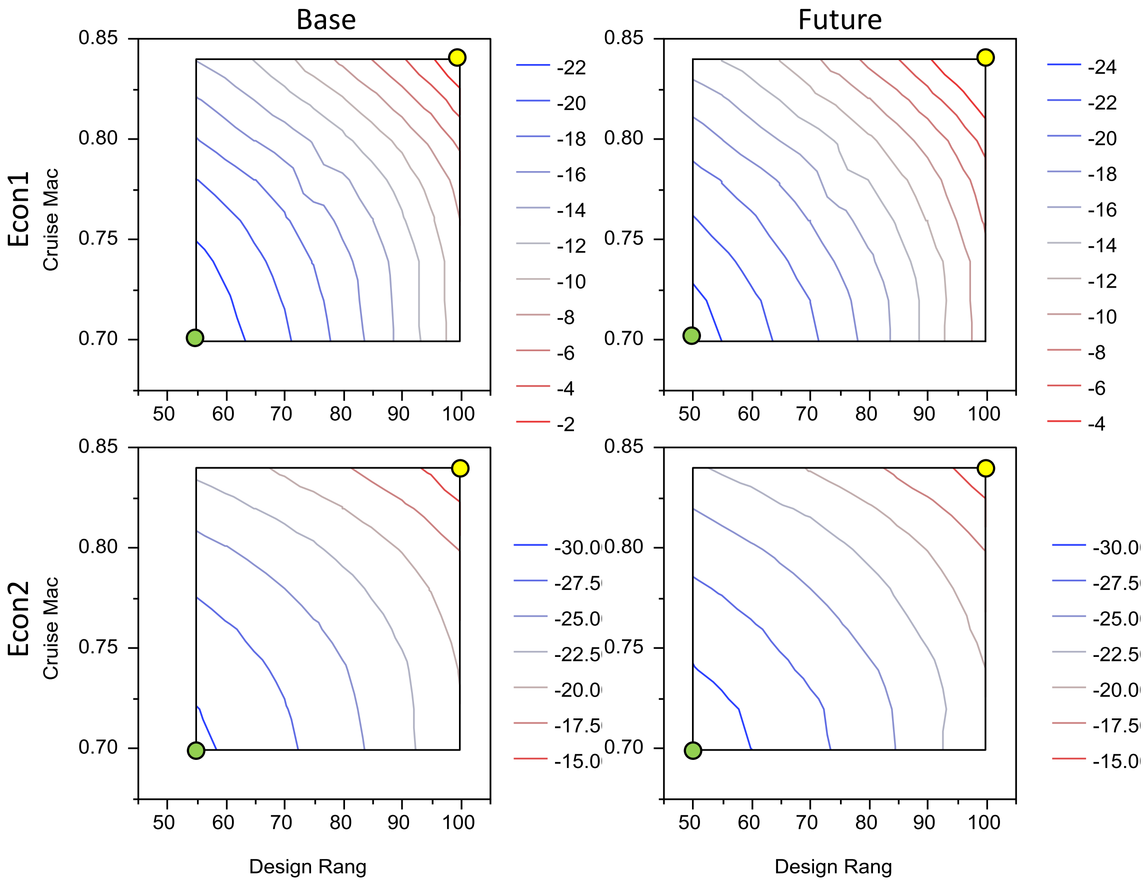


Figure 117. LTA Joint Economic Mission Fuel Burn Performance

The implications of operating cost on these two missions are provided in Figure 118. As with the design mission, the optimal aircraft for minimizing operating cost is the slightly faster M0.72 variant at the minimum range. Again, these findings are not surprising based on the results of the previous two demonstration problems.

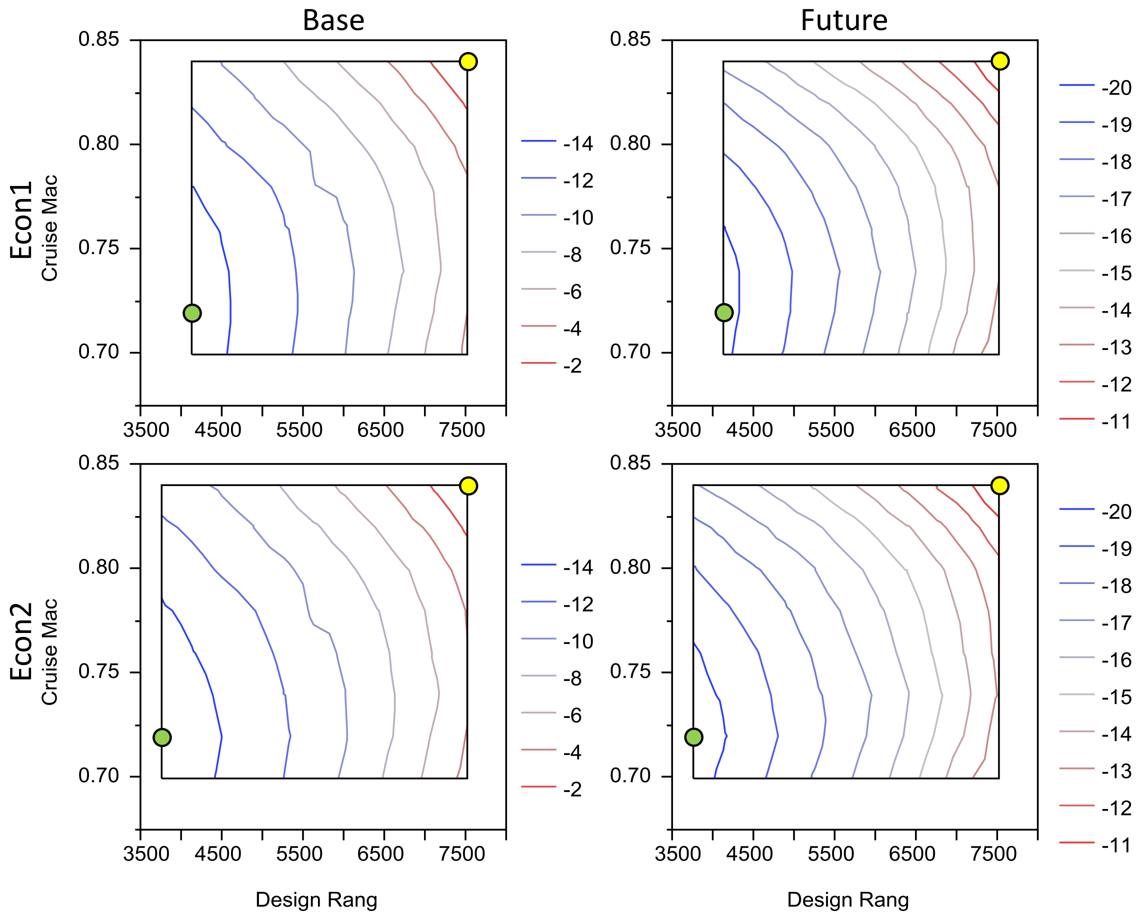


Figure 118. LTA Joint Economic Mission Operating Cost Performance

8.2 Fleet Results

An assessment of intermediate stop feasibility was conducted with respect to speed reduction for the base technology aircraft. This was to assess whether the transition range between a direct flight and one stop strategy was sensitive to reductions in cruise speed as well as identify whether any new operations would need to be modified for fleet analysis. Recall that technology infusion only showed slight decreases in that threshold and range reduction was fairly constant until the direct and one stop curves became separated.

The figures of intermediate stop feasibility are not particularly different than those previously seen. The small twin aisle is most sensitive to speed reduction; however, it was also much more sensitive to range reduction than the other two aircraft and the variation was no different than before. The two larger aircraft were not affected at all. This indicated that no additional operations needed to be modified for fleet analysis.

Additionally, there are two final things worth noting. The first is that the long range variants match the cruise speed of the short range variant as it does not seem practical for a manufacturer to develop two aircraft with different ranges and different cruise speeds. The other is that only the analysis of 100%-0% was analyzed. Results presented here are the cumulative impact of joint reduction for the large twin aisle. Results for the small twin and large quad are in Appendix D.

Figure 119 demonstrates the impact that joint reduction has on the cumulative fuel burn for both technology levels. Ultimately, the impact of technology is negligible on determining which aircraft is optimal as both levels result in the fleet minimum occurring at M0.70, 60% range. In terms of overall fuel savings, the baseline technology benefits are 1.9% with respect to cumulative fuel levels while the future savings are 1.1% in addition to the 5.1% savings just from technology infusion. Similar to the range only analysis, the preferable variant design is driven by operational distribution rather than focus solely on the design mission.

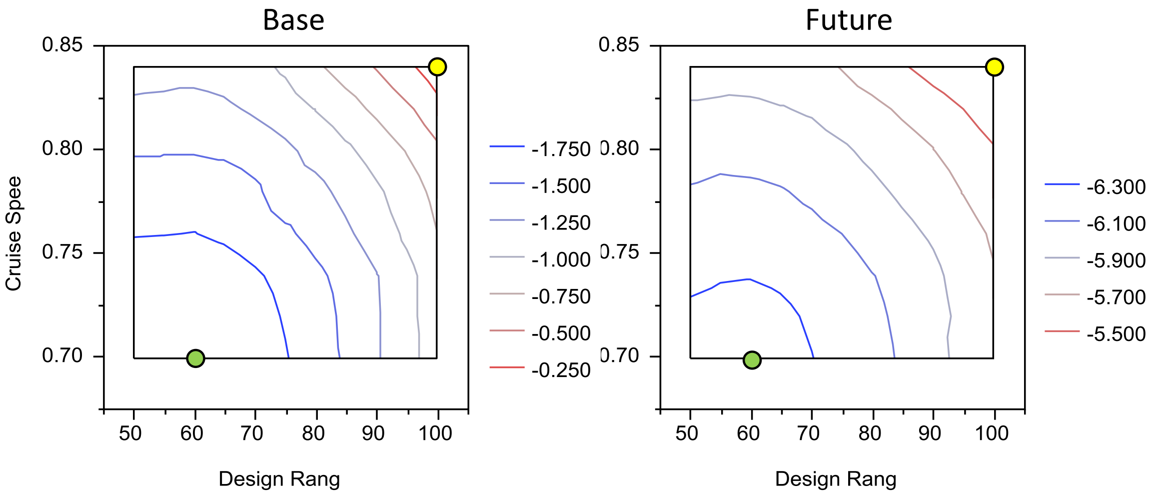


Figure 119. LTA Joint Reduction Fuel Burn Fleet Impact

Figure 120 compares the impact that joint reduction has on NOx emissions. Trends here are largely driven by cruise speed and range is left only as a measure of how many operations are viable for the short range variant to fly on. Additionally, technology introduction significantly reduces the benefits from joint reduction. This outcome is not all the surprising based on results from the speed and range sample problems.

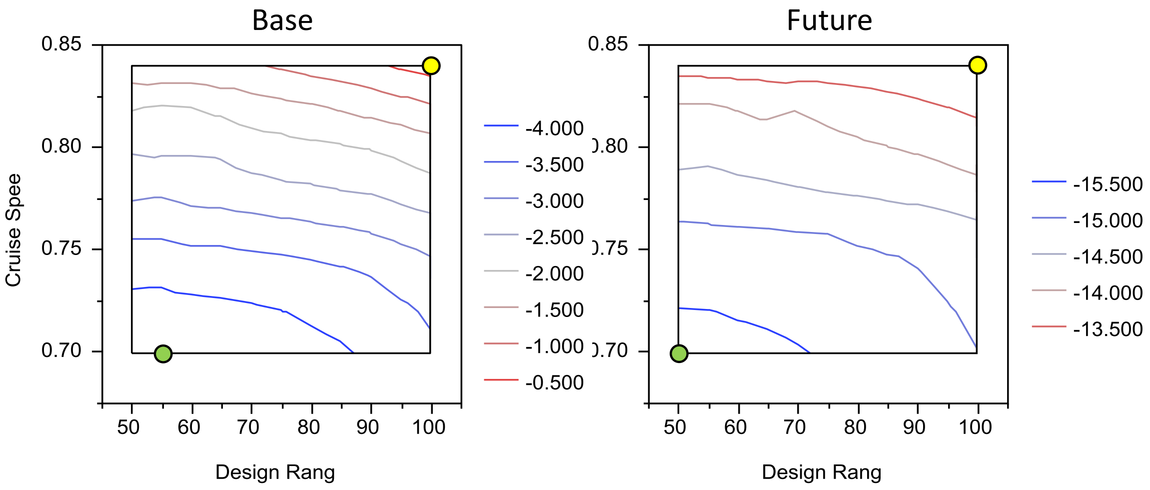


Figure 120. LTA Joint Reduction NO_x Fleet Impact

Compared to the fuel burn, the operating cost trends in Figure 121 are slightly different. This behavior is more in line with what was observed with the speed reduction results as continued reductions in cruise speed eventually increase the crew and maintenance costs at a faster rate than the fuel cost saved. For both technology levels, the optimal variant is the M0.72, 60% range aircraft. The maximum savings are reduced from technology adoption as well decreasing from 1.0% to 0.6%.

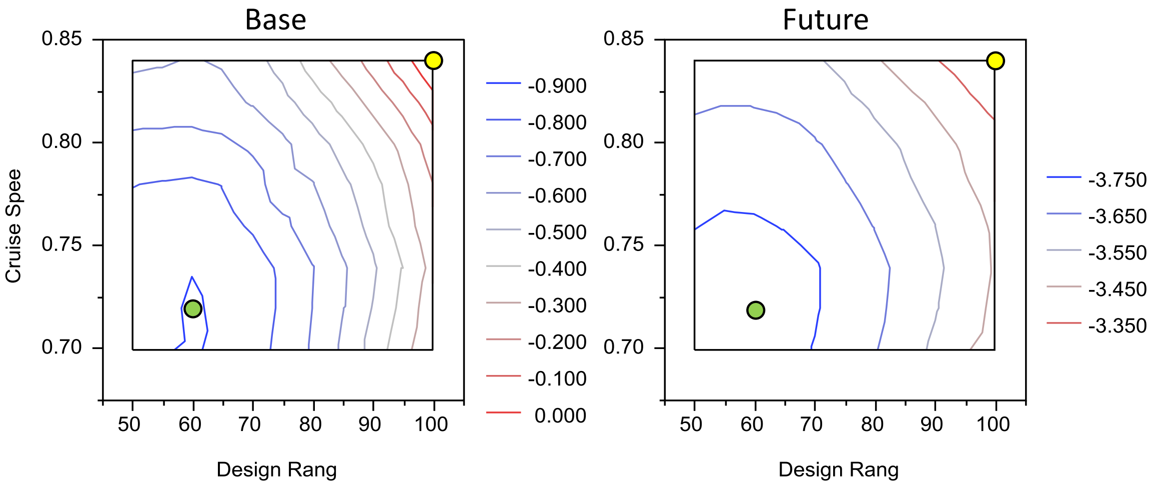


Figure 121. LTA Joint Reduction Operating Cost Fleet Impact

Figure 122 compares the capital cost trends. Unsurprisingly, the optimal aircraft for minimum capital cost is the baseline speed with reduced design range. Since speed reduction requires more aircraft to be purchased, this is ultimately less desirable from this metric's standpoint. The difference between the two technology levels is due to changes in the range threshold values as technology infusion results in variation of those values.

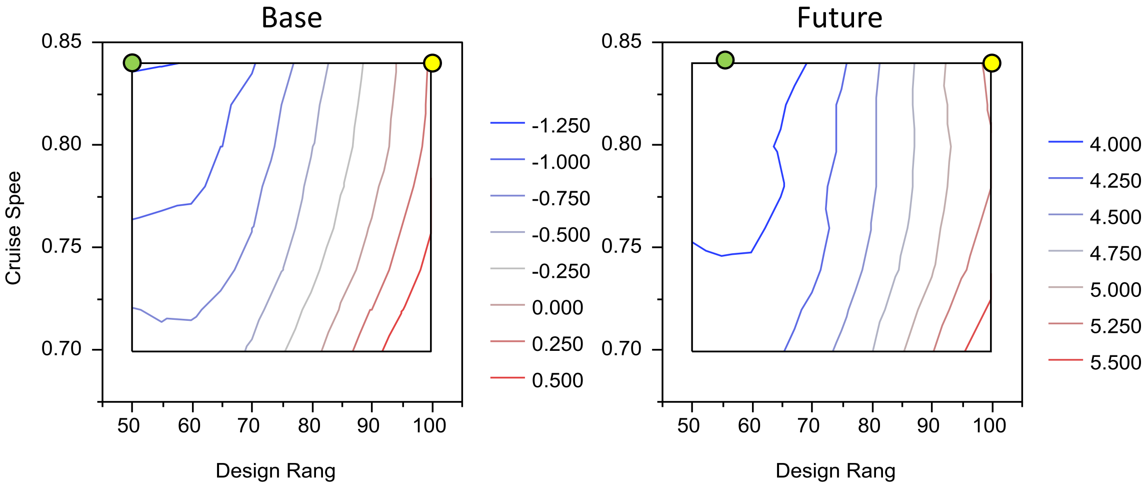


Figure 122. LTA Joint Reduction Capital Cost Fleet Impact

Figure 123 compares the implications of the combination of operating and capital cost for joint reduction. There is clearly a push between more fuel savings from joint reduction while faster aircraft have lower crew and maintenance costs and require many less aircraft. From this perspective, the speed of the selected variants again increases from M0.70 and M0.72 for fuel burn and operating cost to M0.74 for total cost. The variation in range is due to threshold changes due to technology infusions but both variants are much shorter design range – 55% for the baseline and 60% for the future.

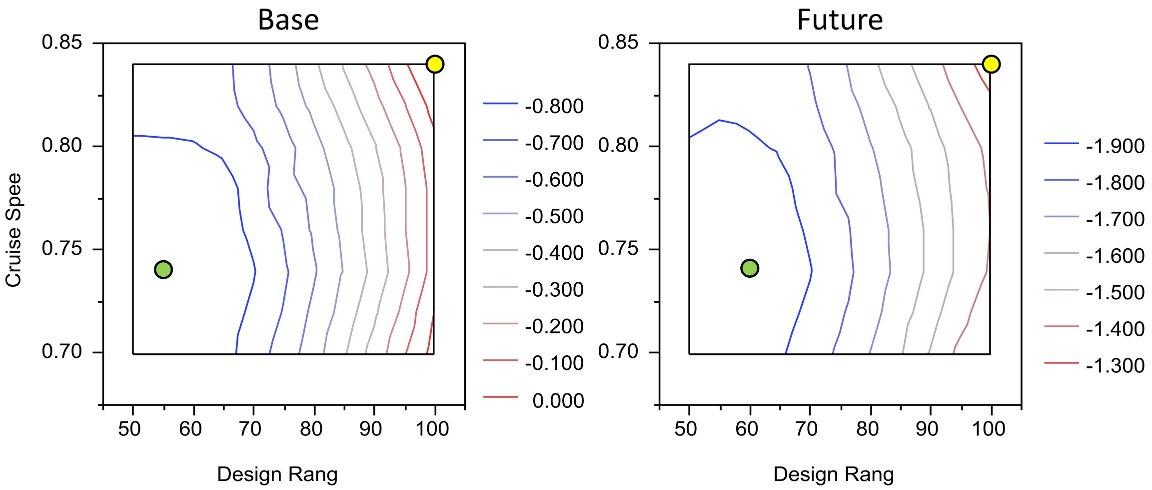


Figure 123. LTA Joint Reduction Total Cost Fleet Impact

8.3 Experimental Results

On completion of the joint speed and range reduction, the final step is to address the hypotheses and experimental results. This discussion will follow the hypotheses in order. Although only the small twin, large twin, and large quad aircraft were modeled at both levels for the joint speed-range analysis, the experimental analysis here has included the associated regional jet and single aisle from the speed only analysis for each respective metric.

8.3.1 Influence of Difference Fleet Metrics on Best Vehicles

Based on the fleet level analysis, the next step was to identify the maximum benefit vehicles for the fleet based on the same three metrics as provided in Table 55.

Table 55. Comparison of Joint Variants Corresponding to Different Metrics

Seat Class	Baseline Technology			Future Technology		
	Min Fuel	Min Ops Cost	Min Total Cost	Min Fuel	Min Ops Cost	Min Total Cost
Regional Jet	0.66,100%	0.72,100%	0.72,100%	0.66,100%	0.70,100%	0.70,100%
Single Aisle	0.70,100%	0.72,100%	0.78,100%	0.68,100%	0.74,100%	0.74,100%
Small Twin Aisle	0.70, 60%	0.70, 60%	0.74, 55%	0.68, 60%	0.72, 55%	0.76, 50%
Large Twin Aisle	0.70, 60%	0.72, 60%	0.74, 55%	0.70, 60%	0.72, 60%	0.74, 60%
Large Quad	0.73, 55%	0.73, 55%	0.81, 50%	0.73, 50%	0.75, 50%	0.81, 50%

Even with both speed and range being modified, there is still a good bit of variation between the three metrics. The baseline small twin and large quad aircraft are the same with respect to fuel burn and operating cost but then increase it speed when capital cost is introduced. The baseline large twin on the other hand gradually increases its speed with small variation to the range over the three metrics. Technology infusion promotes this behavior in all three aircraft.

This analysis demonstrates the benefits of utilizing both speed and range reduction within the fleet while still identifying tradeoffs of the different metrics in Figure 124. These results are much more in line trendwise with speed reduction than range reduction as there is variation between all three metrics. The magnitudes do vary a bit as fuel burn is greater than individually speed and range combined but operating cost and total cost are less due to increases in the number of aircraft required and crew/maintenance costs. Technology introduction follows similarly but the joint benefits are much greater with respect to fuel burn than either metric individually. Costs are more constrained considering the lengthier flight times from elements of speed reduction.

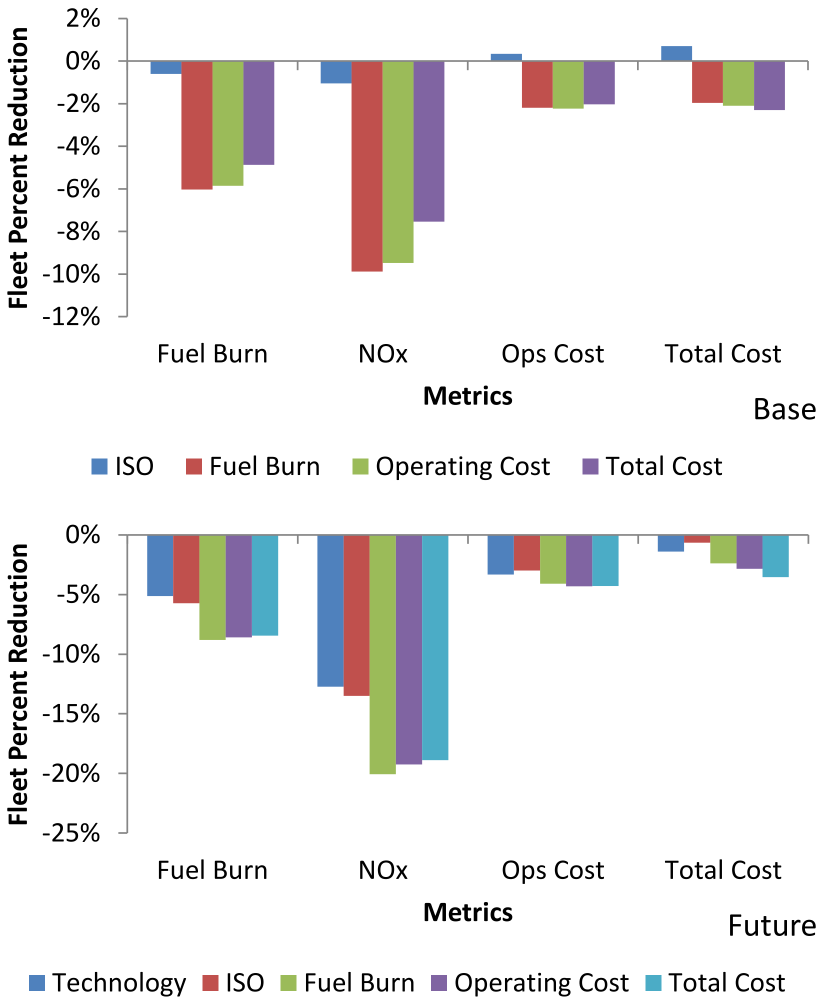


Figure 124. Fleet Performance Based on Metric Minimization for Joint Reduction

Like the speed and range results, noise for the three primary airport groups is relatively constant. There are slight increases in noise but this is attributed to the climb rate differences in the vehicle variants. Noise at the intermediate stop group also significantly rises but less than range alone analysis. Comparisons of the 55 dB areas for both technology levels are in Figure 125.

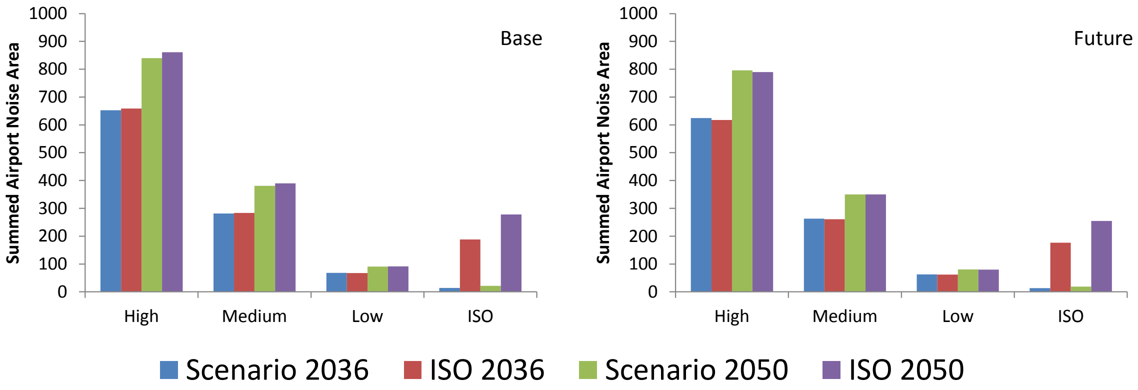


Figure 125. Noise Impact Comparison from Joint Reduced Vehicles – 55 dB

Safety ultimately ends up not being a particularly interesting trend for any of the seat classes. Using the accident rate per operations, the safety penalties between seat classes are the same as the intermediate stop results back in Chapter 7 regardless of range or speed changes. When considering the accident rate per flight time, the trends are solely a function cruise speed and independent of range reduction such that their contours are constant lines in the speed axis and accident likelihood simply increases as aircraft speed is reduced. But this is not all that surprising as the long range variants are the same cruise speed as the short range aircraft.

8.3.2 Comparison of Best Vehicle to Best Fleet Results

At the vehicle level, all aircraft minimize their fuel burn with respect to the minimum range through utilization of intermediate stops. The large twin and large quad aircraft have their minimum fuel burn at the minimum speed analyzed. This is also true for the small twin with future technology. The baseline technology variant is slightly faster. For the fleet level analysis, the speeds are identical to that from the vehicle analysis but the small twin and large twin ranges are different due to the operational distribution utilized in this analysis. This also occurs for the large quad under baseline technology.

Table 56. Joint Comparison for Minimum Fuel Burn

Seat Class	Baseline Technology		Future Technology	
	Vehicle Optimum	Fleet Optimum	Vehicle Optimum	Fleet Optimum
Small Twin Aisle	0.70, 50%	0.70, 60%	0.68, 50%	0.68, 60%
Large Twin Aisle	0.70, 50%	0.70, 60%	0.70, 50%	0.70, 60%
Large Quad	0.73, 50%	0.73, 55%	0.73, 50%	0.73, 50%

Table 57 examines the operating cost results between the vehicle and fleet levels. Like the fuel burn vehicle results, the vehicle minimums are at the 50% range variants but the speeds are faster than the minimum fuel burn. However unlike the speed reduction results, the fleet optimums are for the most part at the same speed as the vehicle level. Ranges differ for five of the six comparisons. Ultimately this is due to interactions between speed and range on the vehicle results.

Table 57. Joint Comparison for Minimum Operating Cost

Seat Class	Baseline Technology		Future Technology	
	Vehicle Optimum	Fleet Optimum	Vehicle Optimum	Fleet Optimum
Small Twin Aisle	0.72, 50%	0.70, 60%	0.72, 50%	0.72, 55%
Large Twin Aisle	0.72, 50%	0.72, 60%	0.72, 50%	0.72, 60%
Large Quad	0.73, 50%	0.73, 55%	0.77, 50%	0.75, 50%

This analysis supports Hypothesis 2 for the joint reduction problem.

8.3.3 Comparison of Replacement Strategies on Future Operations

A comparison of the impact of immediate replacement in comparison to the evolution through retirement of existing aircraft and the phase-in of the replacement ones is conducted here. The minimum fuel burn aircraft are used for this analysis.

Figure 126 demonstrates the impact that immediate replacement with the joint speed and range (speed only in the case of the regional jet and single aisle) for fuel burn, NO_x, operating cost, and total cost. Solid lines represent evolution while dashed lines represent immediate replacement. Baseline technology is in blue and the future technology is in green.

The impact to fuel burn is pretty significant between strategies – 3.6% and 7.8% additional gains over the respective technology levels. This is compared to the 6% and 8.8% benefits from fleet evolution. The benefits are much larger than they are for speed reduction where all five seat classes were considered but they are also much larger than the range as well, where technology for the two smaller seat classes was still introduced immediately. Combination of speed and range reduction is much more substantial with both strategies.

The trends in fuel burn and NO_x trend much closer to speed reduction than range reduction with respect to cumulative results. Overall, the immediate replacement benefits are 5.6% and 17.3% for the respective technology levels on top of the 9.9% and 20.1% from the beginning. The sources causing the differences in NO_x have been highlighted in both previous sections.

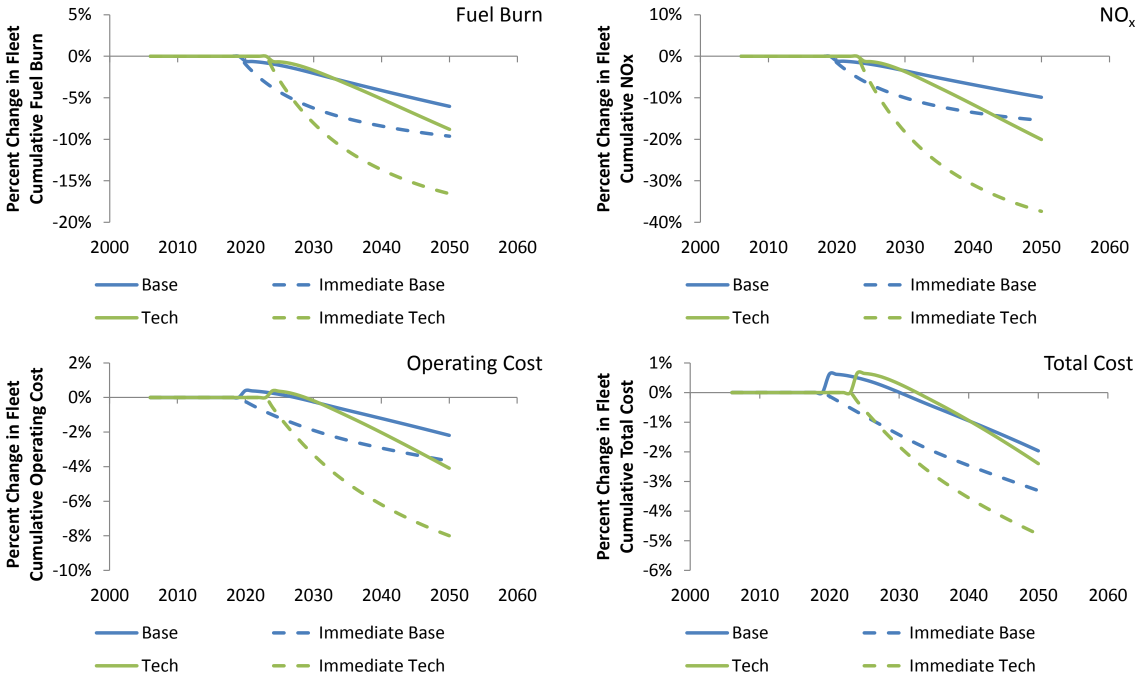


Figure 126. Cumulative Comparison of Replacement Strategies – Joint

On the economic side, the trends are far more similar to the range only analysis than the speed analysis. With respect to the evolutionary approach, this is partially due to the introduction of intermediate stops but future years continue to show cost reductions. Speed only analysis started to become less beneficial in the long term as the fuel savings were significant enough to offset the crew/maintenance costs while range only analysis showed more significant cost savings from the additional fuel savings without having to pay the price from block time dependent costs.

Total cost is more in line with range reduction as well based on the general impact that any level of range reduction has on aircraft price. However, the joint element of speed reduction has a stronger impact on the magnitude of reduction as the future total cost impact due to the increased number of aircraft required over range alone.

Much like the range reduction analysis, it might appear that joint reduction would be a significant boon to the airlines. But the shortcomings of immediate analysis have been discussed in the speed and range reduction sections. Specifically, they are an underestimation of capital costs and a lack of flexibility in aircraft scheduling.

8.3.4 Impact of Technology on Joint Specification Effectiveness

A comparison of the impact of technology on joint mission specification effectiveness was conducted using the minimum fuel burn results. Again, the technology infused aircraft entry year into service was modified to align with the baseline level redesigned aircraft – the year 2020. Figures for all four metrics are provided in Figure 127. As with the range reduction results, the specification scenarios include intermediate stops while the future technology results use the baseline operations set.

Table 58. Technology Impact on Joint Reduction Effectiveness

Scenario	Fuel Burn	NO_x	Operating Cost	Total Cost
Specifications	-6.04%	-9.88%	-2.19%	-1.97%
Technology	-6.36%	-15.67%	-4.13%	-1.73%
Technology + Specifications	-10.71% (-4.36%)	-24.38% (-8.72%)	-5.10% (-0.98%)	-3.04% (-1.31%)

There is a pretty significant reduction with respect to fuel burn and operating cost from technology introduction with the impact being reduced by a third and a half respectively. NO_x benefits are reduced by a percent while total cost is reduced by just over half a percent. This supports the hypothesis that technology infusion reduces the impact of mission specification changes.

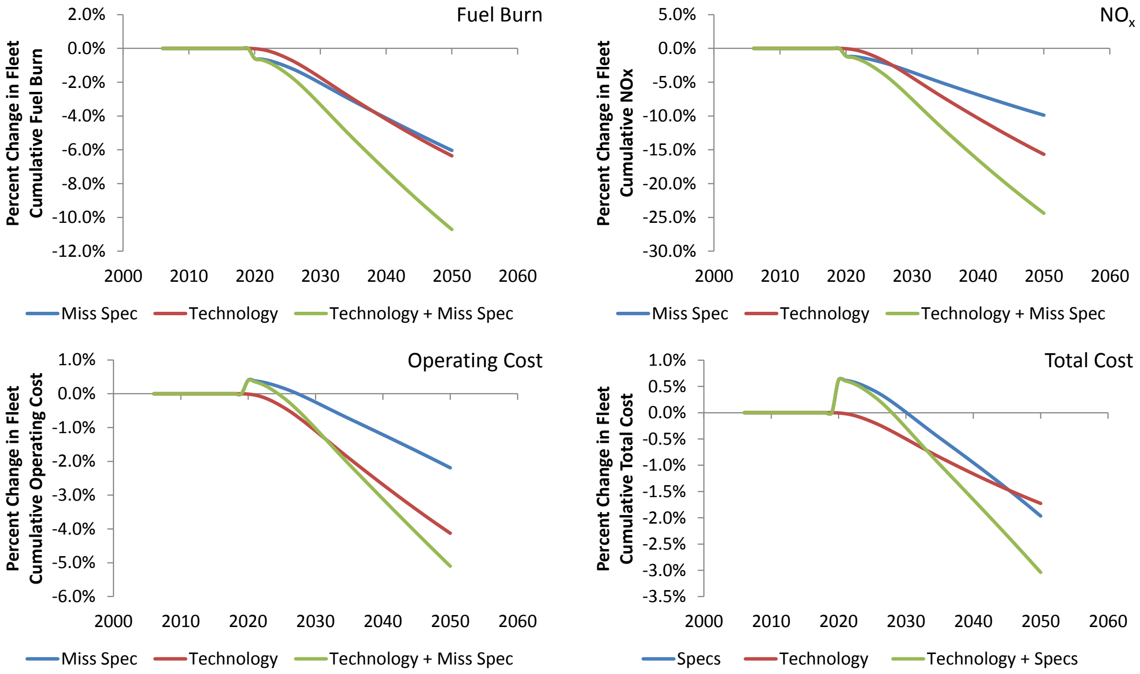


Figure 127. Comparison of Technology Impact on Joint Reduction Effectiveness

8.4 Summary

This chapter has focused on the impact that joint speed and range reduction has at both the vehicle and fleet levels. As with the previous chapters, the representative aircraft were designed with the objective of minimizing fuel burn, subject to a number of performance constraints. Based on the analysis from the previous two chapters, this analysis was limited to the small twin, large twin, and large quad aircraft.

At the fleet level, the scenario relevant speed reduced regional jet and small twin aisle aircraft were also included. Fuel burn, operating cost, and total cost were the metrics of interest. A comparison of these three different scenarios showed that the trends were much more similar to speed reduction as there is significant variation between the three scenarios for both technology levels. Combining range and speed has the additional implication that range essentially falls out with respect to the metrics of interest.

An investigation was conducted to evaluate the importance that vehicle integration has at the fleet with respect to immediate replacement of relevant vehicles in comparison to fleet evolution over time with phased introduction and aircraft retirement. An analysis was conducted using the minimum fuel burn results and showed that this is a significant discrepancy among all metrics. Fuel burn is provided here as an example.

Finally, an analysis was conducted to compare the impact that technology introduction has on joint speed and range reduction effectiveness. Both technology levels were introduced in 2020 to perform this evaluation. Data clearly shows that the impact is significantly reduced for fuel burn and the cost metrics and somewhat less so for NO_x emissions.

Based on this analysis, joint speed and range reduction is a viable fleet level strategy for reducing the environmental impact of aviation going forward. It does have some consequences as it does take the best and worst elements from both. There is a much greater number of aircraft required in the fleet such that it could potentially become undesirable for the airlines to even consider. Range reduction does offset a significant part of the capital cost concerns but that may not be enough to mitigate other challenges. Additionally, range reduction does impact noise significantly at the airports that are utilized as intermediate stops. Regardless, even joint considerations are not enough to result in carbon neutral growth such that additional solutions will be required to offset the environmental impact of aviation growth as indicated in Figure 128.

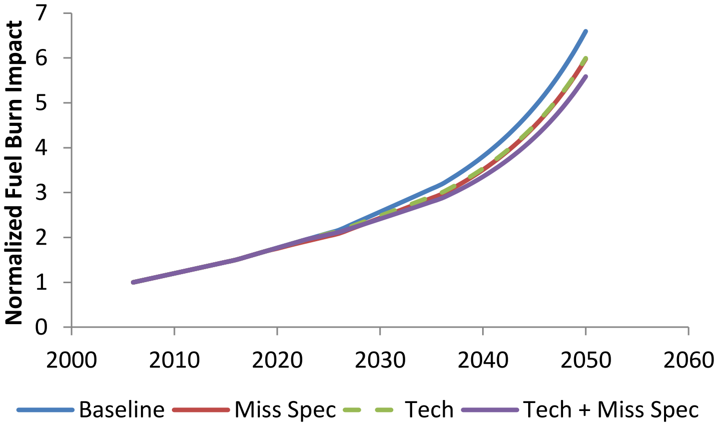


Figure 128. Normalized Impact of Joint Reduction on Fuel Burn

CHAPTER 9

SENSITIVITY ANALYSIS OF ASSUMPTIONS

In the previous three chapters, all of the inputs were fixed except for the respective specification change of interest. Although there is nothing inherently wrong with that approach, changing some of the underlying assumptions will have impacts as to what the resulting best case aircraft would be at the fleet level. The chapter explores three elements to understand how variation in those parameters impacts the best case fleet results. These are changes in the five cost elements, changes in annual aircraft utilization, and variation in the distribution of intermediate stops over the relevant routes.

9.1 Cost Changes

Fixed cost assumptions do not take into account the impact that any changes in costs would have on the fleet. This could have a significant impact in terms of what strategy would become preferential. Therefore, the goal of this study is to assess the influence that any changes would have on total cost due to speed and range reduction. As a reminder, the five cost elements are fuel price, crew rates, maintenance rates, route fees, and landing fees.

9.1.1 Speed Reduction

For speed reduction, the initial operations set is constant such that any changes in route or landing fees would be across the board, which means any changes would be constant. This leaves fuel price and crew/maintenance rates as the remaining assumptions of interest. While it would be ideal to look at increases in crew and maintenance cost separately, there is no easy way to separate the speed reduced aircraft from the baseline speed versions just from the results and therefore their changes will be modeled jointly.

To get perspective on how influential increasing these costs are, Figure 129 compares their impact on cumulative total cost for the baseline technology levels with no speed reduction. The trends are nearly identical for the future results so these will not be provided. Total cost shows significant sensitivity to smaller increases in fuel price with almost a 50% increase in cost from doubling fuel price. This is not surprising as fuel price is a significant portion of fleet costs. In tripling the current crew and maintenance costs, there is a 53% increase in cumulative total cost. On the other hand, while a two thirds fuel price reduction and halving crew/maintenance rates both provide reductions to total cost, reductions in fuel price are significantly more effective.

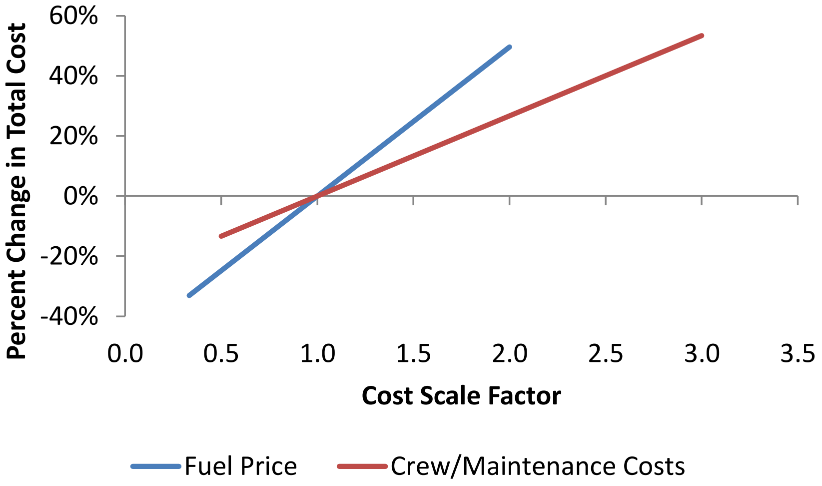


Figure 129. Total Cost Sensitivity to Fuel and Crew/Maintenance Variation – No Action

Fuel price was varied from a third of the baseline price at $1.00/gallon up to $6.00/gallon in $1/gallon intervals to assess the sensitivity that it would have on total cost with respect to each fuel price. The lower bound represents something closer to the turn of the century while the maximum represents a much more severe version of the spike in fuel price during the 2000s.

Figure 130 compares the optimal cruise speed for minimum total cost for all five aircraft seat classes as a function of fuel price for the baseline technology level. As fuel price rises, the larger seat classes shift towards slower cruise speeds. This is not particularly surprising given the strong effect that fuel burn has on total fleet costs. It is worth noting though that as fuel price rises, the total cost benefits yield diminishing returns such that the additional benefits are not as large compared to nearby variants. Conversely, when fuel price drops, the cruise speed for minimum total cost is faster for many of the seat classes; the single aisle is constant as M0.78 is the baseline cruise speed.

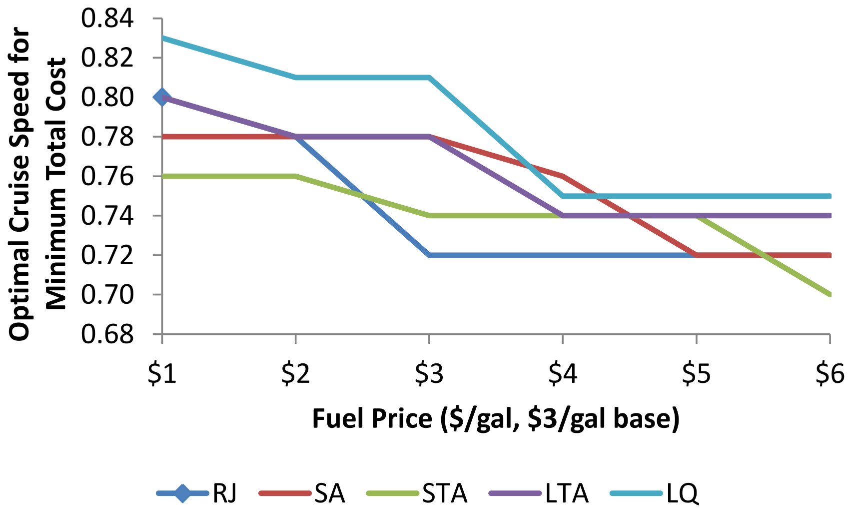


Figure 130. Optimal Cruise Speed for Minimum Total Cost based on Fuel Price - Base Technology

The introduction of technology has different effects to the minimum cruise speed based on the seat class of interest. The regional jet speeds are slower than its baseline counterpart. But for the other four aircraft, the cruise speeds at the higher fuel prices are a step or two faster while largely unchanged for fuel prices below the baseline fuel price. The increase in speed for the larger aircraft is due to the fact that technology has already significantly reduced fuel consumption such that the other cost components become slightly more significant. Additionally, speed reduction is less effective in terms of fuel burn reduction with the introduction of technology such that the fuel savings are much less as well in comparison to the crew and maintenance costs, which are unchanged.

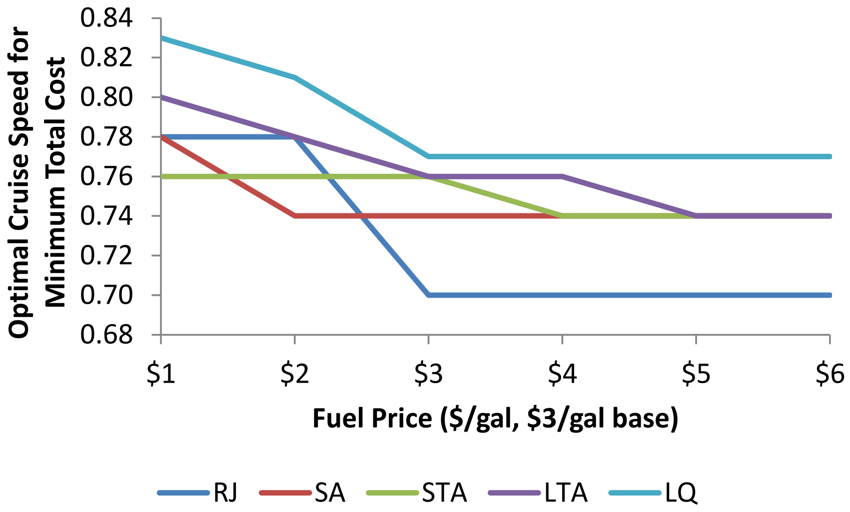


Figure 131. Optimal Cruise Speed for Minimum Total Cost based on Fuel Price - Future Technology

Crew and maintenance rates were uniformly varied from the 50% of the baseline value up to 300% for all seat classes. As previously mentioned, it is far harder to distinguish the two so they have been assessed together. The trends here are the opposite of the fuel price, the expected outcome. If the flight crew unions were to insist on much higher salaries or parts shortages increased maintenance costs, the financial benefits of speed reduction are quickly diminished. However if business continues as usual with flight crew salaries continually decreasing and reliability continuing to improve and bring down maintenance costs, the penalties to flying slower cruise speeds are significantly diminished.

Figure 132 contains the baseline technology trends of optimal cruise speed for minimum total cost for all five aircraft. For the majority of seat classes, increasing the crew and maintenance rates eventually result in faster cruise speeds. The single aisle is not affected as M0.78 is the design cruise speed for this aircraft. It is worth noting though that the larger aircraft are much less sensitive with respect to cruise speed and cost increases than the regional jet as increases for those aircraft are only one variant faster while the regional jet is three. If rates are reduced, three aircraft see potential benefits in cost by flying slower.

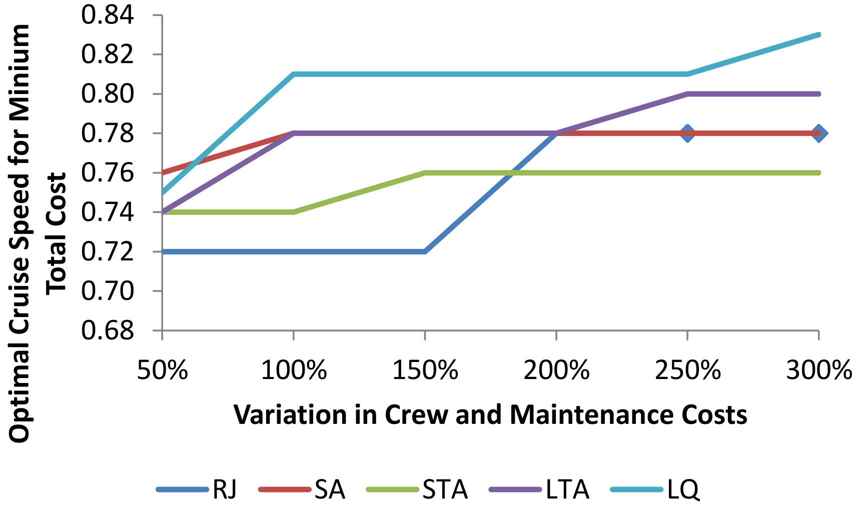


Figure 132. Optimal Cruise Speed for Minimum Total Cost based on Crew/Maintenance Rates - Base Technology

Figure 133 demonstrates the impact of crew and maintenance rate variation for the future technology aircraft. Many of the results are similar between the two technology levels at the higher rates except for the regional jet, which has a much greater preference towards flying faster, especially with a 50% increase in rates. For rates at 150% or less, the single aisle benefits from speed reduction.

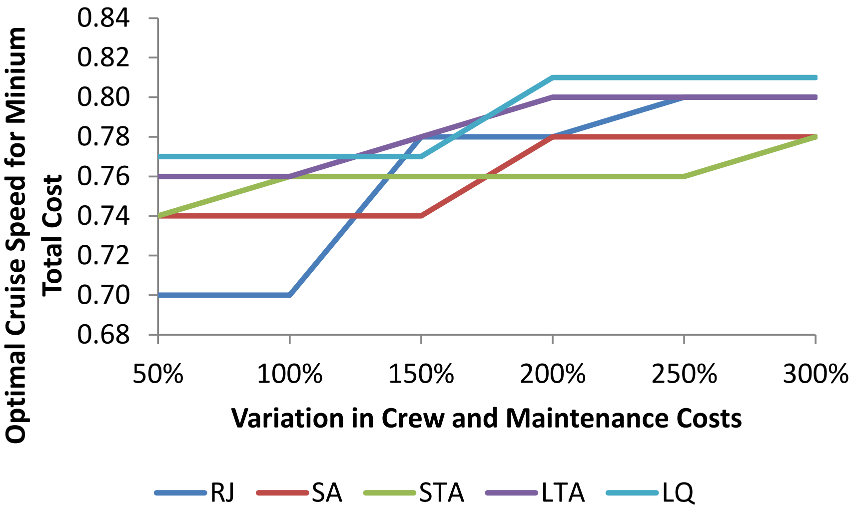


Figure 133. Optimal Cruise Speed for Minimum Total Cost based on Crew/Maintenance Rates - Future Technology

9.1.2 Range Reduction

For range reduction, cruise speed is fixed such that any changes in crew and maintenance rates would be across the board, resulting in any changes being constant. This leaves fuel, route fees, and landing fees as the cost assumptions to explore. The latter two are particularly important as range reduction is also modeled in conjunction with intermediate stops such that any changes to these two components could completely offset fuel cost savings from range reduction. It is worth noting that the operations set with intermediate stops is constant among a given vehicle such that increases to both costs will also be constant – however, these operations are different from the baseline set such that it merits examination. Note that this study was conducted with 100-0 SR-LR variant distribution.

To get perspective on how influential increasing the three costs are, Figure 134 compares their impact on cumulative total cost for the baseline technology levels with no range reduction. Like the speed analysis, the trends are nearly identical to the future results. Fuel price trends are identical to the previous case. Route fee increases ultimately provide no significant penalty – even at ten times the baseline values, the increase in total cost is just over 10%. Landing fees can end up providing a significant impact to fleet total cost but it takes a significant increase to make that happen. At six times the baseline values, total cost increases by 36%. For reference, if landing fees were halved, the cost savings would only be 4%.

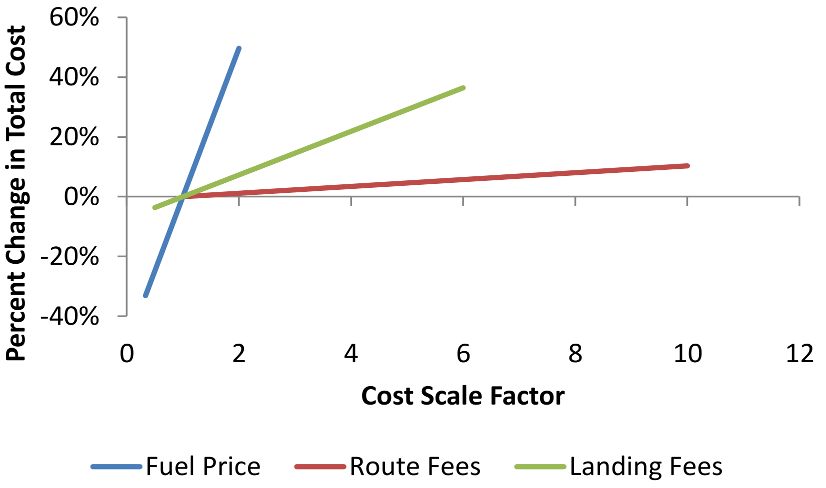


Figure 134. Total Cost Sensitivity to Fuel, Route, and Landing Rate Variation for Range Reduction

Fuel price was varied over the same ranges as before: $1.00/gallon to $6.00/gallon in $1.00/gallon increments. Route fees were varied from the baseline values to ten times those values. The original objective was to scale route fees until the percent change in total cost was similar to fuel burn; however, after a ten times increase and minimal changes to total cost, it was deemed no longer worth of pursuing. Landing fees were examined from half the baseline values up to six times their value. This upper bound was explored due to concerns over operations growth outpacing that of total capacity growth and airports responding with higher fees.

Fuel price variation does not have any significant impact on what short range variant would be considered the optimal aircraft for minimum total cost except for the baseline technology case at $1.00/gallon price. This is demonstrated in Figure 135. For fuel prices $2.00/gallon and above, the short range variant is the same and for the $1.00/gallon price, it becomes the 50% variant for all seat classes due to the significant capital cost savings. However, the initial variants are all relatively close to the 50% results. Future technology remains constant for all fuel prices with the small twin and large twin both minimizing total cost with the 55% variant and the large quad at 50%.

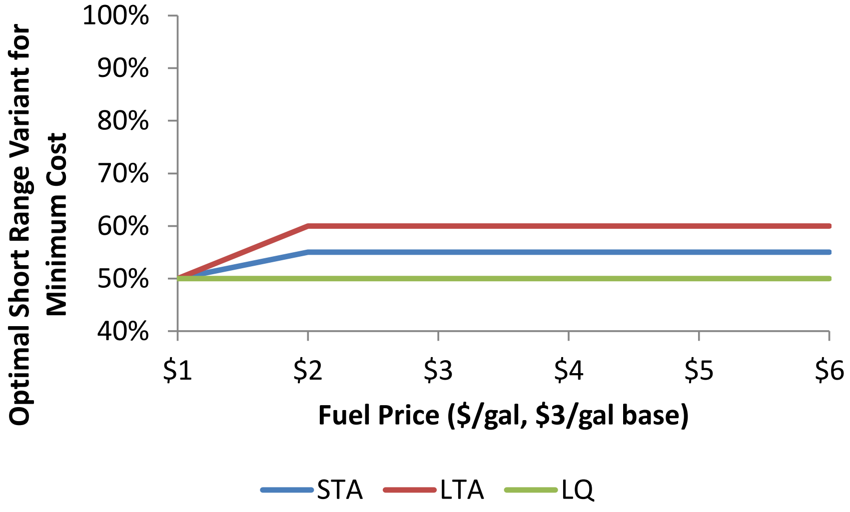


Figure 135. Optimal SR Variant for Minimum Total Cost based on Fuel Price - Base Tech

Varying route fees ultimately proved to be a trivial endeavor with ranges going from the baseline values to 10 times growth. But as route fees do not make up much of a significant component of fleet costs, this is not a surprising finding. With respect to variation on total cost, the impact is most noticeable as vehicle range is reduced and even then, it's at most 0.1% over the three vehicles.

Landing fees were varied from the half the baseline values to up to six times that and unlike route fees, there is a pretty significant impact from landing fee growth even though the changes are constant between all the variants. Although this does not impact which aircraft results in the minimum total cost, the interesting element is where the breakeven design range is for each seat class as that varies significantly between the variations in landing fees. For example, the small twin aisle in Figure 136 initially starts with the 95% range variant being the first to breakeven but when landing fees increase to 3 times, it becomes the 90% variant. At 4 times, the 85% variant is the breakeven variant and then at 5 times, the 80% variant is the breakeven. The large twin and large quad also vary but not to the same degree.

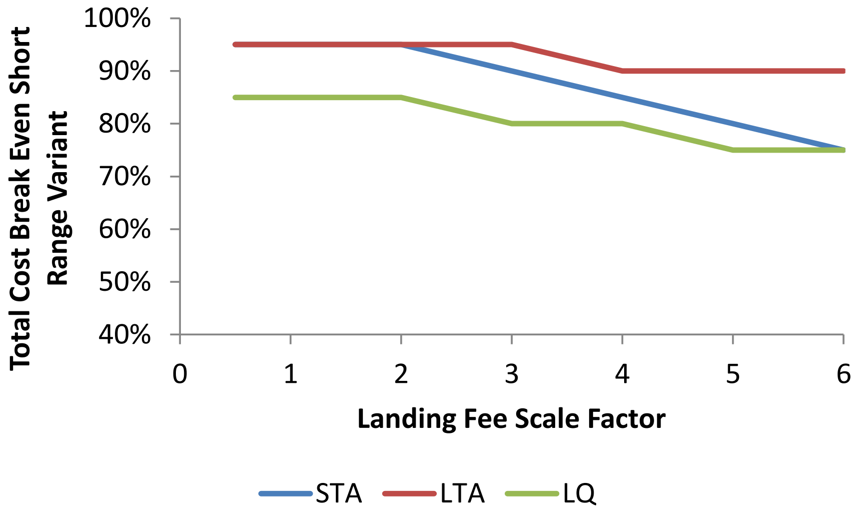


Figure 136. Break Even SR Variant for Landing Fee Variation – Base Tech

Technology introduction has a much greater impact on landing fee sensitivity as its introduction to the aircraft significantly lowers fuel costs and raises capital costs. In Figure 137, there is a much greater level of influence that landing fee increases have on break even variant. Note that all future technology variants save on cost with respect to the cumulative baseline total costs; however, a number of the variants total costs are greater than those with future technology without intermediate stops or range reduction and this will be measured as the break even.

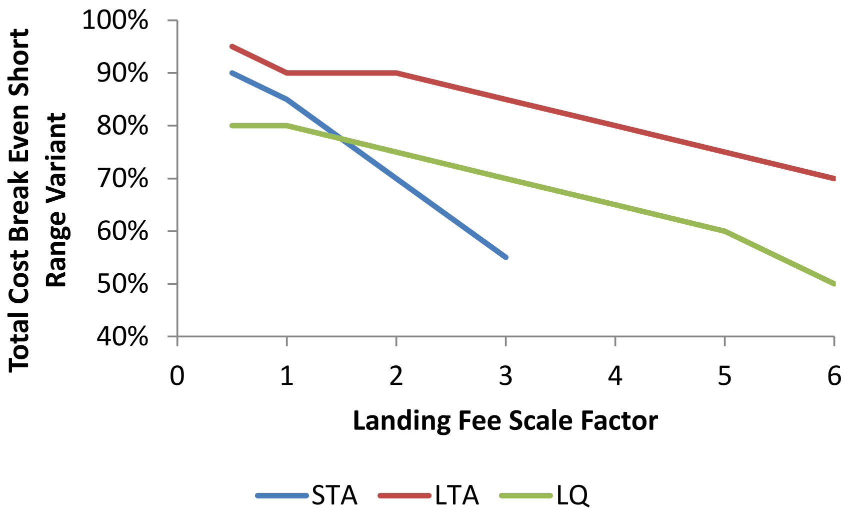


Figure 137. Break Even SR Variant for Landing Fee Variation – Future Tech

The small twin aisle does not break even beyond increased landing fees three times the initial value as the cost penalties from intermediate stops offset the fuel savings that occur. The large twin and large quad require much greater range reduction to break even with respect to the cumulative total cost by 2050 such that for even higher landing fees, the large quad might not break even either.

9.2 Utilization Changes

One of the consequences of speed reduction and intermediate stops is that some flights in the schedule may not work as the aircraft that was intended to be used for one operation has not landed and been turned over, requiring additional aircraft. The analysis in the previous chapters held annual utilization constant and the assumption was that slower aircraft will result in additional flight time and that will require more aircraft. For range reduction and intermediate stops, there is additional flown distance required to arrive at the destination, which will require additional flight time and therefore increase the required total number of aircraft.

However, it may end up that mission specification modified aircraft may not be capable of flying as many hours due to scheduling challenges. In the case of speed reduction, the aircraft may still be capable of operating the same number of flight hours but ultimately these slower cruise speeds may result in the aircraft no longer being able to operate from a particular airport due to curfews or a different aircraft may end up flying that route. For range reduction, the introduction of intermediate stops will require additional turnaround time plus and additional flight time from deviating from the flight track. This would lead to a reduction in annual utilization which will require additional aircraft, ultimately leading to increases capital cost and total cost as well. Therefore, exploring what the sensitivity of utilization on speed and range reduction is important as it will highlight what the impact is as more aircraft are required.

To address the impact that utilization might have on fleet metrics, annual estimates were reduced by 5% and 10% for evaluation for all seat classes modified in the study. As utilization is only used to determine the total number of aircraft, the only metrics evaluated here are the number of replacement aircraft, capital cost, and total cost.

9.2.1 Speed Reduction

Given the number of vehicles, only the trends for the large twin aisle will be provided here. The trends for the other four seat classes are located in Appendix E.

Figure 138 demonstrates the impact that utilization changes have on the required number of aircraft for the large twin for both technology levels. Although it is a little difficult to tell, the future technology results are slightly less due to the four year later entry into service dates for those aircraft. For reference, 1% is approximately 900 aircraft.

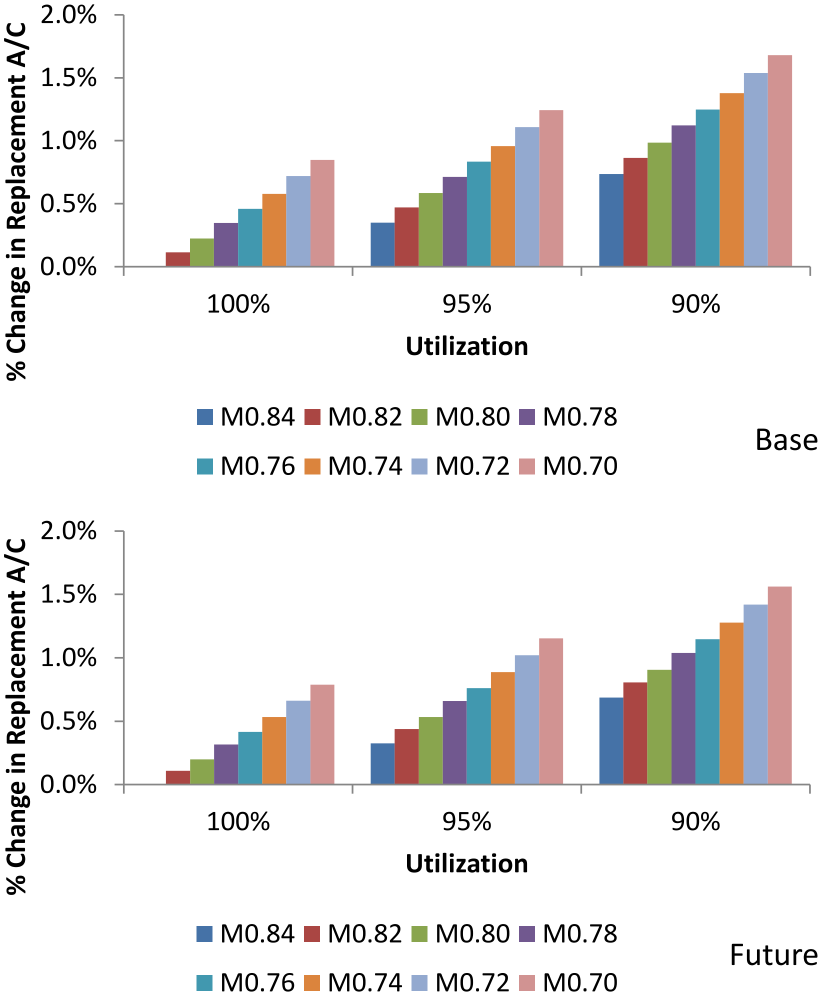


Figure 138. LTA Utilization Sensitivity for Speed Reduction on Number of Aircraft

Capital cost trends are fairly similar to that of the total number of replacement aircraft for the baseline technology results but slightly different for the future technology. This is due to the initial speed reduced variants not requiring more aircraft as quickly as the aircraft price is reduced. Trends for the large twin aisle are in Figure 139 where 1% represents $10.2b cumulatively over six weeks of operations from 2006-2050. Note that the base and future charts are not on the same axis boundaries – the future technology capital cost is much larger due its introduction.

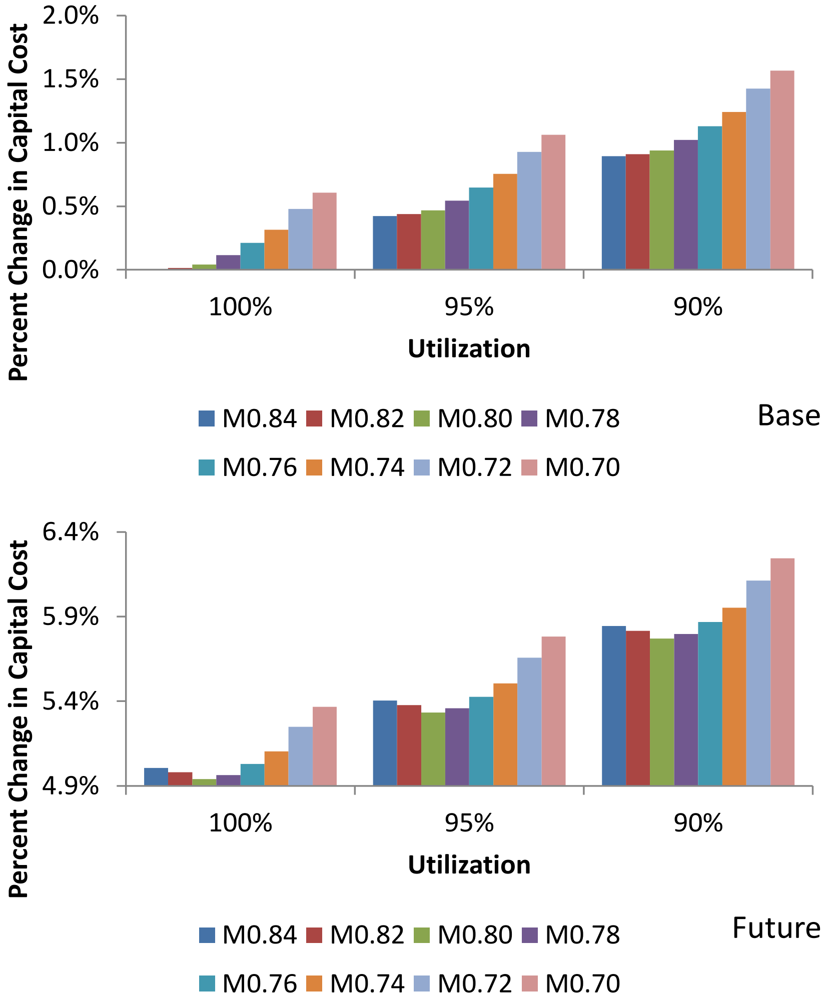


Figure 139. LTA Utilization Sensitivity for Speed Reduction on Capital Cost

Total cost trends provide further insight to the consequences of lowered utilization and are available in Figure 140 for the large twin aisle. At the baseline technology level, the 95% utilization still indicates that a number of speed reduced aircraft can provide total cost savings but they are completely gone at 90% utilization. While all speed reduced variants provide total cost savings over the baseline results, the M0.84 bar (the first one on the left) is the no action savings with just technology. One can see that there are similar trends with utilization reduction in moving from 100% to 95% and 90% when using that bar for comparison purposes. Note that the base and future charts are not on the same axis boundaries – the future technology capital cost is much larger due its introduction. In this figure, 0.1% represents $4.4B over the 2006-2050 for a six week period.

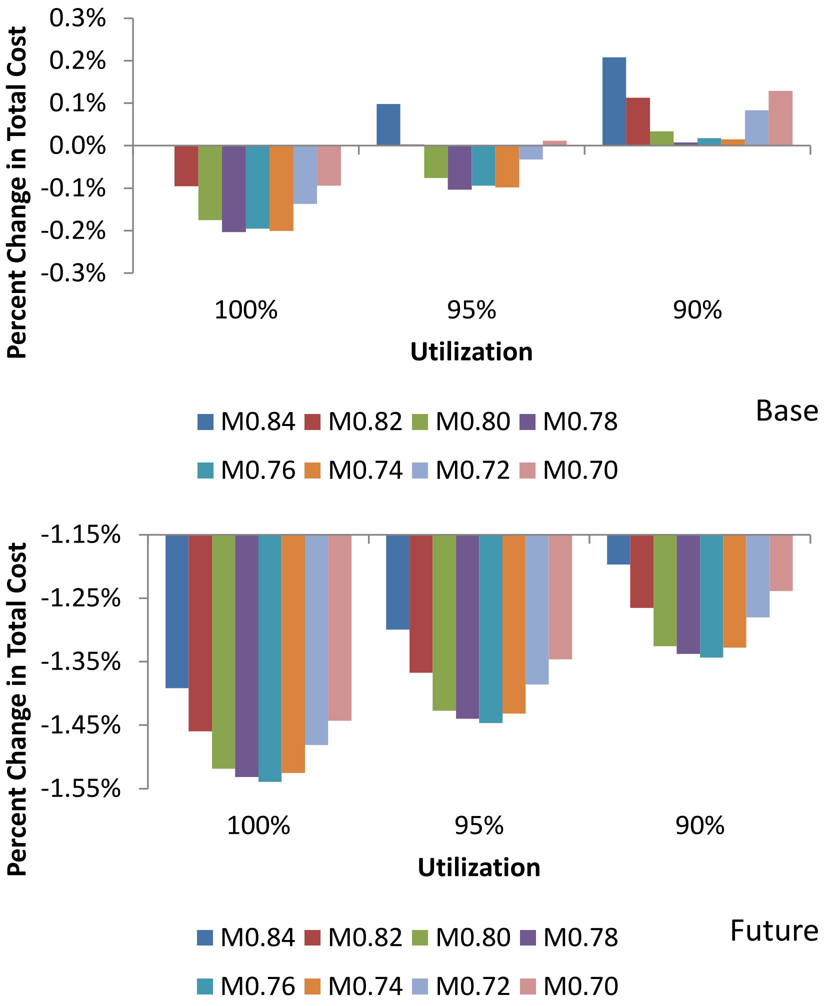


Figure 140. LTA Utilization Sensitivity for Speed Reduction on Total Cost

9.2.2 Range Reduction

Range reduction was modeled slightly differently. It was assumed for the short range variants that the utilization would be decreased by the corresponding percentages while for the long range variants, it would remain the baseline value. This decision was made as the short range variant was most likely to be used on intermediate stops but determining an appropriate distribution to use is somewhat challenging as not all flights are impacted by intermediate stops. The large twin aircraft is presented here. Trends for other two vehicles are located in Appendix E.

For the baseline utilization, the number of aircraft required is constant as all aircraft have the same speed such that there is no contour to be generated. Instead, comparisons will be made between the 95% and 90% results. For reference, the number of required aircraft with 100% utilization is 0.29% for the small twin, 0.13% for the large twin, and 0.53% for the large quad.

Figure 141 compares the differences in the number of aircraft required for the large twin aisle between both utilization and technology levels. The left column is the baseline changes while the right column is the future increase. The top row is the 95% results and their shared contour definitions with the bottom row being the 90% results. As expected, the future results are slightly less than the baseline as the entry into service date is four years later. Another expected behavior from this analysis is that increasing the short range variant distribution results in more aircraft being necessary as those variants have their utilization modified. Again for reference, 1% is approximately 900 aircraft.

The new trend that is the asymptotic behavior of the number of aircraft required beyond a particular range. This occurs due to reaching peak saturation of operations for those variants. So for variants beyond 75% of the original design range of the large twin, the number of flights impacted by utilization changes is nearly constant.

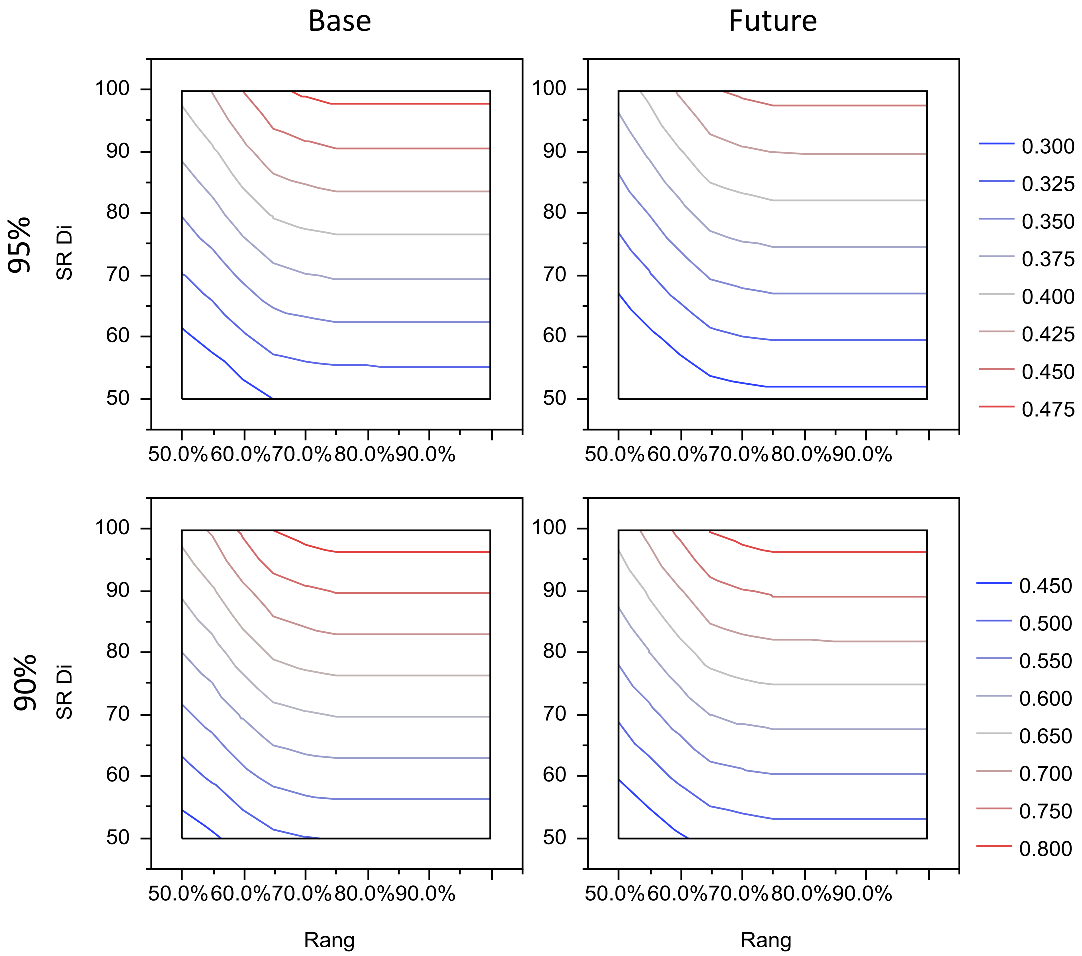


Figure 141. Large Twin Aisle Utilization Sensitivity for Range Reduction on Number of Aircraft

Capital cost trends are similar to total costs such that they will not be provided. A comparison of the total cost impact is available for the utilization and technology levels of the large twin aisle in Figure 142. Note that the columns represent the utilization level while the rows represent the technology level. The corresponding legend for the technology levels is on the right. Decreasing utilization has a profound impact on total cost with respect to range reduction. In particular, the results transition from near universal benefit on the left to approximately 75% benefits. Again, 0.1% represents \$4.4b over the 2006-2050 for a six week period.

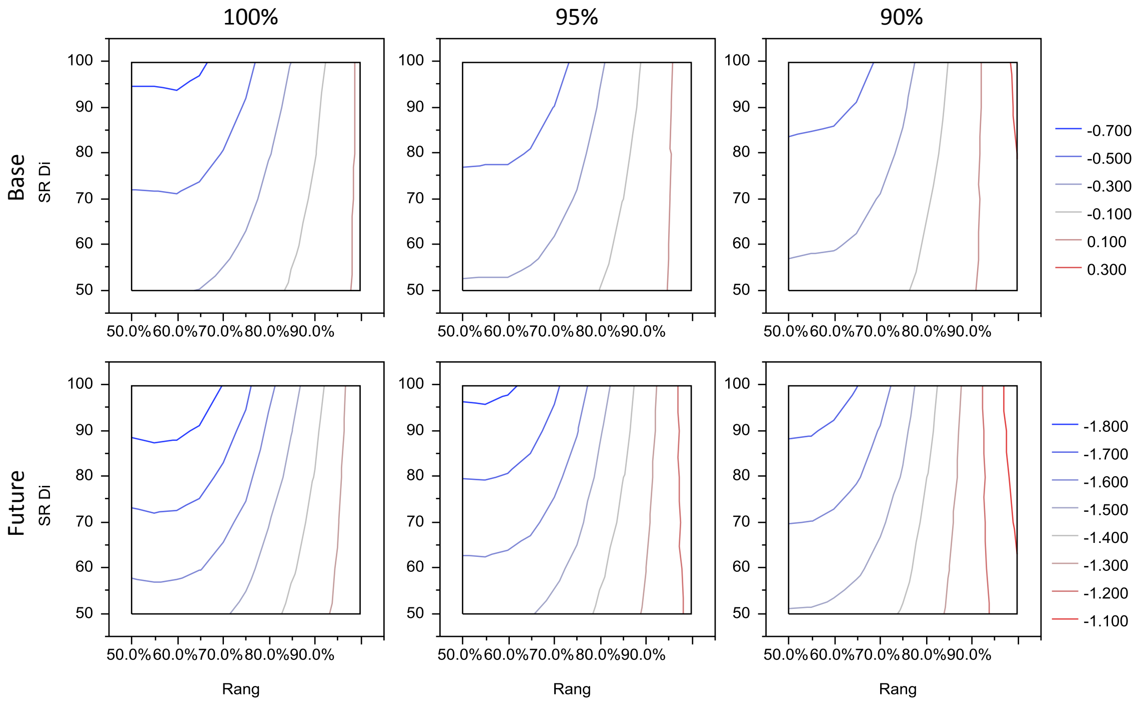


Figure 142. Large Twin Aisle Utilization Sensitivity for Range Reduction on Total Cost

9.3 Intermediate Stop Distribution Variation

Variation in the intermediate stop distribution could occur due to a difference in travel strategies between passenger types. Business or wealthier leisure travelers may ultimately prefer to pay an extra premium for a direct flight over having to make an additional stop. Or some airlines may not adopt the practice at all for logistical reasons. To address this, the range reduced vehicles and variant distributions from the range results are modeled with a 50-50 split of direct-intermediate stop flights for the selected operations and then the initial operating set as is with no modifications. Results for the small twin and large quad are in Appendix E.

The impact to fuel burn is quite significant at both technology levels. Figure 143 demonstrates the sensitivity for the large twin aisle with baseline technology on the top row and future on the bottom. The columns read from intermediate stops to direct only. The impact for the baseline aircraft is around 0.2% greater minimum fuel burn for each transition. The intermediate stop and 50-50 strategies maintain the 60% variant at the minimum fuel burn aircraft but for direct operations, the 65% variant is fuel optimal. The introduction of future technology reduces the impact to 0.1% and the minimum fuel aircraft remains fixed at the 60% range design.

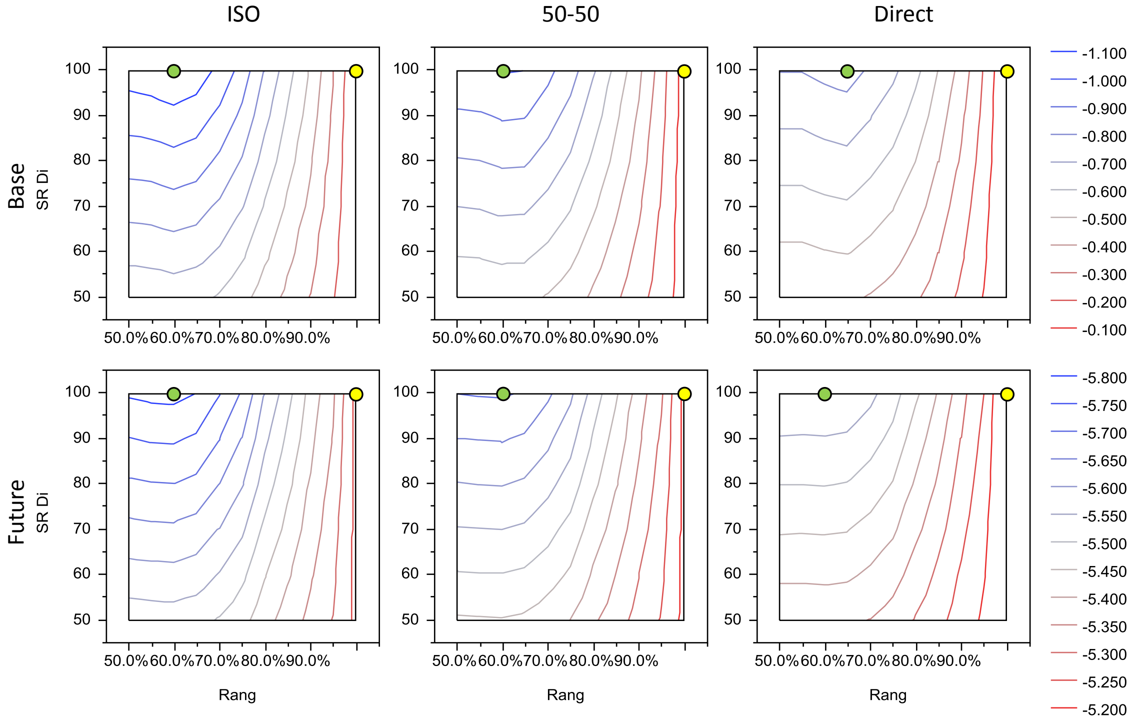


Figure 143. Sensitivity of Intermediate Stop Adoption for Large Twin Aisle Fuel Burn – Range Reduction

Total cost trends behave nearly identical to the fuel burn trends for the baseline technology level. The shift between operating strategies is approximately 0.04%. The selected variants for minimum metric are identical. Future technology behaves fairly similar; however, the aircraft that minimizes total costs remains the 55% design for all strategies. The most notable outcome from transitioning operating schemes is that the nearby variants provide benefits much closer to the 55% variant. For reference, 0.1% represents $4.4B over the 2006-2050 for a six week period.

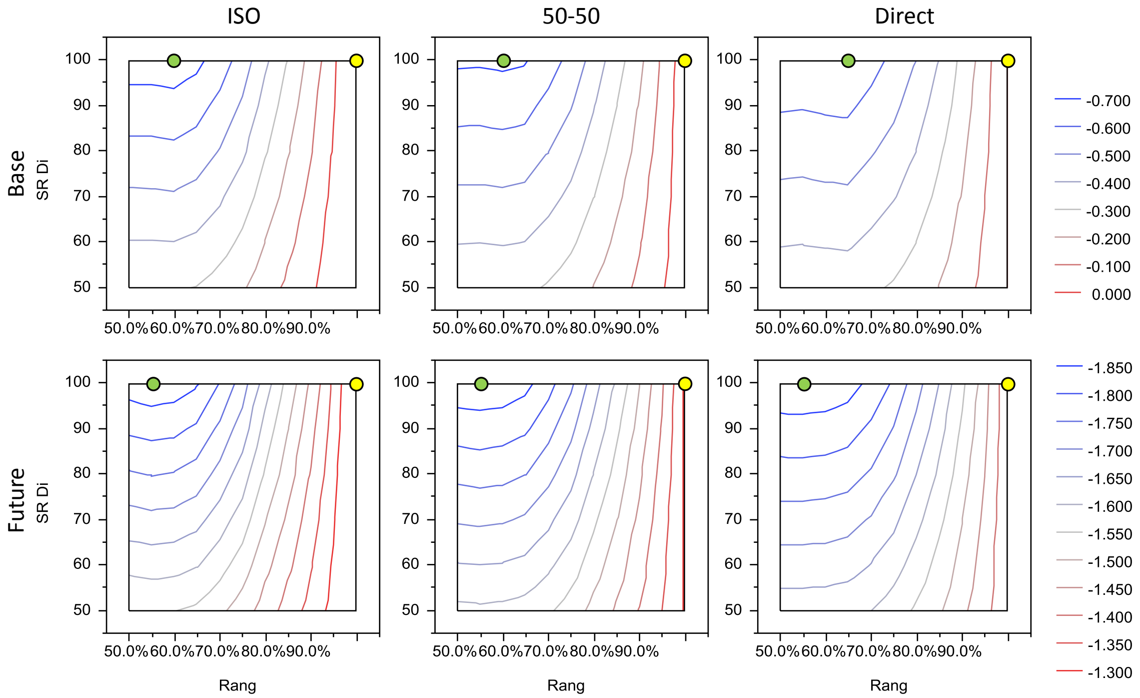


Figure 144. Sensitivity of Intermediate Stop Adoption for Total Cost – Range Reduction

An analysis of the baseline technology noise sensitivity to the variation in operations is available in Figure 145. For the intermediate stop airports, the noise is reduced as expected but when transitioning the operations to the 50-50 split, the noise is also not halved but approximately 60% of the intermediate stop values. The other finding is that noise increases for all the other airport classes in moving from intermediate stops towards direct flights. At first, this was surprising as it was initially expected that the noise would remain in the same general magnitude as the no action. It turns out the increase in noise is due to a mix of the return of louder long range flights that utilize the long range variants and the noisier short range variants operating for short range flights. Combined, they actually increase noise.

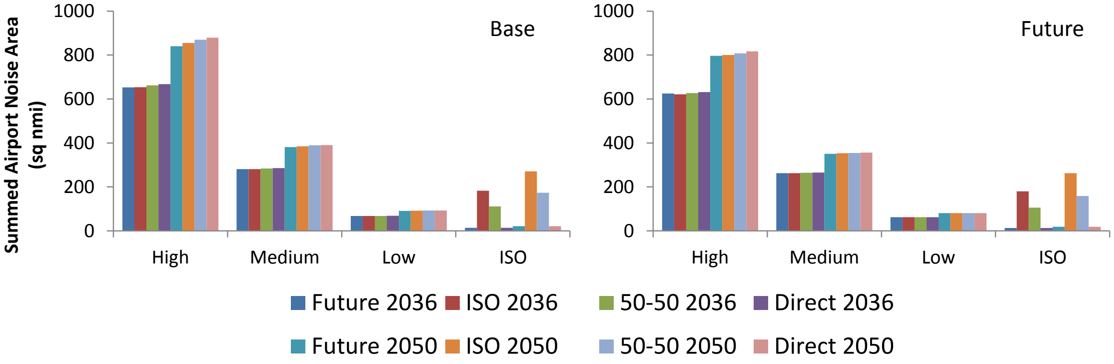


Figure 145. Noise Sensitivity to Intermediate Stop Adoption Variation – 55 dB

Based on these findings, it would appear that varying the level of intermediate stops does not particularly impact the minimum fuel burn or cost aircraft all that significantly. That does not mean to say that 5% or 10% changes in range is small but the initial thought of this study was that the 70% or 75% SR variants would be predominantly more beneficial under direct flights and that was not the case. That being said, the change in magnitudes for all metrics is varied somewhat significantly such that benefits can be reduced by almost half for fuel burn and much less for cost metrics as the fuel savings are somewhat offset by the route and landing fees from using an additional stop. This also suggests that current aircraft designs are overdesigned with respect to range to accommodate a handful of select routes and that it would be far more advantageous to reduce range instead and provide connecting flights for those routes or manufacture two variants. The latter strategy was somewhat considered with the 787-300 but this aircraft was ultimately cancelled from a lack of interested buyers and program delays.

9.4 Summary

The trade studies conducted here have helped to quantify the sensitivities of mission specification changes to changes in economic and operational assumptions. If there is a significant drop in the price of oil, the financial appeal speed and range reduction becomes less appealing strategy even if it reduces uncertainty in operating costs. If there is a continued trend towards reduced crew and maintenance costs, this negative impact is mitigated but one must still address the increase in aircraft. Range reduction, and therefore intermediate stops, will largely be at the mercy of airports and operators will have to hope that landing fees do not significantly increase or this operational strategy will be much less appealing.

Changes to the annual aircraft utilization assumptions were made to help address potential consequences due to baseline estimates potentially being too conservative for estimating the number of aircraft required. For speed reduction, those utilization changes result in many of the aircraft seat classes being no longer cost effective with 95% utilization as the higher capital costs offset the fuel savings and all seat classes being not cost effective at 90%. Range utilization reduction impacts all the variants but predominantly the longer range aircraft are more greatly impacted. This is due to how utilization reduction was modeled – the short range variant was reduced while the long range variant was not as the assumption was that the short range variant was going to operate predominantly on intermediate stop routes.

Variation in operational strategies from intermediate stops to direct flights shows a number of interesting trends. There are reductions in fuel savings as flights transition from intermediate stops to direct but this makes sense as it is the major driver of their usage. Depending on the design range of the variant, total operating costs could rise or decrease due to the interplay between fuel and landing costs. Shorter range variants see operating cost increases while the longer range variants see cost decreases. Additional concerns with respect to capital cost see that higher range aircraft see lower capital costs as the excess distance and flight time from intermediate stops is reduced. Although noise at intermediate stop airports is decreased by shifting back towards direct flights, the louder noise properties of the short range variants in combination with the noise longer range flights result in noisier operations at the other airport groups.

CHAPTER 10

CONCLUSIONS

10.1 Conclusions

This work began by examining the consequences that aviation growth will have on the environment and looked at some of the potential mitigation strategies that are being pursued to aid in reducing the severity of the future impact. This examination led to the observation that many of these efforts are predominantly vehicle or fleet level focused but that mission specification changes are vehicle level changes that could have significant fleet level implications based on the new design requirements. This motivated the research objective of this thesis.

Research Objective: to create a methodology that will enable the evaluation of aircraft mission specification changes at the fleet level over a multitude of metrics.

To address this objective, a literature review on mission specification changes was conducted to understand the state of the art. This identified a predominant number of studies that have been conducted that were focused only at the vehicle level, with only a fixed technology level, predominantly interested in fuel burn only, and one specification change of interest. A handful of these studies looked at the fleet but results were limited only to a fixed technology level, fuel burn, and only one year of fleet operations – essentially all relevant aircraft that could be impacted were replaced with the modified aircraft.

This led to a series of research questions related to mission specification changes:

Research Question 1: What other metrics should be considered when looking at mission specifications?

Research Question 2: How does the introduction of mission specifications impact those metrics?

Research Question 3: How does future growth impact the fleet level metrics?

Research Question 4: How significantly different are the results comparing the immediate replacement vs evolution?

Research Question 5: Does the introduction of advanced technology reduces the impact of mission specification changes?

These questions led to additional literature reviews to eventually generate the following hypotheses.

Hypothesis 1: Fuel burn only analysis is insufficient to adequately capture the impact of mission specification changes at the fleet level.

Hypothesis 2: Mission specification changes must be evaluated at the fleet level and forecasted into the future to capture the overall impact.

Hypothesis 2a: Fleet evolution will be a significant contributor to reducing the overall impact of mission specification changes at the fleet level.

Hypothesis 3: Aircraft technology infusion will reduce the sensitivity of mission specification changes at the fleet level.

When looking at range reduction, one also needs to consider the introduction of intermediate stop operations. This led to two additional questions and one more hypothesis:

Research Question 6: How does one select intermediate airport locations?

Research Question 7: How does airport location impact results in comparison to vehicle level analysis?

Hypothesis 4: A graph theory approach can be used to modify an operations schedule to conduct intermediate stop operations analysis.

To test the Hypotheses 1-3, a modeling and simulation environment was constructed that utilized a number of modeling and simulation tools to conduct vehicle design and fleet forecasting analysis. The metrics that were evaluated were fuel burn and certification NO_x and noise on the vehicle side while the fleet level focused on fuel burn, NO_x emissions, operating cost, capital cost, total cost, safety, and noise over a small set of airports. Three demonstration problems were then conducted to test the methodology: cruise speed reduction, design range reduction, and combined speed and range reduction.

Five reference vehicles were used to design and evaluate mission specification changes that covered the following passenger levels: regional jet, single aisle, small twin aisle, large twin aisle, and large quad. A technology package was identified through literature reviews of current technology programs based on an approximate entry into service date of 2024. These impacted both the engine and airframe such that the interdependencies between the different technologies could be modeled. Mission specification changes were first evaluated at the vehicle level to determine suitability for fleet level consideration.

Cruise speed reduction found that all aircraft benefit from this specification change and therefore moved on to fleet analysis. In testing Hypothesis 1, the results found that all five seat classes have different cruise speeds at the fleet level depending on the metrics of interest. Looking at fuel burn encourages much lower Mach numbers than when one considers operating costs and even more so from the inclusion of capital cost. As a part of testing Hypothesis 2, it was found that three of the seat classes had the same cruise speed for minimum fuel burn in both the vehicle and fleet level with baseline technology; however, the regional jet and large twin aisle showed that the fleet minimum was slower than the vehicle level, indicating that the operational utilization was predominantly much less than the design range. The addition of technology supported this as well. A comparison of the two replacement strategies was conducted to evaluate Hypothesis 2a and it found that when forecasting results to 2050 while baseline technology results ultimately ended up almost the same, the future technology results did not and result in an overestimation of fuel burn savings due to immediate replacement of 2.7% for the baseline vehicles and 9.4% for the future. Finally a comparison of the impacts of speed reduction, technology, and their pairing was conducted to test Hypothesis 3. With respect to fuel burn, the impact was reduced by a quarter while the operating cost and total cost were much more significantly impacted. This analysis largely supports all the hypotheses considered in this sample problem.

Range reduction found that the regional jet and single aisle aircraft did not benefit from range reduction and intermediate stops and were excluded from fleet analysis. The other three aircraft did and required first to identify which operations benefits from their usage and then modification to implement them. The development of an intermediate stop modeling capability serves as a demonstration of Hypothesis 4. The test of Hypothesis 1 resulted in analysis indicating that the variants producing minimum fuel burn and operating cost were the same and when considering capital cost, was constant for the small twin and large quad. The large twin reduced to the minimum range variant as it yields significantly lower capital costs. In testing Hypothesis 2, it was found that with intermediate stops, the small twin and large quad aircraft share the same minimum fuel burn results as their vehicle counterpart while the large twin had a slightly larger range at the fleet level. The evaluation of Hypothesis 2a showed similar results to speed reduction and fuel savings over predictions from immediate replacement of 1.7% and 7.9% for the baseline and future vehicles from entry into service to 2050. Regarding the impact that technology has on range reduction, Hypothesis 3 tests found that future technology reduces fuel savings by 40%, operating cost savings by 45%, and total cost savings by 12%. The cost savings reduction is also heavily influenced by the increase in capital cost from introducing technology. This analysis does not support Hypotheses 1 or 2 but Hypotheses 2a and 3 are still supported.

Based on the results of the speed and range results, the small twin, large twin, and large quad were evaluated for joint speed and range reduction, with the respective speed reduced regional jet and single aisle included. In testing Hypothesis 1, the minimum results for fuel burn, operating cost, and total cost all showed trends that were quite similar to speed and range individually. The cruise speeds of the joint aircraft varied depending on the metric while the ranges did not vary except when capital cost was considered. Hypothesis 2 showed that the speed elements of joint reduction did not vary between vehicle and fleet level analysis; however, their interaction with range did draw the small twin fleet minimum fuel burn to a range that was larger than the vehicle level minimum. Overprediction from immediate replacement was against present in comparing the two replacement strategies with 4.6% more fuel savings reported for the baseline and 10.7% for the future in testing Hypothesis 2a. Baseline technology results become almost the same with this approach but the future technology results are still separated by a large gap. With respect to Hypothesis 3, technology with joint reduction reduced fuel savings by 30%, operating cost savings by 50%, and total cost savings by 25%.

Trade studies were conducted to evaluate how significant variations in the assumptions impact the outcomes from the speed and range analysis. These assumptions were changes in all five cost inputs, aircraft utilization assumptions, and variation of intermediate stops operations from full use to none. For increases in fuel price, both specification changes become more desirable and less so if they decrease. Increases to crew and maintenance rates by 50% will drive cruise speed preferences closer to the baseline speed. Route fee changes have minimal impact to range reduction while landing fees can have a pretty significant impact with respect to what range variant is necessary to break even. Aircraft utilization reductions by even 5% have a significant increase in capital costs and ultimately eliminate the cost feasibility of speed reduction while range reduction is affected but far less significantly. Finally, a variation of intermediate stop feasibility has a strong impact on fuel burn savings but mixed impacts on cost. Both fuel savings and landing fees are reduced which results in higher costs for the short range variants but additional savings for the long range aircraft. Noise is also alleviated at the intermediate stop airports but increases slightly at the larger traffic airports due to interactions between the longer range flights and the noisier short range variants.

10.2 Future Opportunities

In the process of conducting this research, a number of potential future endeavors were found. The first is modifying the vehicle design requirements. In the process of designing the mission specification modified vehicles, the only objective was minimizing the design mission fuel burn. This resulted in very similar noise performance for those aircraft to the baseline variants. If one were to add noise or other metrics as a part of the evaluation process, the overall results will be much different. Additional considerations could be made to the vehicle performance constraints, especially with the addition of technology. This may result in higher fuel burn but could potentially reduce the noise impact of these aircraft and provide some insight to how much fuel burn savings would be sacrificed to get a certain level of noise reduction.

Another observation that came up in doing this work is the limitations that occur when one does not consider tail-tracking. Aircraft do not fly the same route back and forth for their entire lifespan but fly the routes where the airlines need them for future flights. An example might be a flight departing from San Francisco to New York then goes to Miami, Houston, and finally back to San Francisco. Each one of those flights has a departure time that is set based on a number of constraints. If cruise speed reduction were to disrupt one of those legs, then a different aircraft would have to fill that operation. This may not have any significant consequence to the airline if the original aircraft can fit into a later flight. Similar considerations would need to be made for range reduction. To do this analysis, one would need a reference time period, say a week or two, to conduct this analysis and then re-optimize the schedule around mission specification changes. This would give a more realistic picture of changes to the number of aircraft required as well as critical logistical changes that would occur. Ideally, one could also forecast that reference period into a future year and conduct similar analysis with more operations.

Finally, the observation from all three sample problems is that mission specification changes with and without future technology are not a silver bullet in reducing the environmental impact of aviation. Logically, the next step is to evaluate other mitigation strategies that could be used to determine how significant their impact is at the fleet level. If it turns out there is no single mitigation strategy that is capable of doing this on its own, then the next step would be to develop a trade environment between mitigation strategies such that one can make informed decisions between what combinations would reduce the environmental impact of aviation and whether they have other implications and measure their cost effectiveness.

10.3 Contributions

This work provided several contributions to understanding the impact of mission specification changes in both aircraft design and fleet environmental analysis. The primary contribution is the development of a methodology that one can use to evaluate the implications of mission specification changes from the aircraft design level and up through the fleet level. This enables one to have a repeatable process to expand on if other metrics come of interest or different approaches to modeling specification changes are desired.

The second is the analysis of speed reduction, range reduction, and their combination on metrics beyond fuel burn at both the vehicle and fleet level. Much of literature has only focused on the fuel burn savings at the vehicle level and that does not paint the entire picture of the impact of specification changes. Speed reduction is particularly sensitive to cost changes such that increases in certain costs will drive airlines towards faster aircraft regardless of fuel savings. Range reduction is much less sensitive to cost impacts except for landing fees but the potential safety implications as well as noise impacts at the intermediate stop airports may make this strategy infeasible.

The third contribution is a clear approach on how one should consider modeling and evaluating intermediate stops. Existing literature treats this process as a vague step when in reality, it is just as critical as vehicle design and fleet analysis. Criteria for airport selection stem from real physical constraints regarding aircraft size and this is essential to preventing selection of airports that cannot feasibly handle them. A graph theory approach is utilized to identify and select routes based on viable distance and aircraft performance.

The fourth is the importance of fleet forecasting and future technology to evaluating the impact of mission specifications. Traditional fleet level analysis in this area has largely focused on utilizing only one fixed year set of operations and applying the vehicles directly to determine the fleet level impact, which neglects the impact of future growth. While baseline technology level results may not particularly sensitive to this, future technology results are such that it can lead to expectations greater than what could feasibly happen. Additionally, the infusion of technology can offset some of the financial benefits of adopting mission specifications such that its consideration in analysis is important as mission specifications, just like technologies, have to buy their way into the fleet.

APPENDIX A   INTERMEDIATE STOP ANALYSIS SOURCE CODE

This section contains the source code used for the intermediate stop operations generation, analysis, and selection. The main executable is on the following page called ISO_calculate. It sets up some of the assumptions as well as the associated file names where data is located. ISO_calculate also calls the three main functions.

AirportSetup reads in all the airport data as well as calculates the great circle distance between all the input airports for rapid route generation. It requires the lat and long data of all the airports and uses the function greatcircledistance.m, which follows immediately after airportSetup. Note that any filtering based on runway length and width must be done as the code does not conduct any of that analysis itself.

CalculateIntermediateAirports conducts all the distance constraint analysis and generates all the prospective flight paths that should be considered for the performance step. This iterates between all input routes of interest before moving to assess performance.

CalculateIntermediatePerformance does all the fuel burn and cost analysis based in input aircraft data. The current assumption is that aircraft data is input as a second order function of fuel burn and block time as a function of flown distance. If one wishes to directly call an analysis tool, this will need to be developed independently. It was felt that it would be far more rapid to use a surrogate of the code rather than direct calls as the number of prospective flights grows with the number of airports and routes considered.

Some code was written to aid in world plot generation and that is made available for future convenience to anyone that wishes to use it. Finally, the input files for the sample problems are provided as a means to test that the code functions properly.

```
% ISO_calculate.m
% MAIN PROGRAM FOR INTERMEDIATE STOP OPERATIONS %

            %SETUP%
% Route Generation Inputs
  % contains airport id number, lat/long information, and airport region
  % code
airportsfile = 'airports3.csv';
  % contains airport identifier pairs and the aircraft identifier numbers
  % for each route
odpairsfile = 'odpairs2.csv';
GCratio = 1.2;
LBratio = 0.1;

% Route Evaluation Inputs
  % contains aircraft identifier number and performance surrogates for fuel burn and block time -
  % quadratic fit
acdata = importdata('aircraft_data.csv');
aircraftdata = acdata.data;
seatclass = 7;
fuelprice = 3;
  % both are seat class across
crewcost = [190.06 449.72 449.72 475.76 562.59 777.88 886.08 972.88 1165.95 1336.87];
maintenancecost = [276.32 421.1 421.1 421.1 511.79 511.79 511.79 574.64 574.64 574.64];

  % seat class down, region across
landingfees = csvread('landingfees.csv');
  % seat class down, route group across
routefees = csvread('routefees.csv');

routearray.setup = 'false';

% Read in airport information and create a distance matrix between all
% airports
[airports, GCmatrix] = airportSetup(airportsfile);
% Create the prospective routes based on the airports used and the distance
% between them for the odpairs that are input
[routes, routearray] = calculateIntermediateAirports(airports, GCmatrix, odpairsfile, GCratio,
LBratio, routearray);
% Calculate the performance of the aircraft assigned along the routes of
% interest
[fuel_cost, routearray] = calculateIntermediatePerformance(airports, routes, odpairsfile,
aircraftdata, fuelprice, crewcost, maintenancecost, landingfees, routefees, seatclass, routearray);
```

```
function [airports, GCmatrix] = airportSetup(airportsfile)
% for a given input list of airport indentifiers and associated lat/long
% coordinates, this calculates the great circle distance between
%
% INPUTS:
% airportsfile = string containing the name of the csv file with the
%    airport information
%
% OUTPUT:
% airports = airport array from the csv file
% GCmatrix = matrix containing the great circle distance between all the
%    airport pairs - note this is an upper triangular matrix

% read in the airprot data and find the total number of airports
airports = csvread(airportsfile);
apcnt = size(airports,1);

% size the distance matrix appropriately
GCmatrix = zeros(apcnt);

% for each airport, run through and calculate the great circle distance
%    between it and the others remaining on its row. this matrix is an
%    upper triangular as it is symmetrical
for i=1:apcnt,
  lat1 = airports(airports(:,1)==airports(i,1),2);
  long1 = airports(airports(:,1)==airports(i,1),3);
  for j=i:apcnt,
     lat2 = airports(airports(:,1)==airports(j,1),2);
     long2 = airports(airports(:,1)==airports(j,1),3);
     gcdist = greatCircleDistance(lat1*pi/180,long1*pi/180,lat2*pi/180,long2*pi/180) *
0.539957;
     % greatCircleDistance uses radians so lat/long needs to be converted
     GCmatrix(i,j) = gcdist;
  end
  disp(i);
end
```

```
function d = greatCircleDistance(phi_s, lambda_s, phi_f, lambda_f, r)
% compute the great circle distance given lat and long for two points
% optionally, a fifth parameter (r) can be specified. If this paramter
% isn't specified it's assumed to be the mean radius of the earth. The
% calculation is done using the Vincenty formula.
%
% INPUTS:
% phi_s    = latitude of the standpoint (base) [rad]
% lambda_s = longitude of the standpoint (base) [rad]
% phi_f    = latitude of the forepoint (destination) [rad]
% lambda_f = longitude of the forepoint (destination) [rad]
% r        = radius of the sphere [units determine units of d]
%
% OUTPUT:
% d        = great circle distance from standpoint to forepoint
%
% See http://en.wikipedia.org/wiki/Great-circle_distance

% If no arguments, bail out
if nargin < 4
    fprintf('Usage: greatCircleDistance(phi_s, lambda_s, phi_f, lambda_f, r)\n')
    return
end

% If no radius supplied, assume the mean radius of the earth in km
if nargin < 5
    r = 6371.01; % km
end

% convert from degrees minutes seconds to radians as needed
if isstruct(phi_s) || (length(phi_s) > 1 && ~isstruct(phi_s))
    phi_s = dms2r(phi_s);
end
if isstruct(lambda_s) || (length(lambda_s) > 1 && ~isstruct(lambda_s))
    lambda_s = dms2r(lambda_s);
end
if isstruct(phi_f) || (length(phi_f) > 1 && ~isstruct(phi_f))
    phi_f = dms2r(phi_f);
end
if isstruct(lambda_f) || (length(lambda_f) > 1 && ~isstruct(lambda_f))
    lambda_f = dms2r(lambda_f);
end

% Compute Delta lambda (delta longitude)
Delta_lambda = lambda_f - lambda_s;

% Compute Delta sigma (central angle)
Delta_sigma = atan2(sqrt((cos(phi_f)*sin(Delta_lambda))^2 + (cos(phi_s)*sin(phi_f) -
sin(phi_s)*cos(phi_f)*cos(Delta_lambda))^2), ...
```

```
    sin(phi_s)*sin(phi_f) + cos(phi_s)*cos(phi_f)*cos(Delta_lambda));

d = r*Delta_sigma;

function r = dms2r(dms)

if isstruct(dms)
    r = sign(dms.deg)*(abs(dms.deg) + (dms.min + dms.sec/60)/60)*pi/180;
elseif length(dms) == 3
    r = sign(dms(1))*(abs(dms(1)) + (dms(2) + dms(3)/60)/60)*pi/180;
elseif length(dms) == 2
    r = sign(dms(1))*(abs(dms(1)) + dms(2)/60)*pi/180;
else
    r = nan;
end
```

```
function [routes, routearray] = calculateIntermediateAirports(airports, GCmatrix, odpairsfile,
GCratio, LBratio, routearray)
% for a given input list of airport indentifiers and associated lat/long
% coordinates, this calculates the great circle distance between
%
% INPUTS:
% airports    = matrix containing all the airport information
% GCmatrix    = matrix containing the great circle distance between all
% odpairsfile = string containing the name of the odpairs for analysis
% GCratio     = the ratio for which the threshold for neglecting a route
%    of a distance beyond the initial great circle distance
%    threshold = GCratio * (baseline GCdistance)
% LBratio     = the ratio for which the threshold for including an airport based
%    on distance from the departure or arrival airports
%
% OUTPUT:
% routes      = matrix of dimensions: # airports x 6 x # routes
%         the six columns are origin airport, intermediate airport, destination
%                airport, segment 1 distance, segment 2 distance, total distance
% routearray = storage array for all major data

% read in the odpairs data and find the total number of routes
odpairs = csvread(odpairsfile);
odct = size(odpairs,1);

% create a matrix to store all the prospective route information
apcnt = size(airports,1);
routes = zeros(apcnt,6,odct);
debug = zeros(apcnt,6);
% loop through each odpair
for r=1:odct,
   % locates the correct row for distance calculations and the initial
   %    great circle distance
   deprow = find(airports(:,1)==odpairs(r,1));
   arrrow = find(airports(:,1)==odpairs(r,2));
   gcdist = GCmatrix(deprow,arrrow);
   if(gcdist == 0)
      gcdist = GCmatrix(arrrow,deprow);
   end

   % adds the initial route to the routes matrix
   routect = 1;
   disp(r);
   routes(routect,:,r) = [odpairs(r,1) 0 odpairs(r,2) gcdist 0 gcdist];
   debug(routect,:) = [odpairs(r,1) 0 odpairs(r,2) gcdist 0 gcdist];
   routect = routect + 1;

%   prospective route generation calculations
%   - loop through that row in the matrix to evaluate routes
```

```
%       if a segment distance is greater than the GC distance, ignore it
%       if the total distance is greater than GCratio * baseline GC
%         distance, ignore it
%       if both conditions met, then add to a matrix storing all the
%         prospective routes
   for k=1:apcnt,
      if(airports(k,1) ~= odpairs(1,1) && airports(k,1) ~= odpairs(1,2))
         seg1 = GCmatrix(deprow,k);
         seg2 = GCmatrix(k,arrrow);
         % as the matrix is upper triangular, inverse reference if the
         %    distance is 0
         if(seg1 == 0)
            seg1 = GCmatrix(k,deprow);
         end
         if(seg2 == 0)
            seg2 = GCmatrix(arrrow,k);
         end
         routedist = seg1 + seg2;

         % evaluate conditions
         if(seg1 >= gcdist || seg2 >= gcdist || routedist > GCratio * gcdist || seg1 <= LBratio * gcdist || seg2 <= LBratio * gcdist)
         else
            routes(routect,:,r) = [odpairs(r,1) airports(k,1) odpairs(r,2) seg1 seg2 routedist];
            debug(routect,:) = [odpairs(r,1) airports(k,1) odpairs(r,2) seg1 seg2 routedist];
            routect = routect + 1;
         end
      end
   end
   routearray(r).routes = debug(1:(routect-1),:);
end
```

```
function [fuel_cost, routearray] = calculateIntermediatePerformance(airports, routes, odpairsfile,
aircraftdata, fuelprice, crewcost, maintenancecost, landingfees, routefees, seatclass, routearray)

% for a given input list of routes, this determines the performance and cost information for all
% relevant aircraft
%
% INPUTS:
% airports    = matrix containing all the airport information
% routes      = matrix of dimensions: # airports x 6 x # routes
% odpairsfile = string containing the name of the odpairs for analysis
% aircraftdata = input array of surrogate data for aircraft performance
%         aircraft name, aircraft id, fuel burn coefficients, block time coefficients
% fuel price = price of fuel
% crewcost = crew cost array organized by seat class
% maintenancecost = maintenance cost array organized by seat class
% landingfees = landing fees organized by airport region
% routefees = route fees organized by route group and seat class
% seatclass = input setting for the associated seat class of interest
% routearray = storage array for all major data
%
% OUTPUT:
% fuel_cost      = matrix of dimensions: # airports x 6 x # routes
% the six columns are origin airport, intermediate airport, destination
%    airport, segment 1 distance, segment 2 distance, total distance
% routearray = storage array for all major data


odct = size(routearray,2);
fuel_cost = zeros(size(routes,1),10,5,odct);
odpairs = csvread(odpairsfile);

routegroupmatrix = [18 17 6 17 17 1 2;
                    17 19 5 4 10 4 4;
                    6 5 20 3 7 1 2;
                    17 4 3 21 17 9 21;
                    17 10 7 17 22 1 2;
                    1 4 1 9 1 23 8;
                    2 4 2 21 2 8 21];

for i=1:odct,
    apcnt = size(routearray(i).routes,1);
    disp(i);
    for j=1:apcnt,
        accnt = 1;
        while (accnt + 2 <= size(odpairs,2)) && (odpairs(i,2+accnt) ~= 0)
            fuel_s1 = aircraftdata(odpairs(i,2+accnt),2) + aircraftdata(odpairs(i,2+accnt),3) *
routes(j,4,i)+ aircraftdata(odpairs(i,2+accnt),4) * routes(j,4,i)^2;
            fuel_s2 = aircraftdata(odpairs(i,2+accnt),2) + aircraftdata(odpairs(i,2+accnt),3) *
routes(j,5,i)+ aircraftdata(odpairs(i,2+accnt),4) * routes(j,5,i)^2;
```

```
        if(routes(j,5,i) == 0)
          fuel_s2 = 0;
        end
        tot_fuel = fuel_s1 + fuel_s2;

        % cost calculation
        time_s1 = aircraftdata(odpairs(i,2+accnt),5) + aircraftdata(odpairs(i,2+accnt),6) *
routes(j,4,i)+ aircraftdata(odpairs(i,2+accnt),7) * routes(j,4,i)^2;
        time_s2 = aircraftdata(odpairs(i,2+accnt),5) + aircraftdata(odpairs(i,2+accnt),6) *
routes(j,5,i)+ aircraftdata(odpairs(i,2+accnt),7) * routes(j,5,i)^2;
        if(routes(j,5,i) == 0)
          time_s2 = 0;
        end
        routegroup1 =
routegroupmatrix(airports(find(airports(:,1)==routes(j,1,i)),4),airports(find(airports(:,1)==routes(j
,2,i)),4));
        routegroup2 =
routegroupmatrix(airports(find(airports(:,1)==routes(j,2,i)),4),airports(find(airports(:,1)==routes(j
,3,i)),4));
        if(routes(j,5) == 0)
          routegroup1 =
routegroupmatrix(airports(find(airports(:,1)==routes(j,1,i)),4),airports(find(airports(:,1)==routes(j
,3,i)),4));
          %routegroup2 = 0;
        end
        cost_s1 = fuelprice * fuel_s1 * 2.20/6.71 + time_s1 * (crewcost(seatclass+1) +
maintenancecost(seatclass+1)) + 0.539957 * routes(j,4,i) * routefees(seatclass+1,routegroup1) +
landingfees(seatclass+1,airports(find(airports(:,1)==routes(j,2,i)),4));
        cost_s2 = fuelprice * fuel_s2 * 2.20/6.71 + time_s2 * (crewcost(seatclass+1) +
maintenancecost(seatclass+1)) + 0.539957 * routes(j,5,i) * routefees(seatclass+1,routegroup2) +
landingfees(seatclass+1,airports(find(airports(:,1)==routes(j,3,i)),4));
        if(routes(j,5,i) == 0)
          cost_s2 = 0;
          cost_s1 = fuelprice * fuel_s1 * 2.20/6.71 + time_s1 * (crewcost(seatclass+1) +
maintenancecost(seatclass+1)) + 0.539957 * routes(j,4,i) * routefees(seatclass+1,routegroup1) +
landingfees(seatclass+1,airports(find(airports(:,1)==routes(j,3,i)),4));
        end
        tot_cost = cost_s1 + cost_s2;

        fuel_cost(j,:,accnt,i) = [routes(j,1,i) routes(j,2,i) routes(j,3,i) odpairs(i,2+accnt) fuel_s1
fuel_s2 tot_fuel cost_s1 cost_s2 tot_cost];
        routearray(i).aircraft(accnt).id = odpairs(i,2+accnt);
        routearray(i).aircraft(accnt).fuelburn(j,:) = [fuel_s1 fuel_s2 tot_fuel];
        routearray(i).aircraft(accnt).cost(j,:) = [cost_s1 cost_s2 tot_cost];
        accnt = accnt + 1;
      end
  end
end
```

Aids for figure generation

```
% WorldPlotter.m

model = 'LTA';
ISOflag = 0;

if(strcmp('STA',model) == 1)
   csvfile = 'STA-flights.csv';
   csv2 = 'STA-ISO.csv';
elseif(strcmp('LTA',model) == 1)
   csvfile = 'LTA-flights.csv';
   csv2 = 'LTA-ISO.csv';
else
   csvfile = 'LQ-flights.csv';
   csv2 = 'LQ-ISO.csv';
end

worldmap world;
whos -file coast.mat;
load coast;
plotm(lat,long,'k');

flights = csvread(csvfile);
flights2 = csvread(csv2);

ilimit = size(flights,1);
jlimit = size(flights2,1);

for i = 1:ilimit

%[lat,lon] = track2(lat1,lon1,lat2,lon2)
% Need to iterate on this function to do all of it!
   latdep = flights(i,1);
   londep = flights(i,2);
   latarr = flights(i,3);
   lonarr = flights(i,4);
   [lat2,long2] = track2(latdep, londep, latarr, lonarr);
   plotm(lat2,long2,'b');

end

for j = 1:jlimit

%[lat,lon] = track2(lat1,lon1,lat2,lon2)
% Need to iterate on this function to do all of it!
   latdep = flights2(j,1);
   londep = flights2(j,2);
   if(ISOflag == 0)
```

```
        latarr = flights2(j,5);
        lonarr = flights2(j,6);
        [lat2,long2] = track2(latdep, londep, latarr, lonarr);
        plotm(lat2,long2,'r');
    else
        latiso = flights2(j,3);
        loniso = flights2(j,4);
        latarr = flights2(j,5);
        lonarr = flights2(j,6);
        [lat2,long2] = track2(latdep, londep, latiso, loniso);
        plotm(lat2,long2,'r');
        [lat2,long2] = track2(latiso, loniso, latarr, lonarr);
        plotm(lat2,long2,'r');
    end

end
```

```
% ISO_example_airports

worldmap world;
whos -file coast.mat;
load coast;
plotm(lat,long,'k');

airports = csvread('airports_example.csv');
airports2 = csvread('airports_example2.csv');

scatterm(airports(:,1),airports(:,2),30,'k','filled');
scatterm(airports2(1,1),airports2(1,2),30,'r','filled');
scatterm(airports2(2,1),airports2(2,2),30,'r','filled');
scatterm(airports2(3,1),airports2(3,2),30,'r','filled');
scatterm(airports2(4,1),airports2(4,2),30,'b','filled');
```

```
% ISO_example_plotter.m

ax = worldmap('World');
setm(ax, 'Origin', [0 180 0])
%worldmap world;
whos -file coast.mat;
load coast;
plotm(lat,long,'k');

flights = csvread('results.csv');

ilimit = size(flights,1);

for i = 1:ilimit

%[lat,lon] = track2(lat1,lon1,lat2,lon2)
% Need to iterate on this function to do all of it!
   j = ilimit - i + 1;
   if(j == 1)
      latdep = flights(j,1);
      londep = flights(j,2);
      latarr = flights(j,5);
      lonarr = flights(j,6);
      [lat2,long2] = track2(latdep, londep, latarr, lonarr);
      plotm(lat2,long2,'b','LineWidth',3);
   else
      latdep = flights(j,1);
      londep = flights(j,2);
      latiso = flights(j,3);
      loniso = flights(j,4);
      latarr = flights(j,5);
      lonarr = flights(j,6);
      [lat2,long2] = track2(latdep, londep, latiso, loniso);
      if(j == 2)
         plotm(lat2,long2,'r','LineWidth',3);
      else
         plotm(lat2,long2,'k','LineWidth',1.5);
      end
      [lat2,long2] = track2(latiso, loniso, latarr, lonarr);
      if(j == 2)
         plotm(lat2,long2,'r','LineWidth',3);
      else
         plotm(lat2,long2,'k','LineWidth',1.5);
      end
   end
end
```

Input vehicle information

Note that the heading rows are provided only for context for the reader. They should be removed in implementation. Additionally, the airports list has been split to be included all on one page. It should be only fifty three rows by three columns (CITY NAMES SHOULD BE REMOVED – they are provided for reference).

Vehicle Name	TotFB a	TotFB b	TotFB c	TotBT a	TotBT b	TotBT c
B747 G2	5624.4001	16.598963	0.0010421	0.169425666	0.002040988	2.33E-10

Route O	Route D
23742	6025
23742	22065
23742	946

APT_ID	LAT	LON	City	APT_ID	LAT	LON	City
1	24.44339	54.65271	Abu Dhabi	28	52.30861	4.763889	Amsterdam
2	25.25142	55.37056	Dubai	29	-37.0081	174.7917	Auckland
3	-37.6733	144.8433	Melbourne	30	-43.4889	172.5322	Christchurch
4	-33.9461	151.1772	Sydney	31	-12.0219	-77.1143	Lima
5	48.93702	-54.5681	Gander	32	10.30754	123.9794	Philippines
6	43.67722	-79.6306	Toronto	33	14.50865	121.0196	Philippines
7	45.68042	-74.0387	Montreal	34	55.9727	37.4148	Moscow
8	23.39244	113.2988	Guangzhou	35	41.98165	-87.9067	Chicago
9	40.07244	116.5975	Beijing	36	39.04884	-84.6678	Cincinnati
10	31.14409	121.7924	Shanghai	37	32.89683	-97.038	Dallas
11	50.03331	8.570456	Frankfurt	38	39.86167	-104.673	Denver
12	40.49544	-3.56011	Madrid	39	42.21244	-83.3534	Detroit
13	-17.755	177.4438	Fiji	40	42.36297	-71.0064	Boston
14	49.01278	2.55	Paris	41	29.98443	-95.3414	Houston
15	51.14806	-0.19028	London	42	33.63672	-84.4281	Atlanta
16	51.4775	-0.46139	London	43	21.31868	-157.922	Honolulu
17	13.48387	144.7972	Guam	44	40.63975	-73.7789	New York City
18	-6.12572	106.6565	Indonesia	45	33.9425	-118.408	Los Angeles
19	41.80448	12.2508	Rome	46	25.79536	-80.2901	Miami
20	34.85842	136.8054	Nagoya	47	40.6925	-74.1687	Newark
21	34.43361	135.2336	Osaka	48	39.87225	-75.2409	Philadelphia
22	35.77706	140.3824	Tokyo	49	33.43428	-112.012	Phoenix
23	37.46414	126.4405	Seoul	50	40.78839	-111.978	Salt Lake City
24	33.36743	-7.58996	Morocco	51	37.61897	-122.375	San Francisco
25	19.43644	-99.0719	Mexico City	52	61.17408	-149.998	Anchorage
26	2.745578	101.7099	Malaysia	53	38.94744	-77.4599	Washington DC
27	5.297139	100.2769	Malaysia				

APPENDIX B SPEED REDUCTION FIGURES

This appendix contains figures for the vehicles not included in the speed reduction chapter as well as respective aircraft prices. For vehicle design and fleet analysis, this is the single aisle, small twin aisle, and large quad.

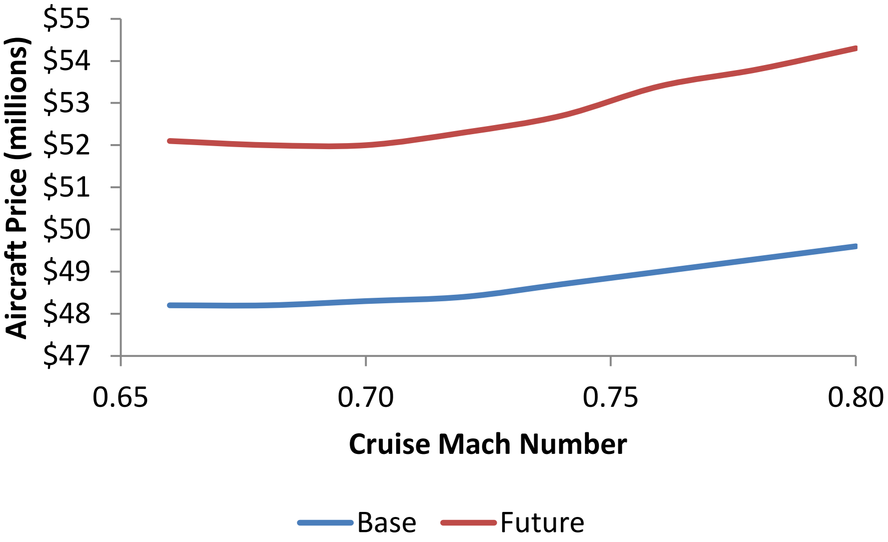


Figure 146. RJ Speed Reduction Aircraft Prices

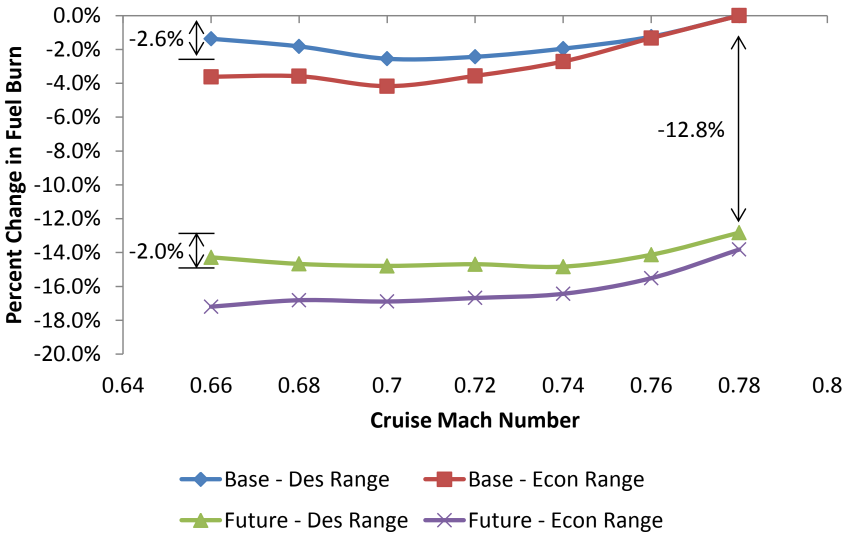


Figure 147. SA Fuel Burn Impact of Speed Reduction

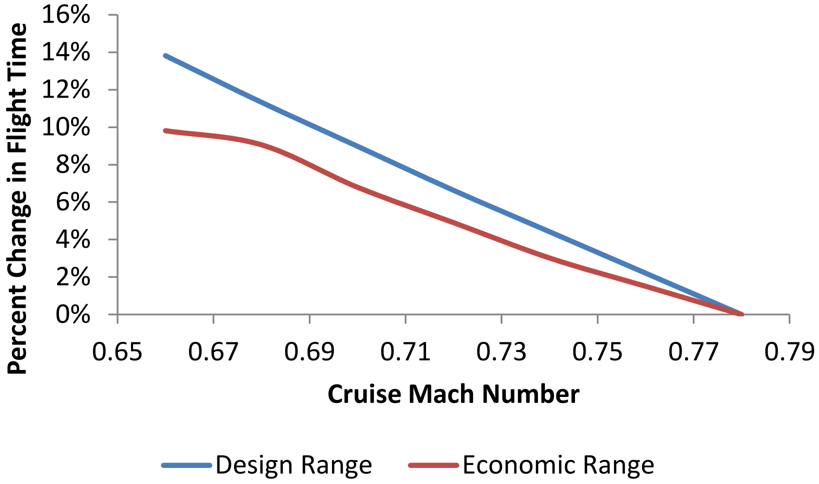


Figure 148. Impact of Speed Reduction on SA Flight Time

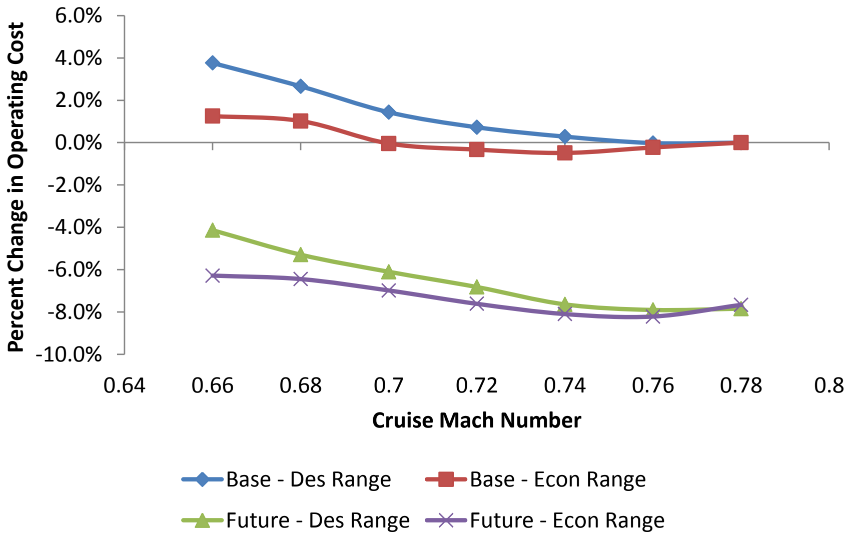


Figure 149. SA Operating Cost Impact of Speed Reduction

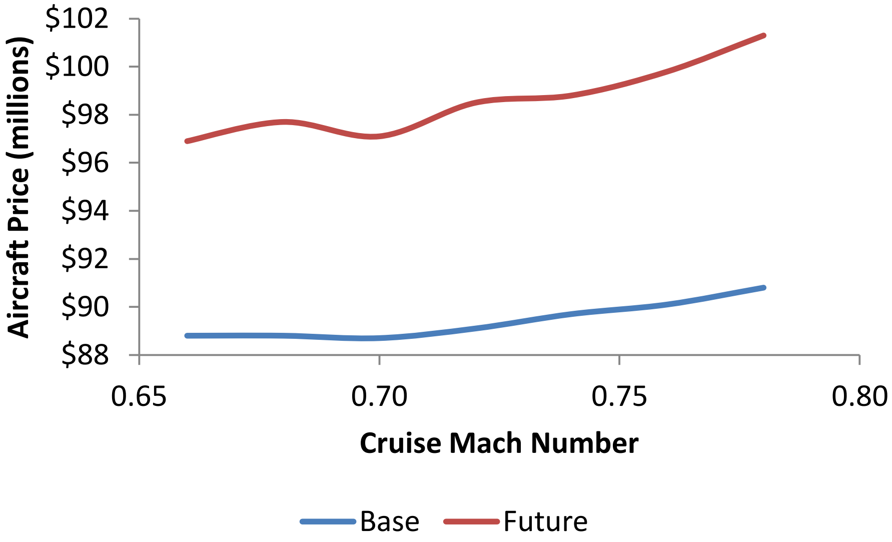


Figure 150. SA Speed Reduction Aircraft Prices

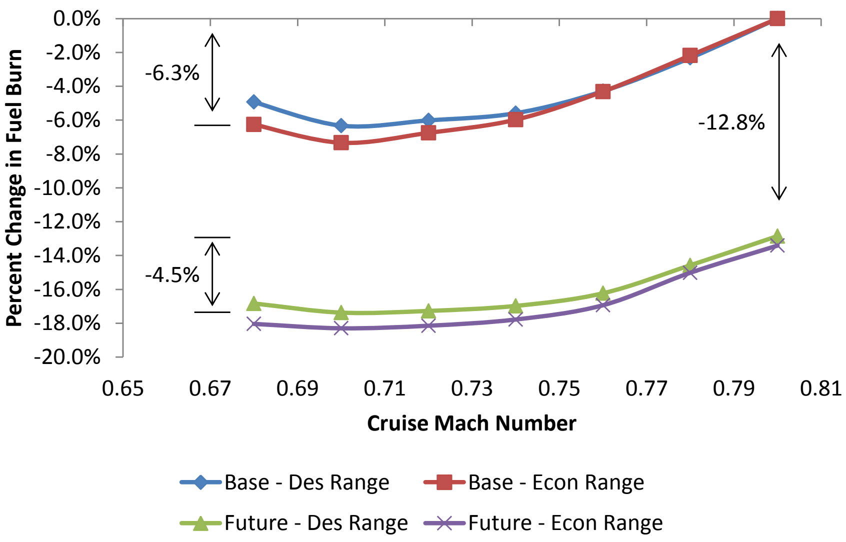


Figure 151. STA Fuel Burn Impact of Speed Reduction

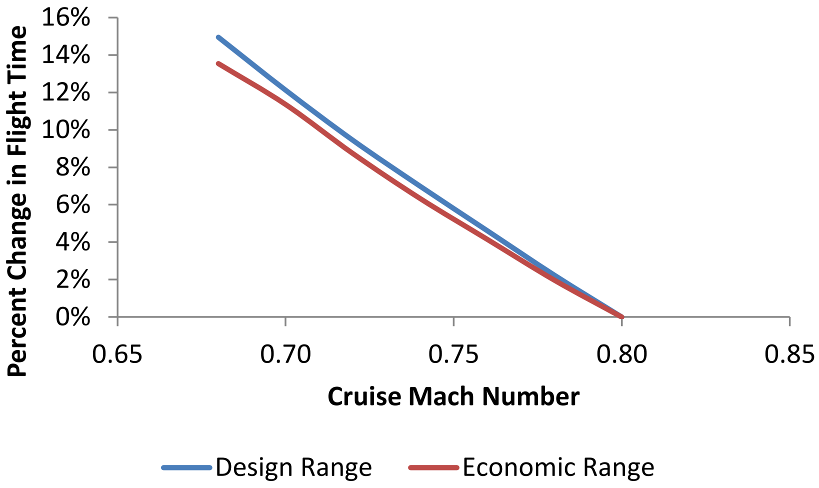


Figure 152. Impact of Speed Reduction on STA Flight Time

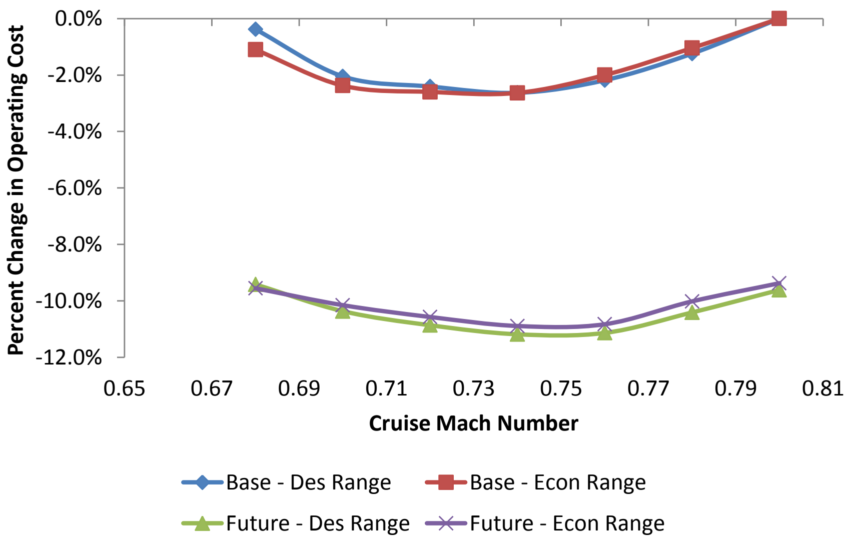


Figure 153. STA Operating Cost Impact of Speed Reduction

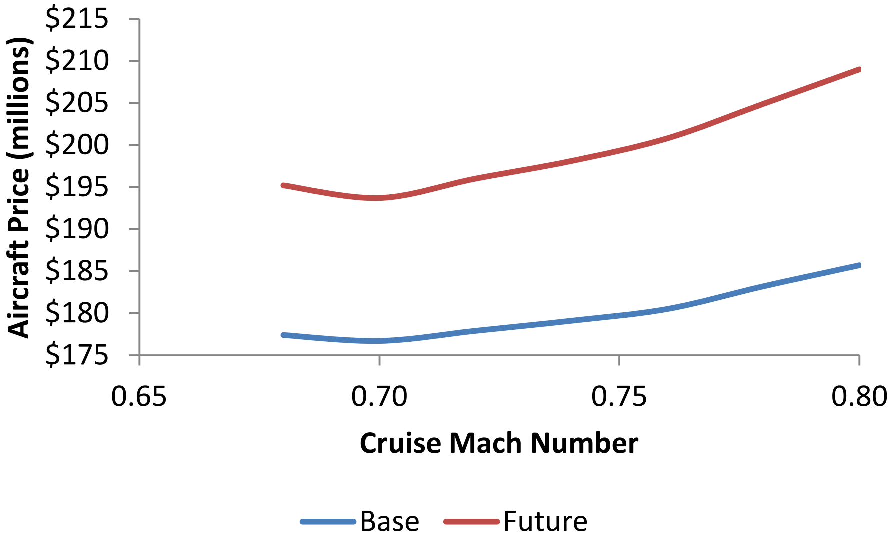


Figure 154. STA Speed Reduction Aircraft Prices

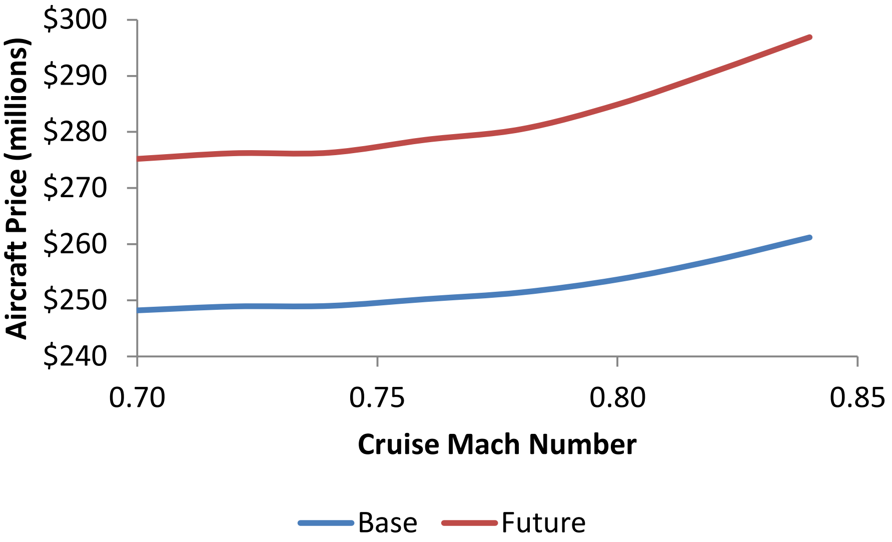


Figure 155. LTA Speed Reduction Aircraft Prices

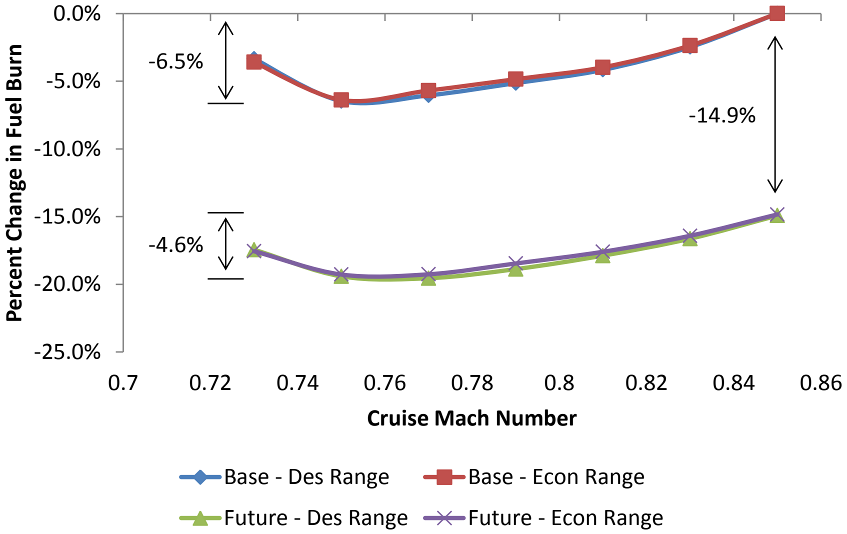


Figure 156. LQ Fuel Burn Impact of Speed Reduction

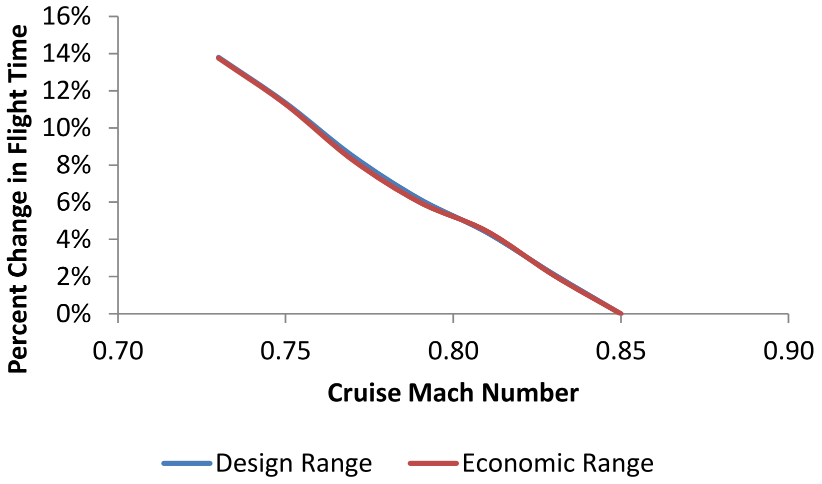


Figure 157. Impact of Speed Reduction on the LQ Flight Time

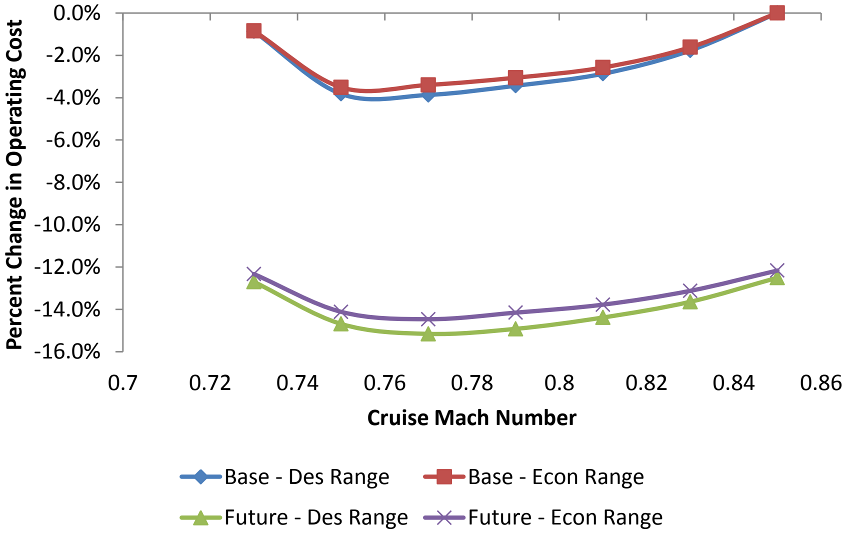


Figure 158. LQ Operating Cost Impact of Speed Reduction

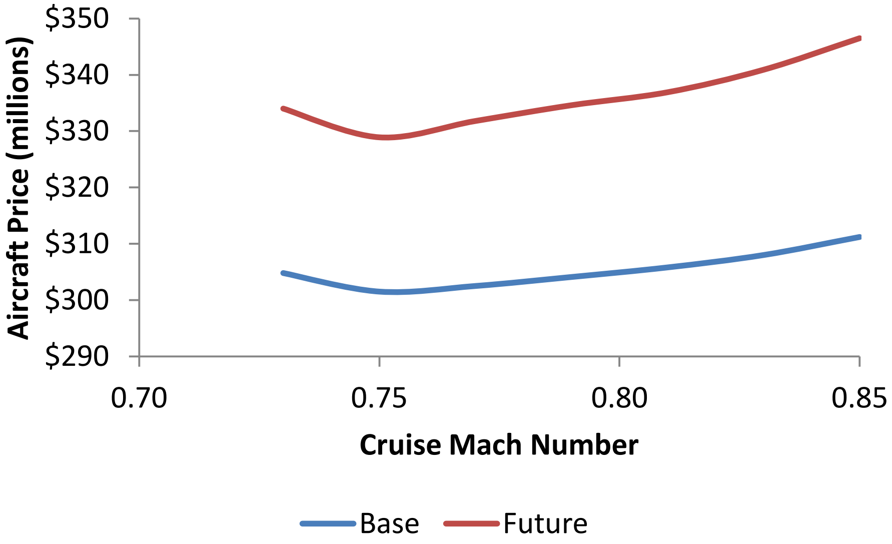


Figure 159. LQ Speed Reduction Aircraft Prices

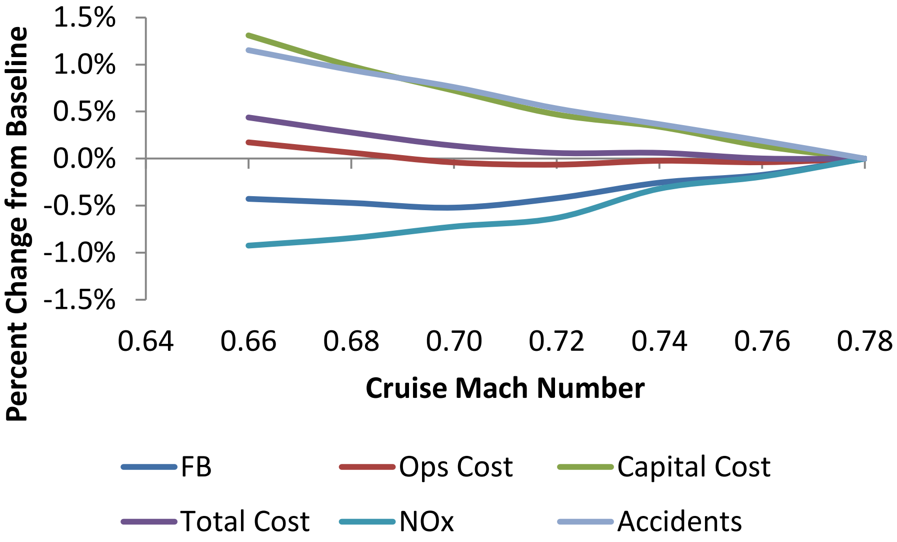


Figure 160. SA Base Cumulative Speed Reduction Fleet Results

Table 59. SA Base Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO_x	Number of Aircraft	Accidents
0.78	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.76	-0.17%	-0.04%	0.13%	0.00%	-0.19%	0.51%	0.19%
0.74	-0.26%	-0.02%	0.34%	0.06%	-0.32%	0.98%	0.37%
0.72	-0.42%	-0.06%	0.47%	0.06%	-0.63%	1.43%	0.53%
0.70	-0.52%	-0.04%	0.72%	0.14%	-0.72%	2.04%	0.76%
0.68	-0.47%	0.06%	0.98%	0.28%	-0.85%	2.52%	0.94%
0.66	-0.43%	0.17%	1.31%	0.44%	-0.92%	3.09%	1.15%

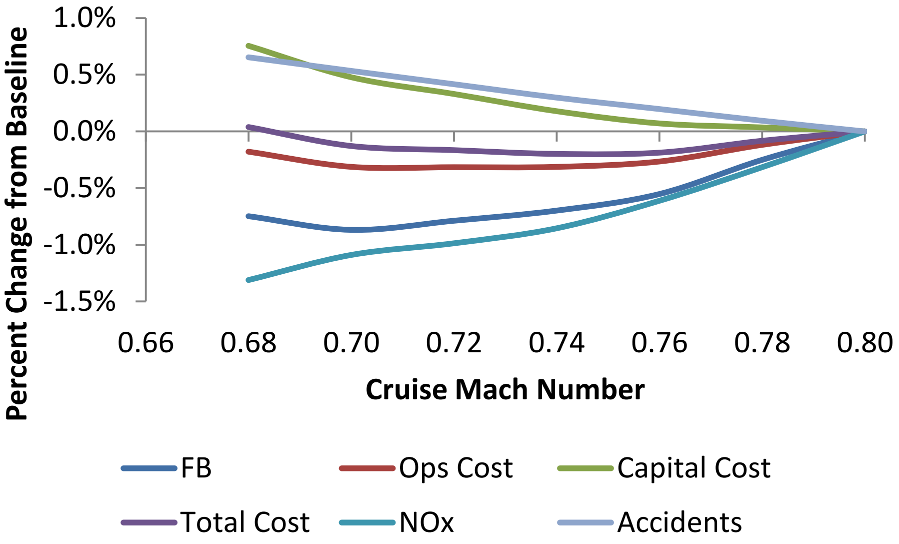


Figure 161. STA Base Cumulative Speed Reduction Fleet Results

Table 60. STA Base Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO_x	Number of Aircraft	Accidents
0.80	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.78	-0.25%	-0.12%	0.04%	-0.08%	-0.32%	0.19%	0.09%
0.76	-0.55%	-0.27%	0.07%	-0.19%	-0.61%	0.39%	0.20%
0.74	-0.70%	-0.31%	0.18%	-0.20%	-0.85%	0.59%	0.30%
0.72	-0.79%	-0.32%	0.33%	-0.17%	-0.99%	0.83%	0.42%
0.70	-0.87%	-0.31%	0.48%	-0.13%	-1.09%	1.06%	0.53%
0.68	-0.75%	-0.18%	0.75%	0.04%	-1.31%	1.30%	0.65%
0.66	-0.25%	-0.12%	0.04%	-0.08%	-0.32%	0.19%	0.09%

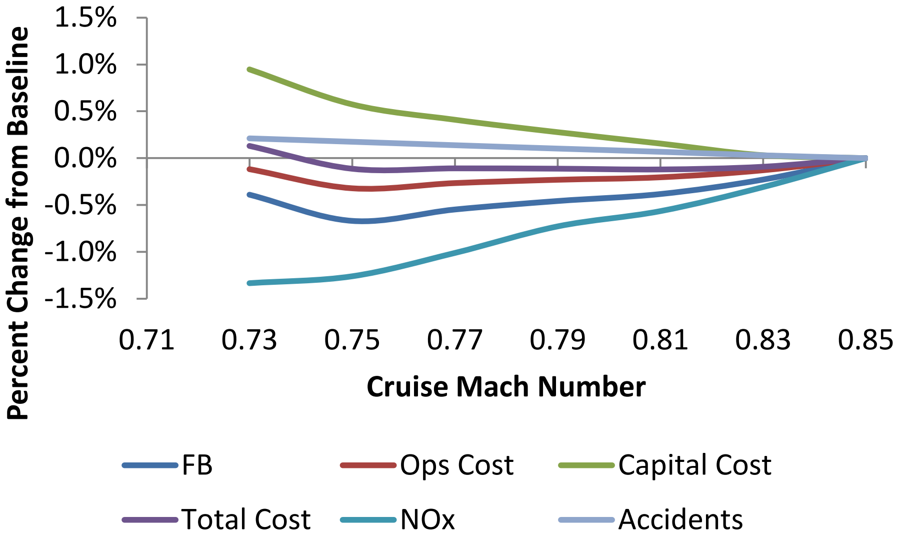


Figure 162. LQ Base Cumulative Speed Reduction Fleet Results

Table 61. LQ Base Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO_x	Number of Aircraft	Accidents
0.85	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.83	-0.23%	-0.13%	0.03%	-0.09%	-0.31%	0.12%	0.03%
0.81	-0.38%	-0.20%	0.16%	-0.12%	-0.57%	0.29%	0.07%
0.79	-0.46%	-0.23%	0.28%	-0.11%	-0.73%	0.44%	0.10%
0.77	-0.55%	-0.27%	0.41%	-0.11%	-1.01%	0.60%	0.14%
0.75	-0.67%	-0.32%	0.57%	-0.11%	-1.26%	0.75%	0.17%
0.73	-0.39%	-0.12%	0.95%	0.13%	-1.33%	0.91%	0.21%

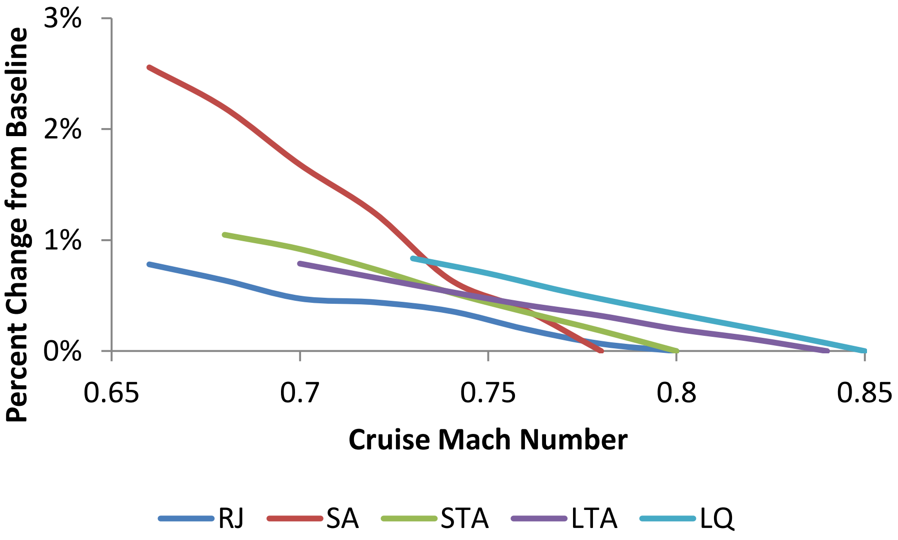
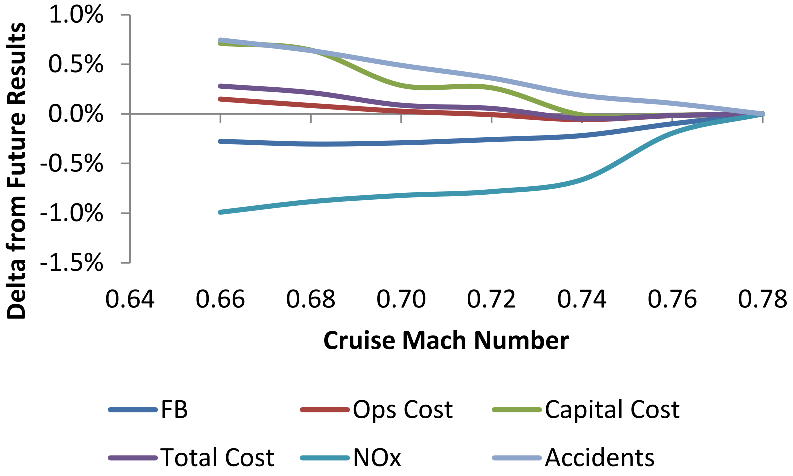


Figure 163. Number of Required Aircraft due to Future Speed Reduction

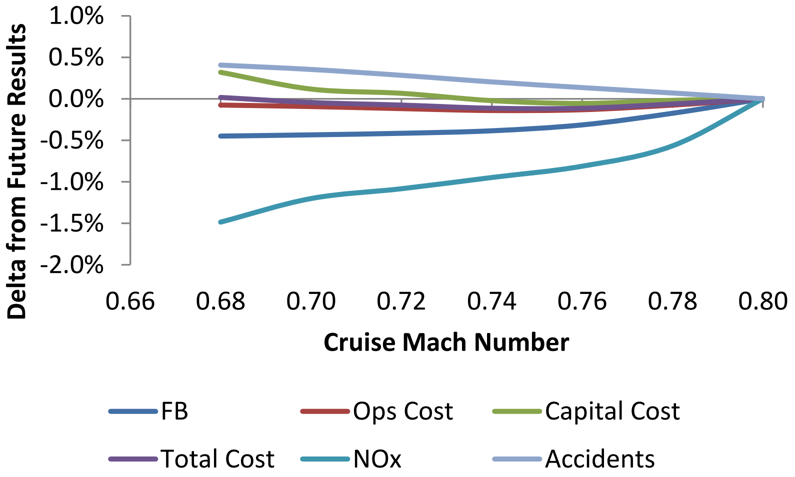


Fuel Burn	-5.13%
Ops Cost	-3.33%
Capital Cost	5.01%
Total Cost	-1.39%
NO$_x$	-12.74%
Accidents	0.00%

Figure 164. SA Future Cumulative Speed Reduction Fleet Results

Table 62. SA Future Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO$_x$	Number of Aircraft	Accidents
0.78	-5.13%	-3.33%	5.01%	-1.39%	-12.74%	0.00%	0.00%
0.76	-5.23%	-3.35%	4.99%	-1.41%	-12.93%	0.37%	0.11%
0.74	-5.35%	-3.39%	5.00%	-1.44%	-13.40%	0.64%	0.19%
0.72	-5.39%	-3.34%	5.27%	-1.34%	-13.52%	1.24%	0.36%
0.70	-5.42%	-3.31%	5.29%	-1.30%	-13.56%	1.68%	0.49%
0.68	-5.44%	-3.25%	5.65%	-1.18%	-13.62%	2.19%	0.64%
0.66	-5.41%	-3.18%	5.72%	-1.11%	-13.73%	2.56%	0.74%

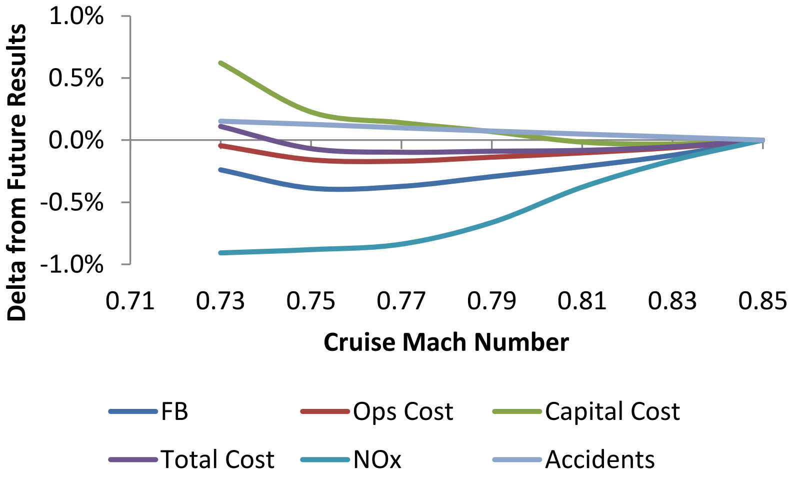


Fuel Burn	-5.13%
Ops Cost	-3.33%
Capital Cost	5.01%
Total Cost	-1.39%
NO$_x$	-12.74%
Accidents	0.00%

Figure 165. STA Future Cumulative Speed Reduction Fleet Results

Table 63. STA Future Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO$_x$	Number of Aircraft	Accidents
0.80	-5.13%	-3.33%	5.01%	-1.39%	-12.74%	0.00%	0.00%
0.78	-5.31%	-3.41%	4.99%	-1.45%	-13.31%	0.18%	0.07%
0.76	-5.45%	-3.46%	4.95%	-1.51%	-13.55%	0.35%	0.14%
0.74	-5.52%	-3.47%	4.98%	-1.51%	-13.69%	0.53%	0.20%
0.72	-5.55%	-3.45%	5.07%	-1.47%	-13.82%	0.74%	0.28%
0.70	-5.57%	-3.43%	5.12%	-1.44%	-13.94%	0.92%	0.35%
0.68	-5.58%	-3.41%	5.33%	-1.38%	-14.22%	1.05%	0.41%



Fuel Burn	-5.13%
Ops Cost	-3.33%
Capital Cost	5.01%
Total Cost	-1.39%
NO_x	-12.74%
Accidents	0.00%

Figure 166. LQ Future Cumulative Speed Reduction Fleet Results

Table 64. LQ Future Cumulative Data

Mach Number	Fuel Burn	Operating Cost	Capital Cost	Total Cost	NO_x	Number of Aircraft	Accidents
0.85	-5.13%	-3.33%	5.01%	-1.39%	-12.74%	0.00%	-5.13%
0.83	-5.25%	-3.39%	4.97%	-1.45%	-12.90%	0.14%	-5.25%
0.81	-5.35%	-3.44%	4.99%	-1.47%	-13.12%	0.27%	-5.35%
0.79	-5.43%	-3.47%	5.07%	-1.48%	-13.40%	0.40%	-5.43%
0.77	-5.51%	-3.50%	5.15%	-1.49%	-13.58%	0.54%	-5.51%
0.75	-5.52%	-3.49%	5.23%	-1.46%	-13.62%	0.70%	-5.52%
0.73	-5.37%	-3.38%	5.63%	-1.28%	-13.65%	0.84%	-5.37%

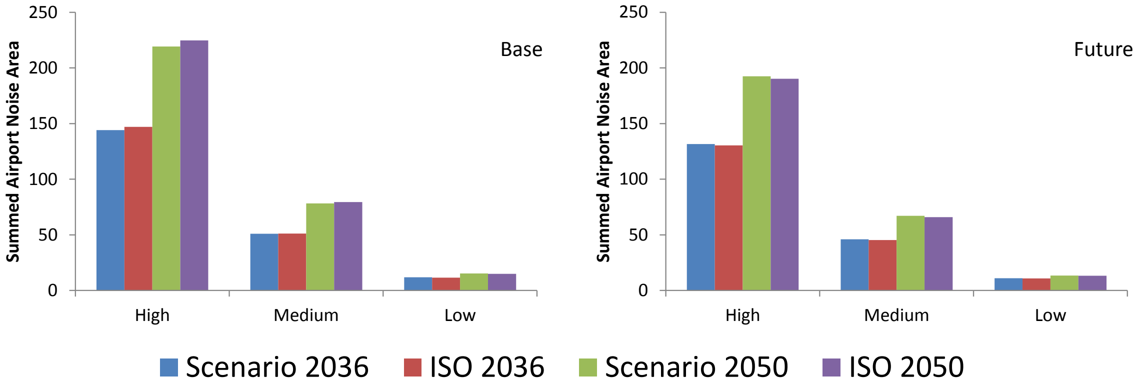


Figure 167. Noise Impact Comparison from Speed Reduction – 65 dB

APPENDIX C RANGE REDUCTION FIGURES

This appendix contains figures for the vehicles not included in the range reduction chapter as well as respective aircraft prices. For vehicle design, this is the single aisle, small twin aisle, and large quad. The intermediate stop feasibility of the small twin and large quad are provided. Finally, fleet analysis of the small twin and large quad are included.

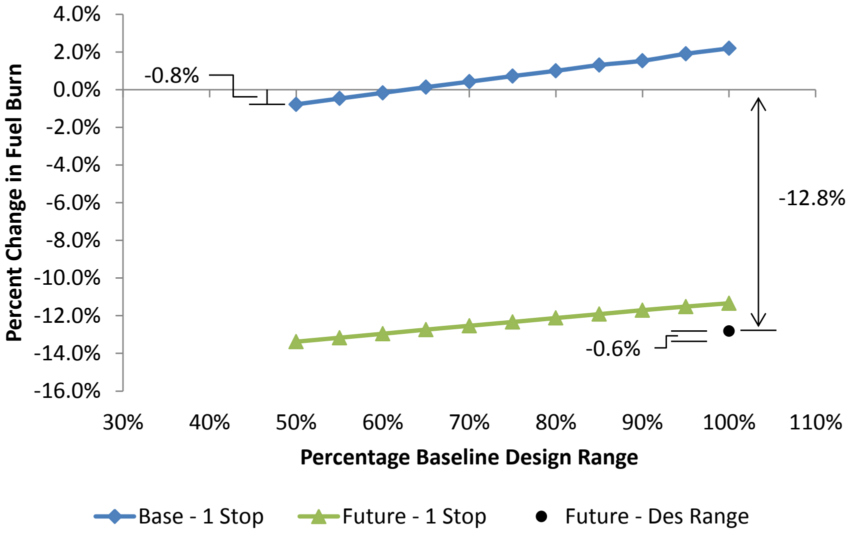


Figure 168. SA Fuel Burn Impact of Range Reduction

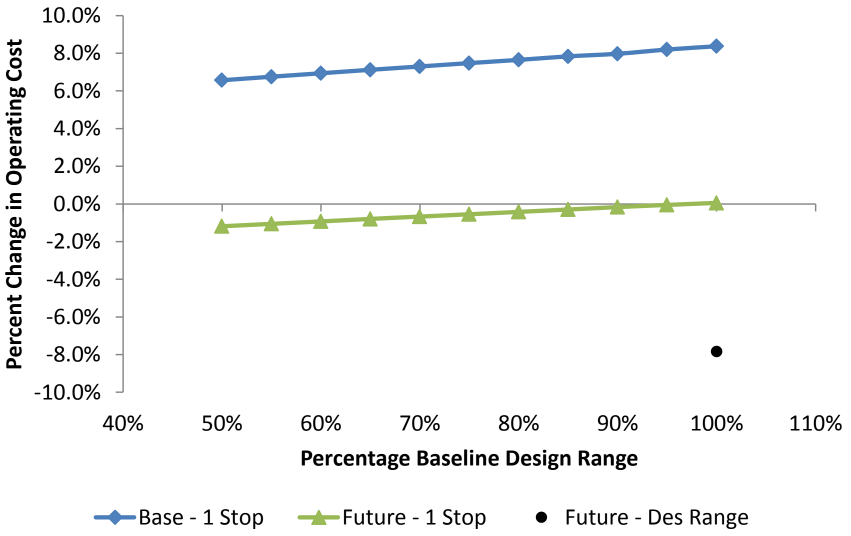


Figure 169. SA Operating Cost Impact of Range Reduction

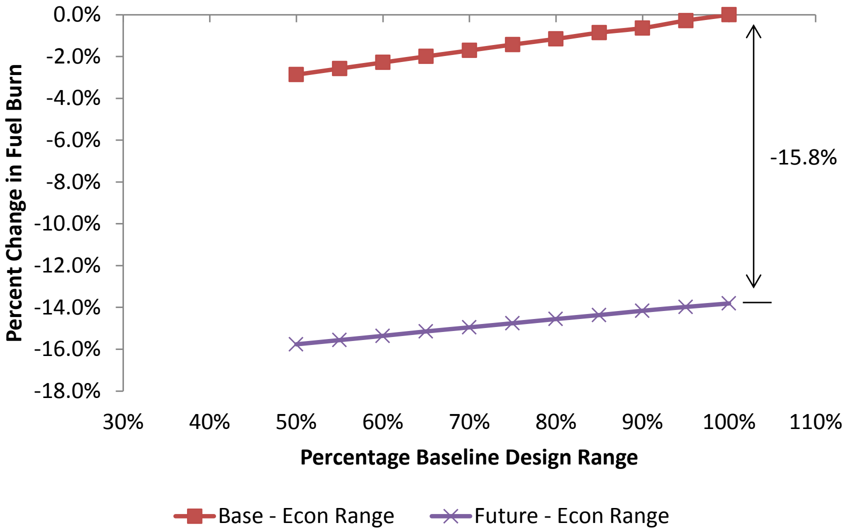


Figure 170. SA Fuel Burn Impact of Range Reduction on Economic Mission

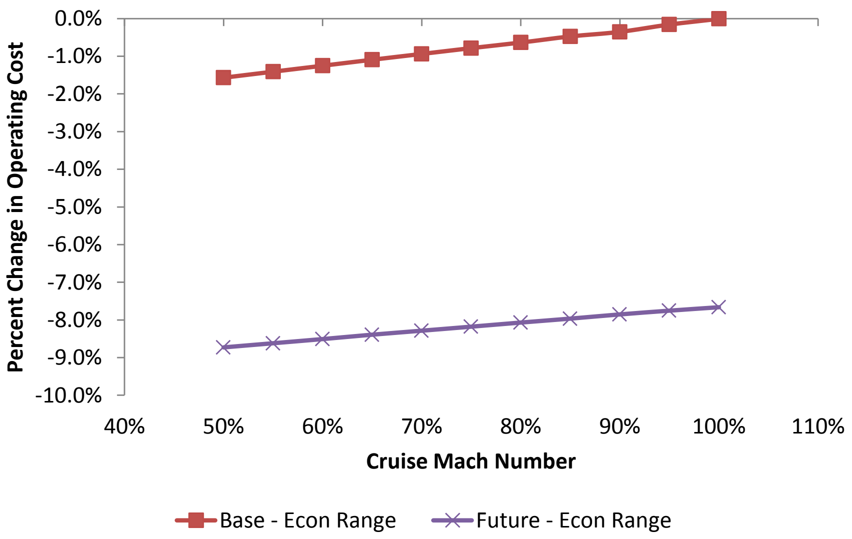


Figure 171. SA Operating Cost Impact of Range Reduction on Economic Mission

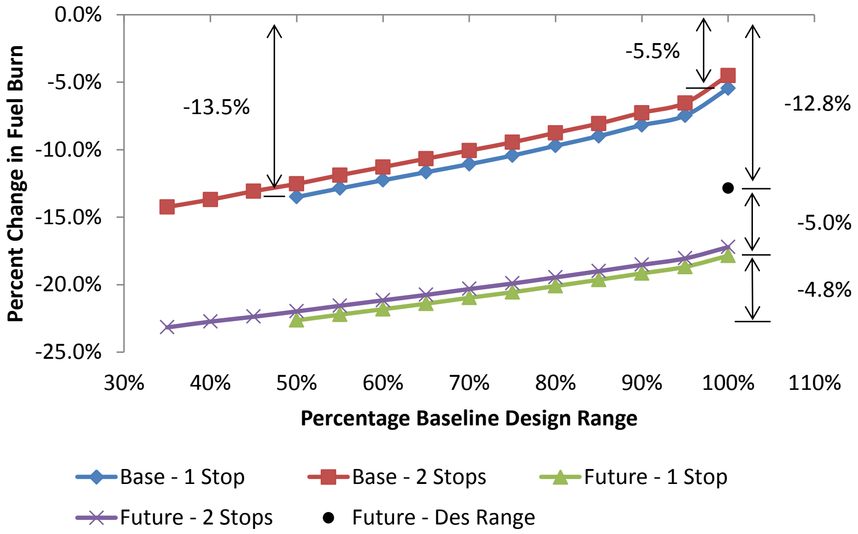


Figure 172. STA Fuel Burn Impact of Range Reduction

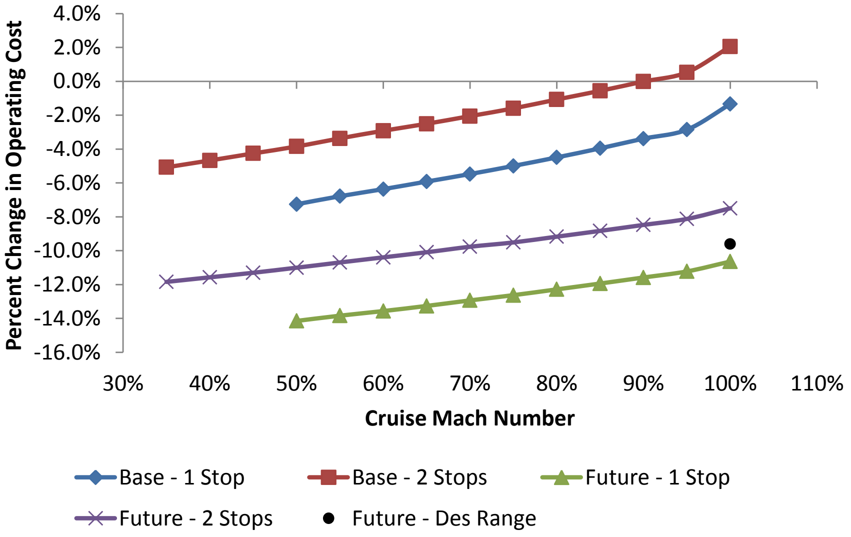


Figure 173. STA Operating Cost Impact of Range Reduction

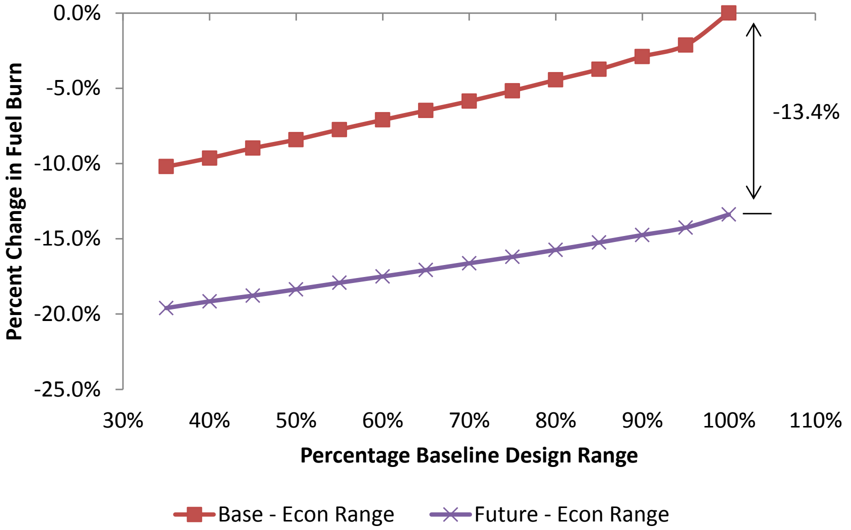


Figure 174. STA Fuel Burn Impact of Range Reduction on Economic Mission

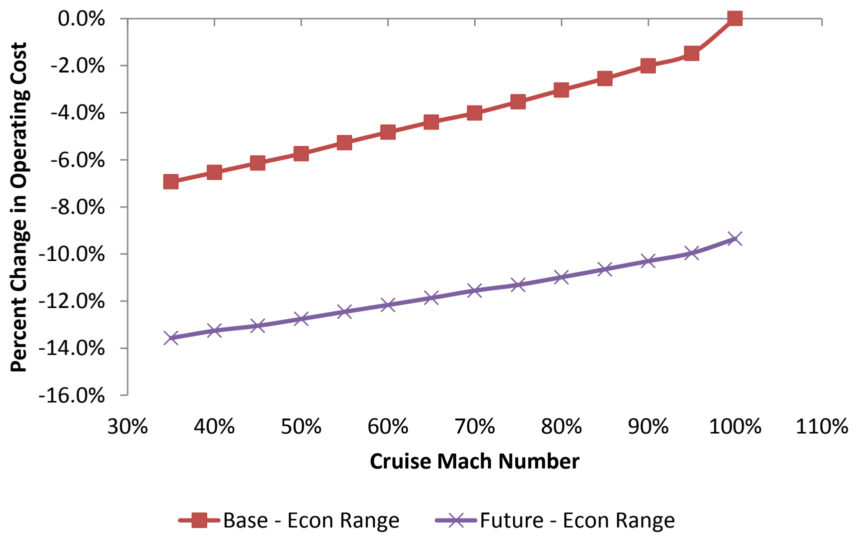


Figure 175. STA Operating Cost Impact of Range Reduction on Economic Mission

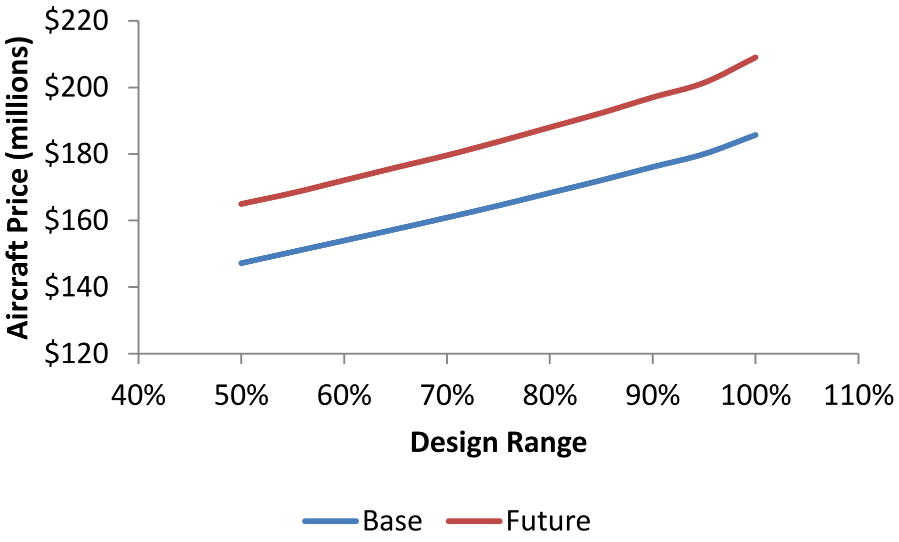


Figure 176. STA Range Reduction Aircraft Prices

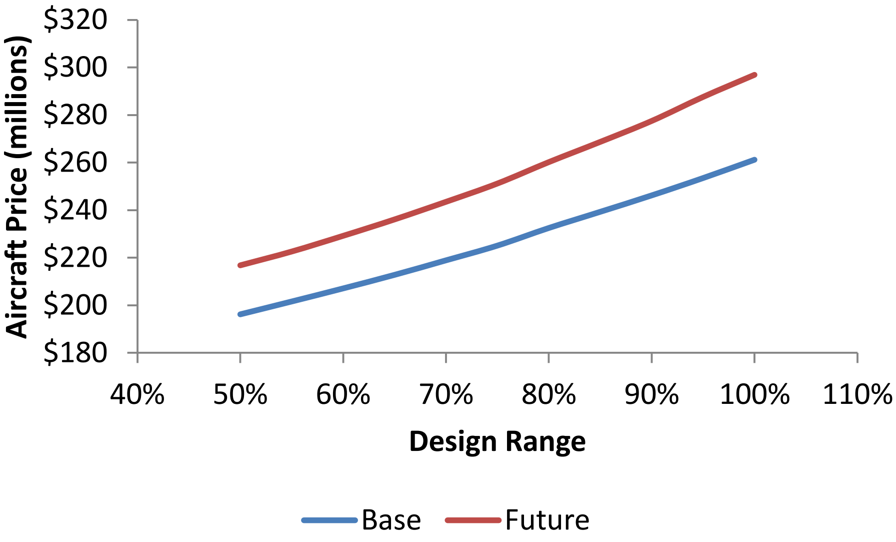


Figure 177. LTA Range Reduction Aircraft Prices

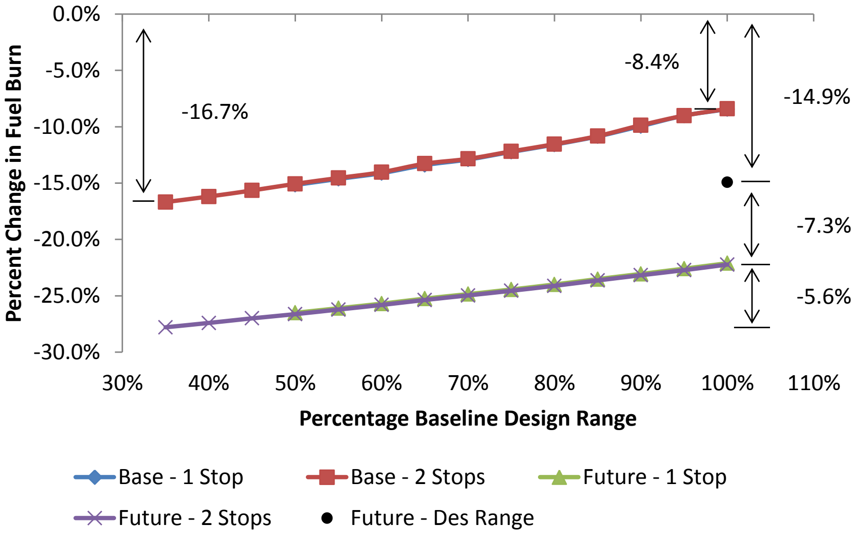


Figure 178. LQ Fuel Burn Impact of Range Reduction

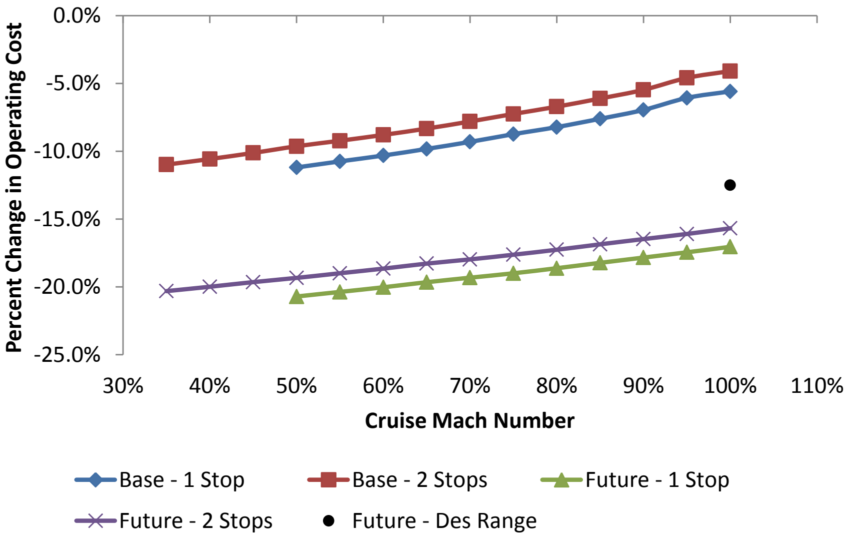


Figure 179. LQ Fuel Burn Impact of Range Reduction

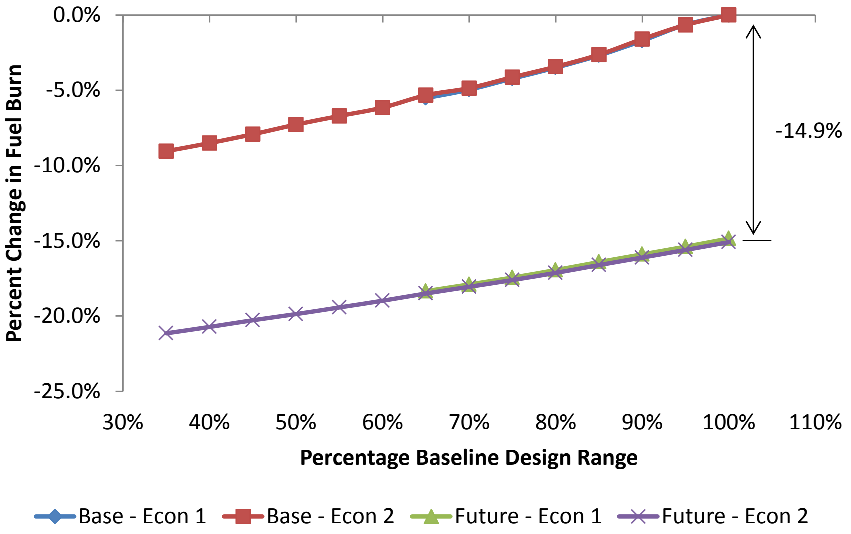


Figure 180. LQ Fuel Burn Impact of Range Reduction on Economic Missions

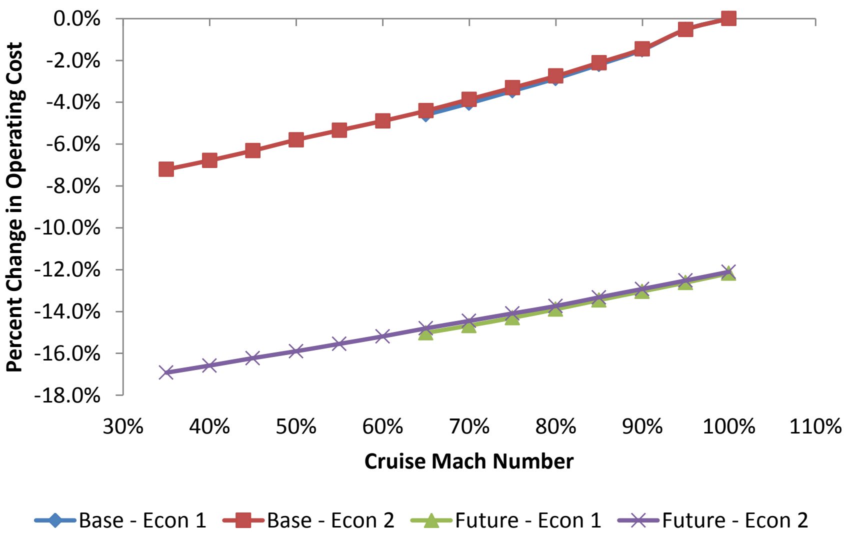


Figure 181. LQ Operating Cost Impact of Range Reduction on Economic Missions

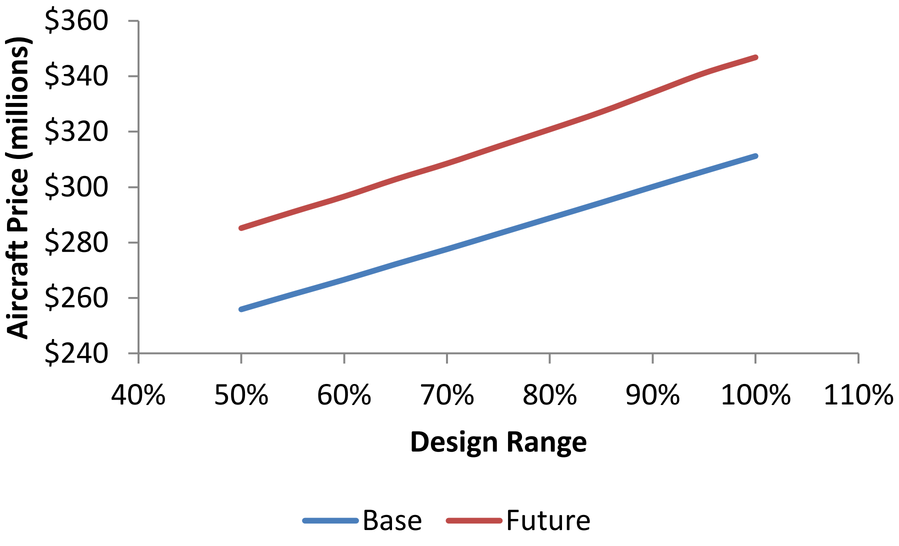


Figure 182LQ Range Reduction Aircraft Prices

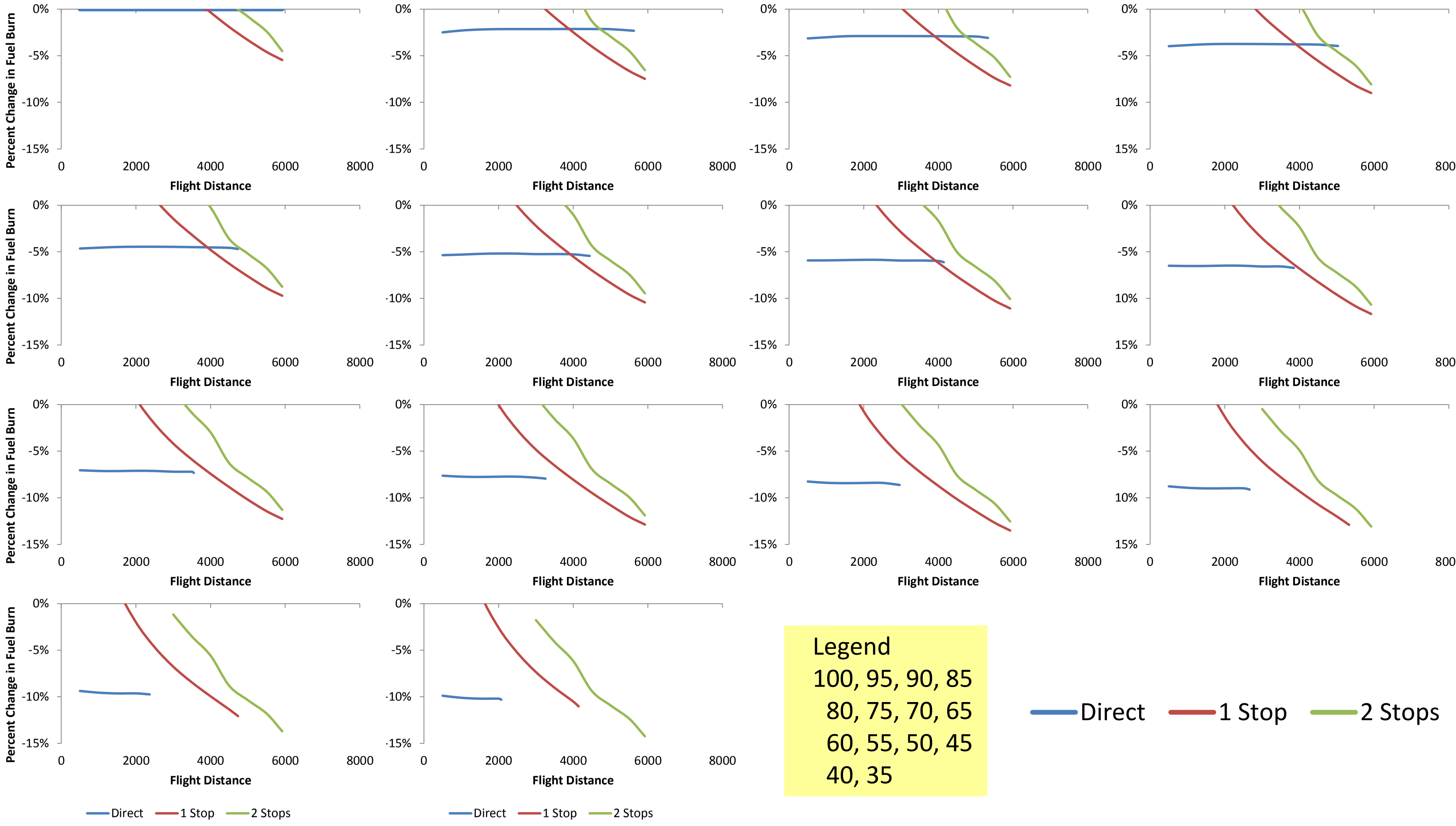


Figure 183. Intermediate Stop Feasibility for STA Baseline Technology

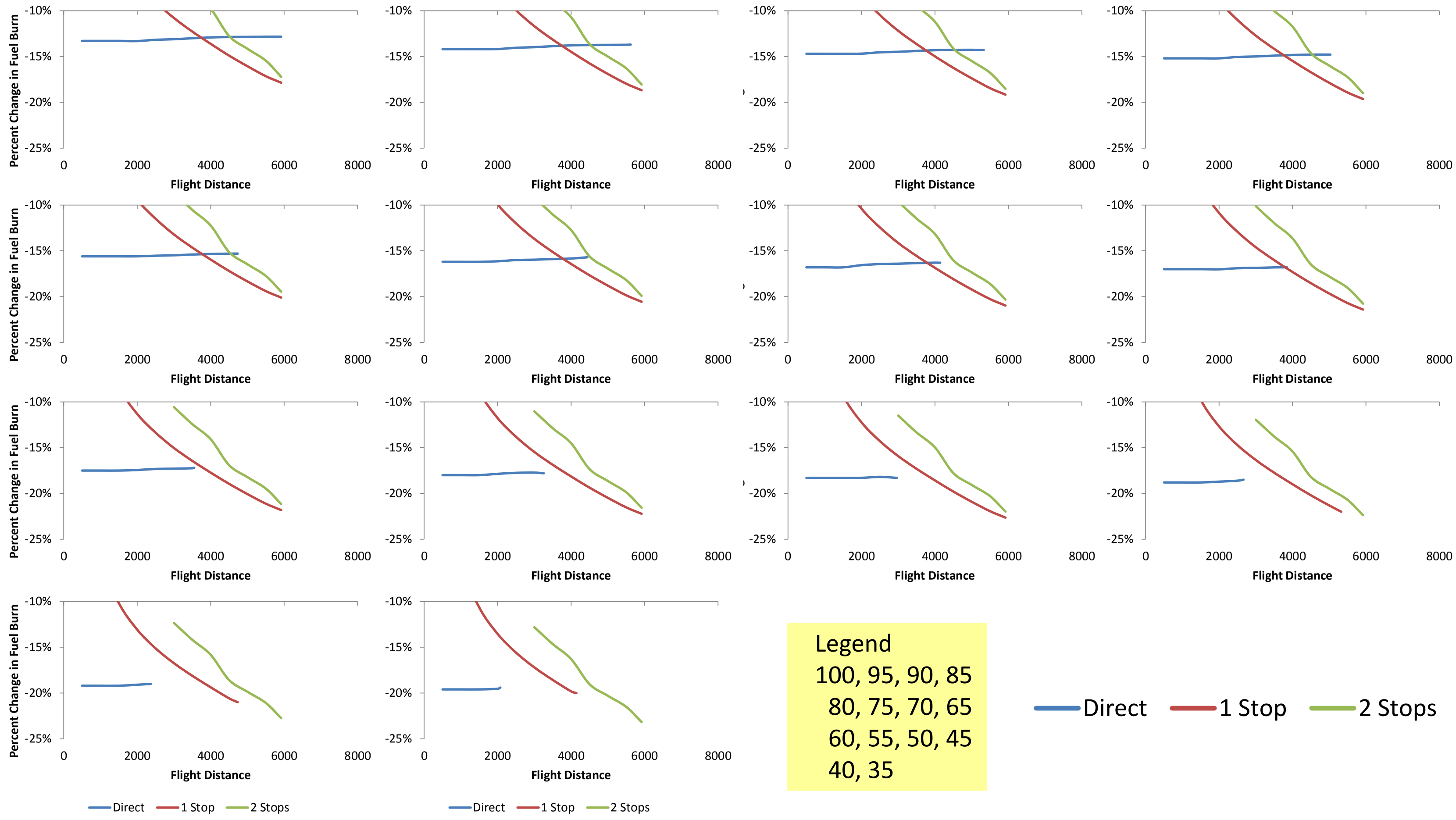


Figure 184. Intermediate Stop Feasibility for STA Future Technology

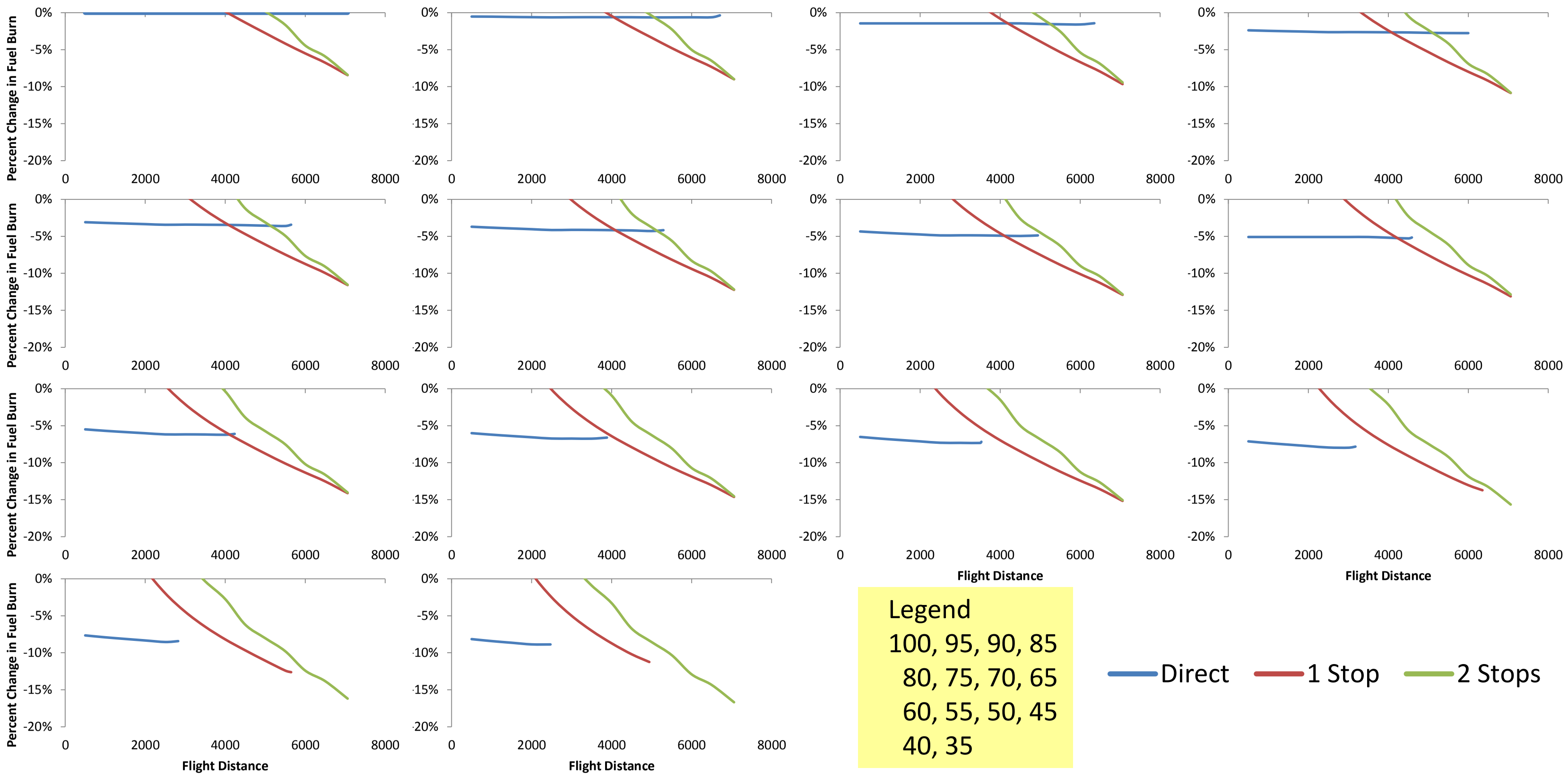


Figure 185. Intermediate Stop Feasibility for LQ Baseline Technology

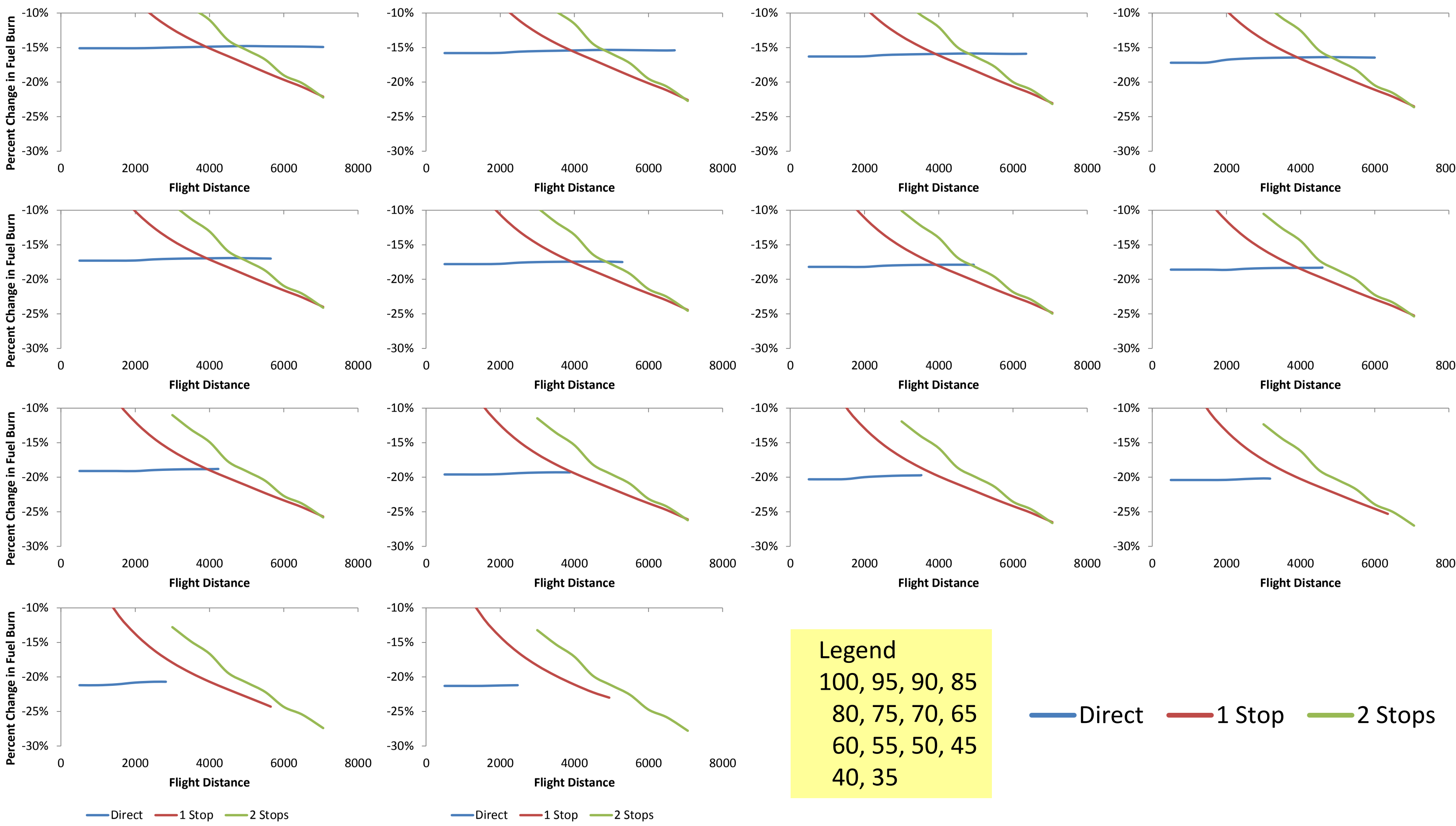


Figure 186. Intermediate Stop Feasibility for LQ Future Technology

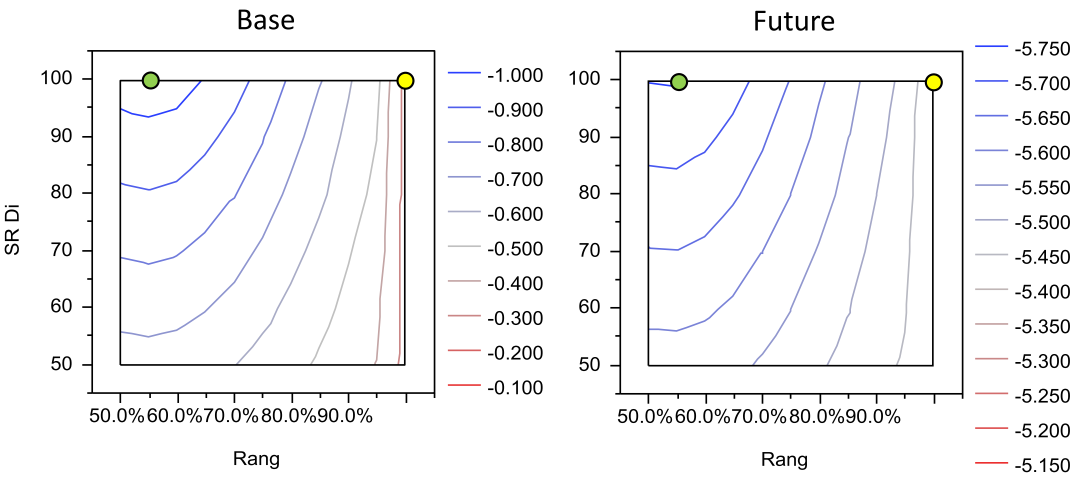


Figure 187. STA Fleet Fuel Burn Range Reduction Sensitivity

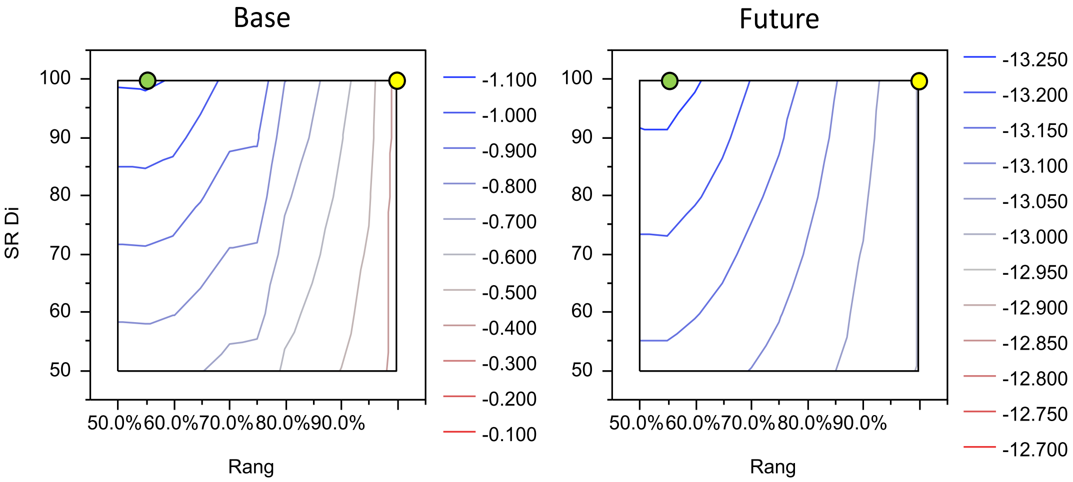


Figure 188. STA Fleet NO_x Range Reduction Sensitivity

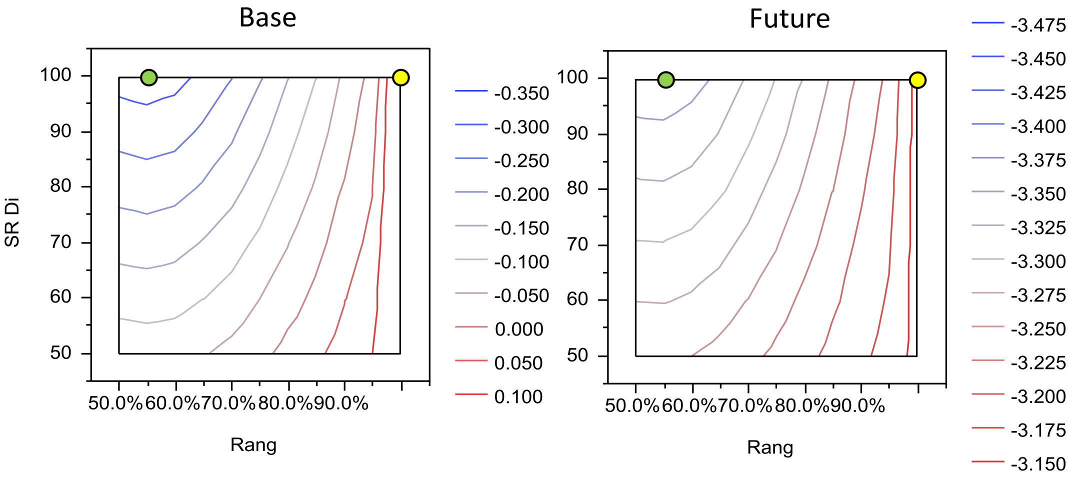


Figure 189. STA Fleet Operating Cost Range Reduction Sensitivity

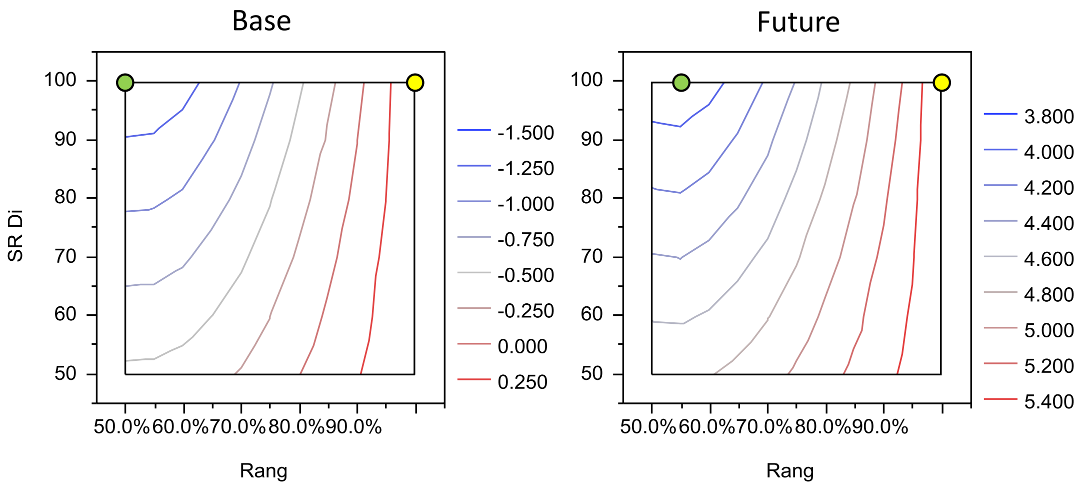


Figure 190. STA Fleet Capital Cost Range Reduction Sensitivity

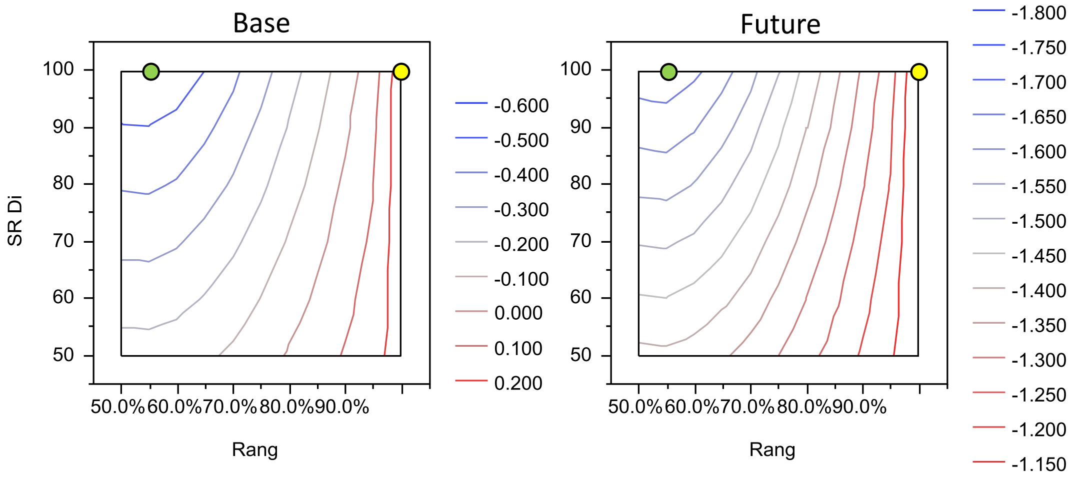


Figure 191. STA Fleet Total Cost Range Reduction Sensitivity

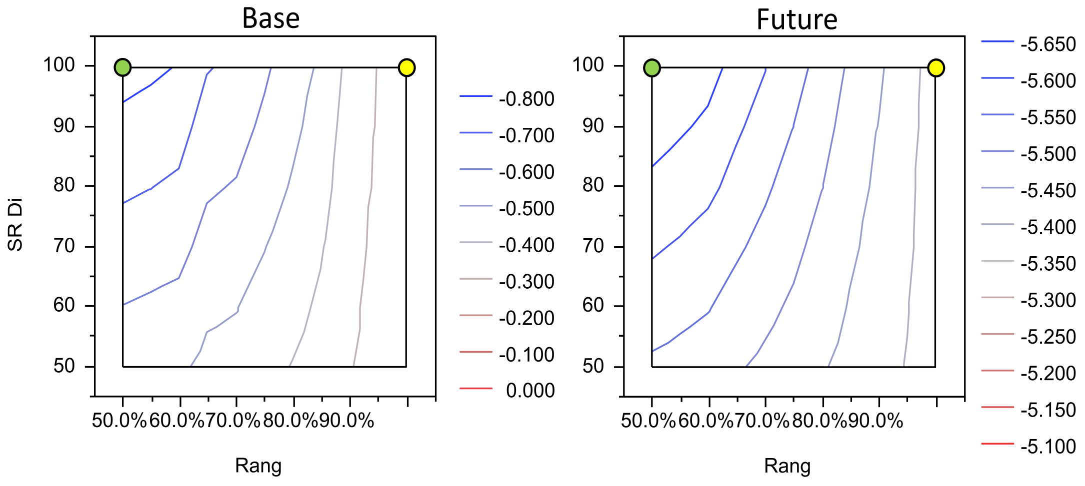


Figure 192. LQ Fleet Fuel Burn Range Reduction Sensitivity

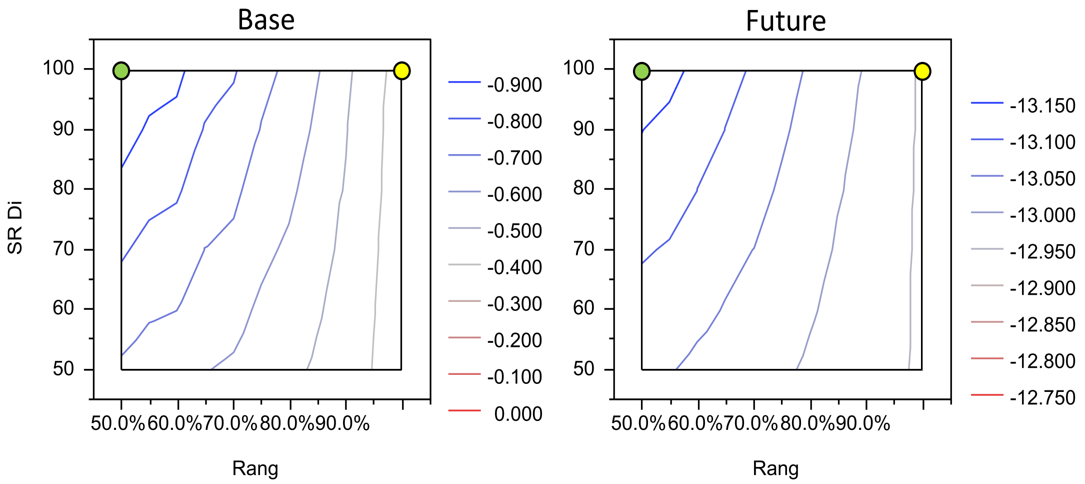


Figure 193. LQ Fleet NO_x Range Reduction Sensitivity

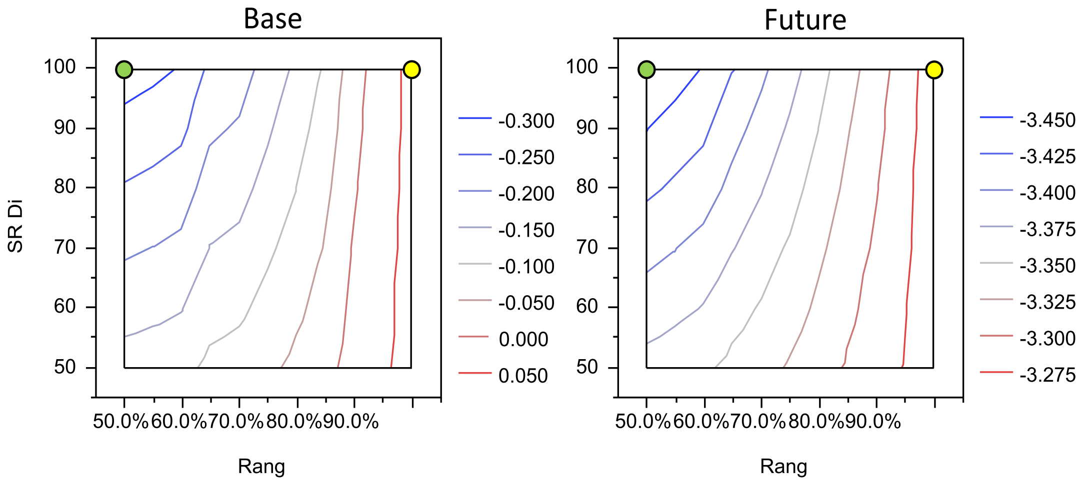


Figure 194. LQ Fleet Operating Cost Range Reduction Sensitivity

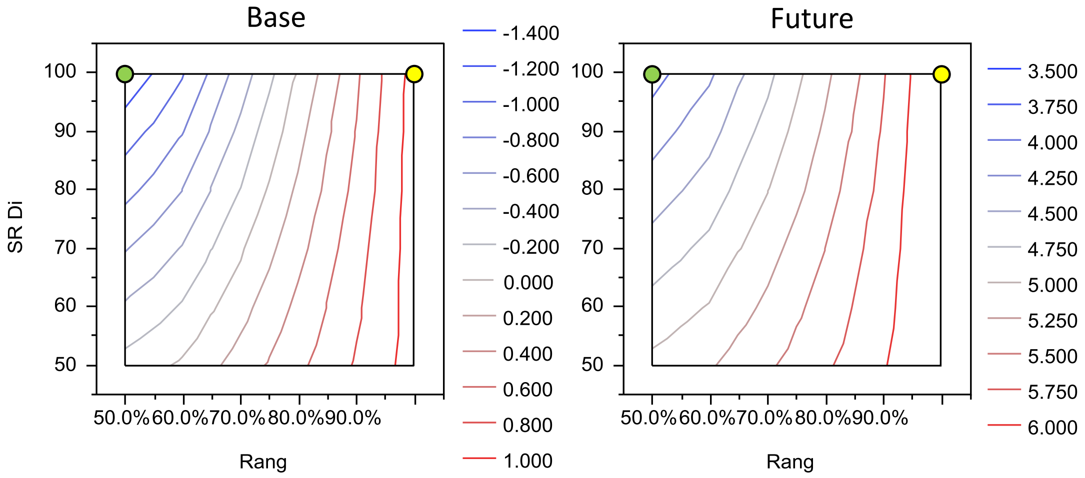


Figure 195. LQ Fleet Capital Cost Range Reduction Sensitivity

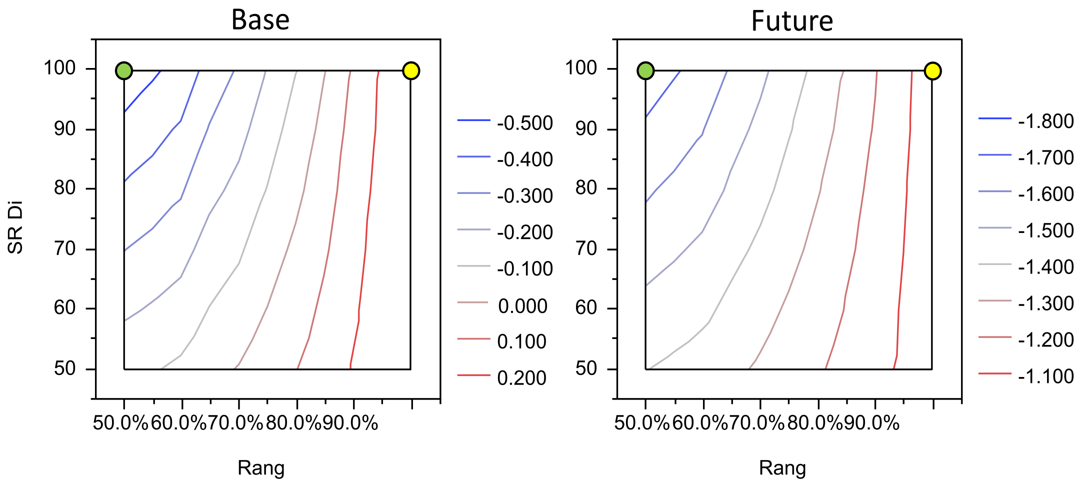


Figure 196. LQ Fleet Total Cost Range Reduction Sensitivity

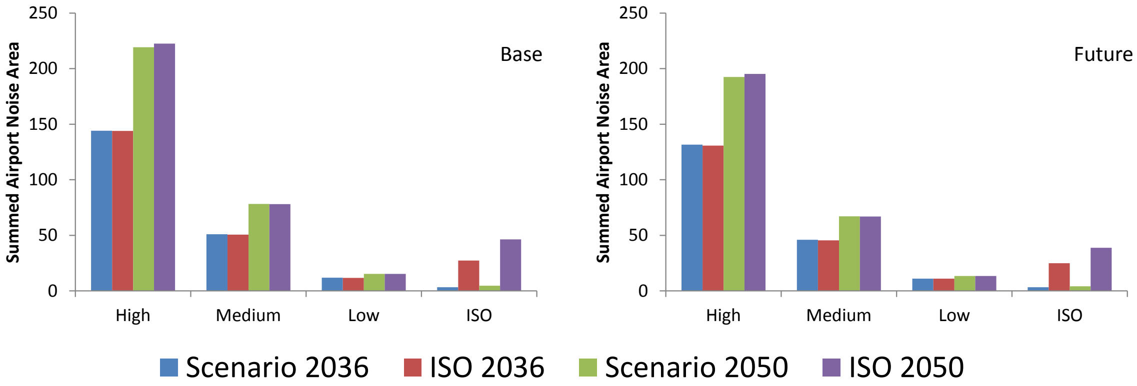


Figure 197. Noise Impact Comparison from Range Reduction – 65 dB

APPENDIX D JOINT REDUCTION FIGURES

This appendix contains figures for the vehicles not included in the joint reduction chapter as well as respective aircraft prices. For vehicle design, this is the small twin aisle and large quad. The intermediate stop feasibility of the small twin and large quad is not included as cruise speed does not significantly impact results. Finally, fleet analysis of the small twin and large quad are included.

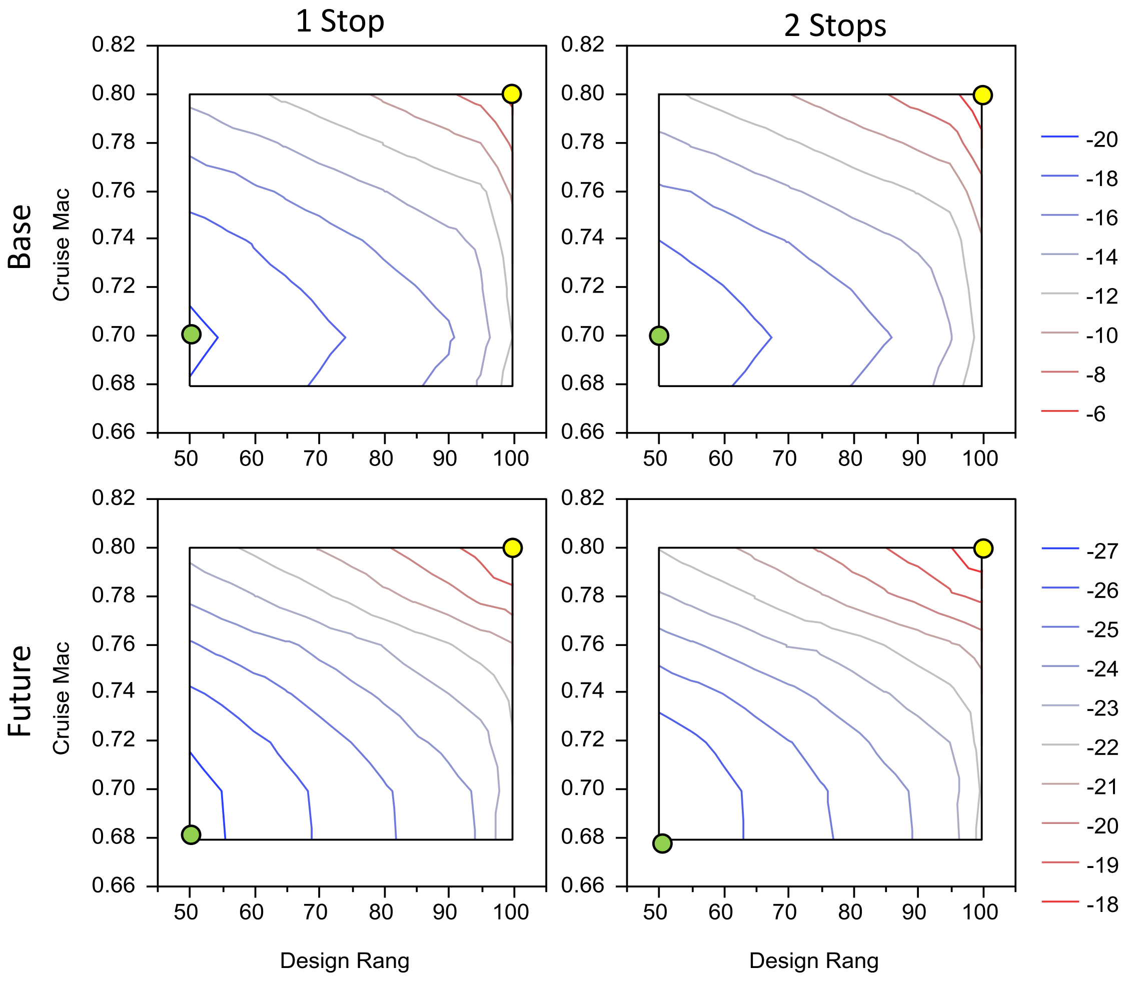


Figure 198. STA Joint Design Mission Fuel Burn Performance

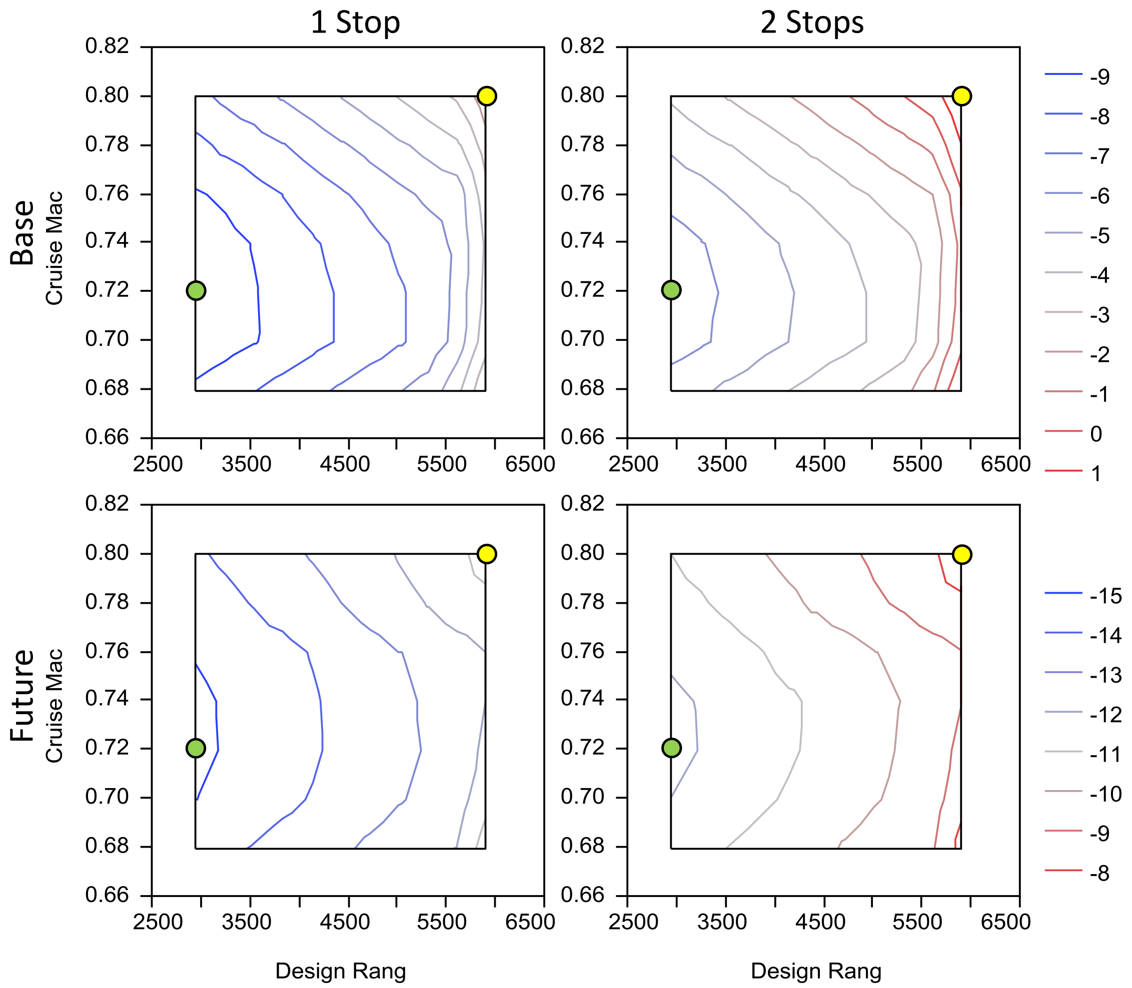


Figure 199. STA Joint Design Mission Operating Cost Performance

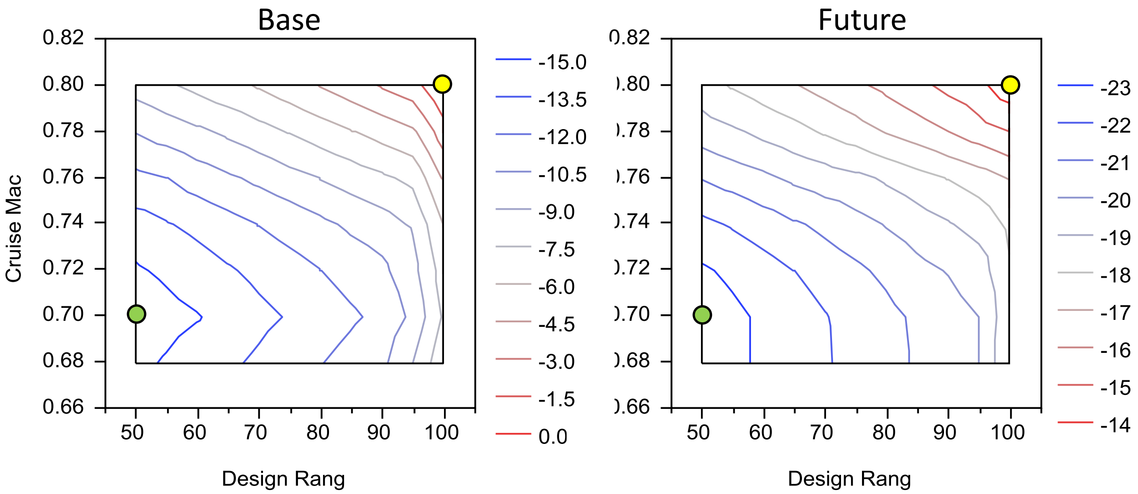


Figure 200. STA Joint Economic Mission Fuel Burn Performance

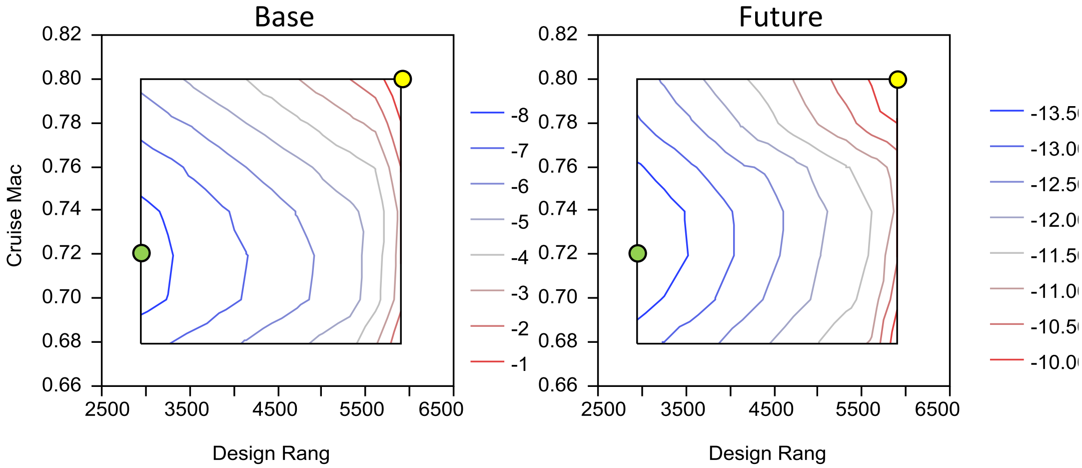


Figure 201. STA Joint Economic Mission Operating Cost Performance

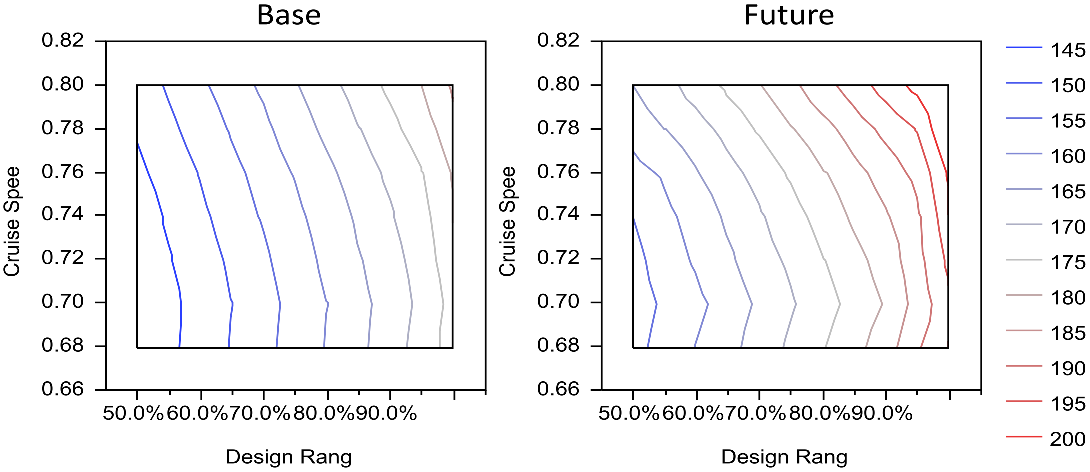


Figure 202. STA Joint Aircraft Prices

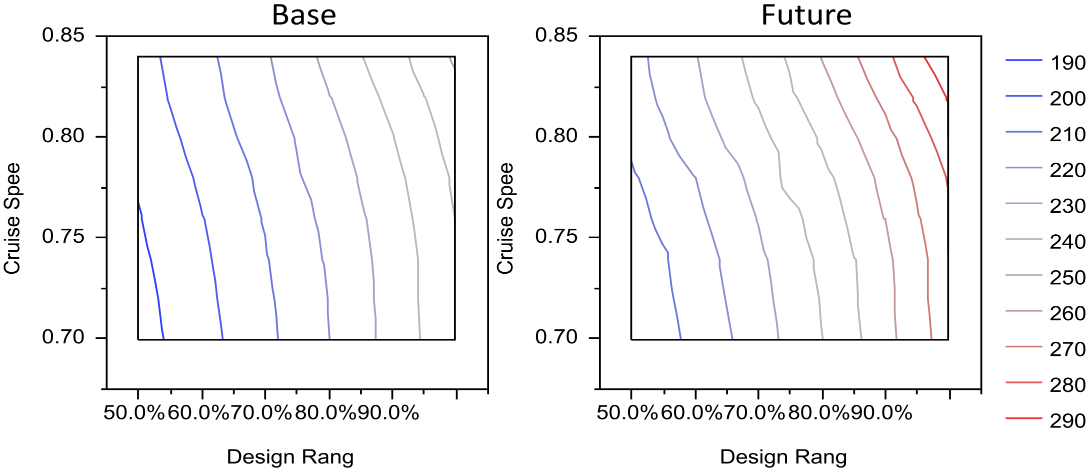


Figure 203. LTA Joint Aircraft Prices

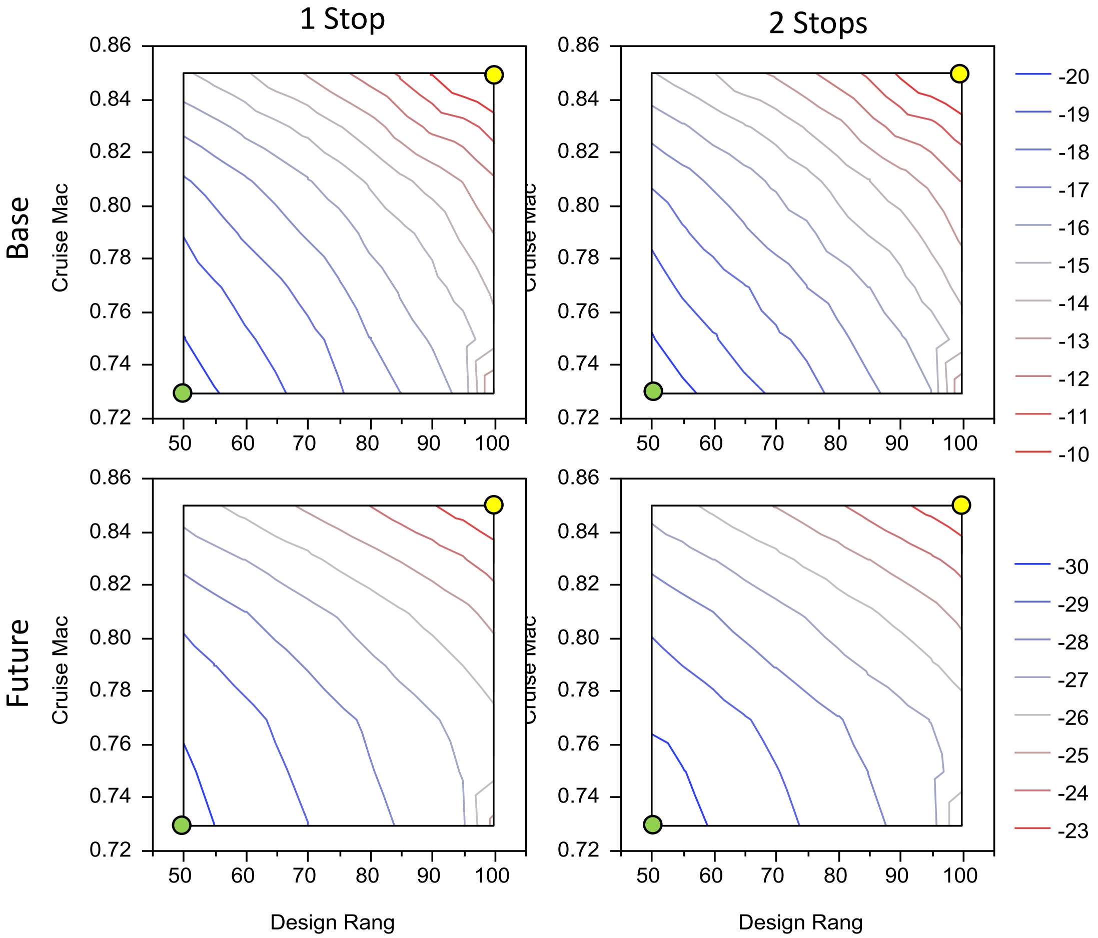


Figure 204. LQ Joint Design Mission Fuel Burn Performance

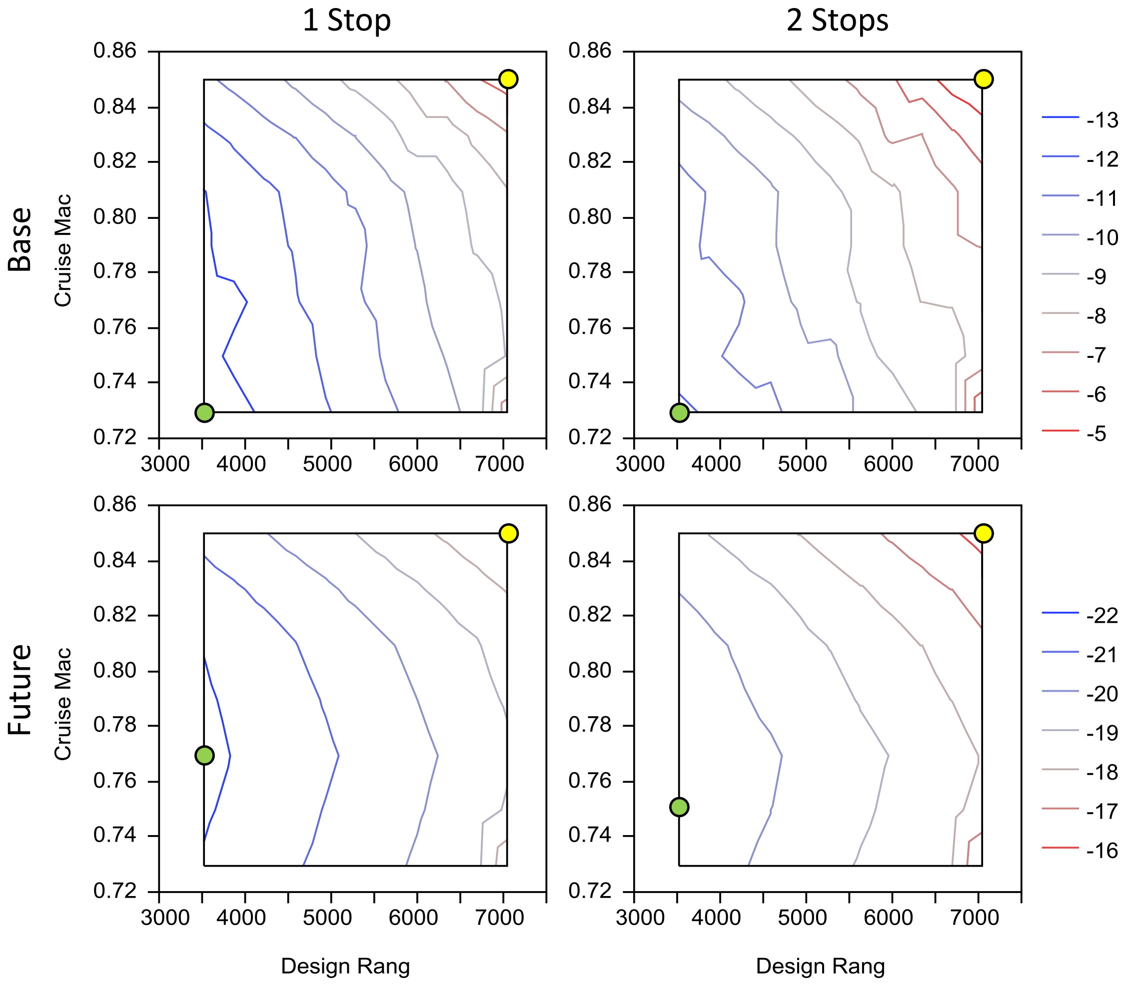


Figure 205. LQ Joint Design Mission Operating Cost Performance

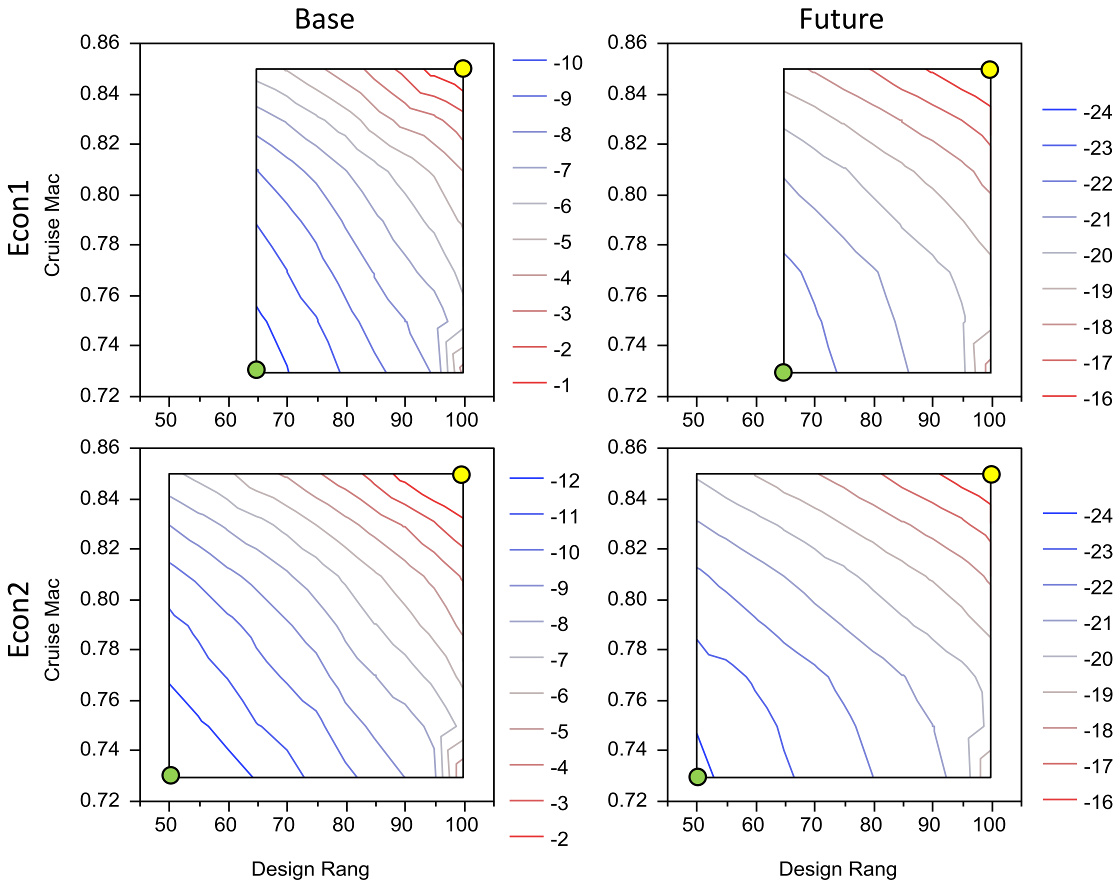


Figure 206. LQ Joint Economic Mission Fuel Burn Performance

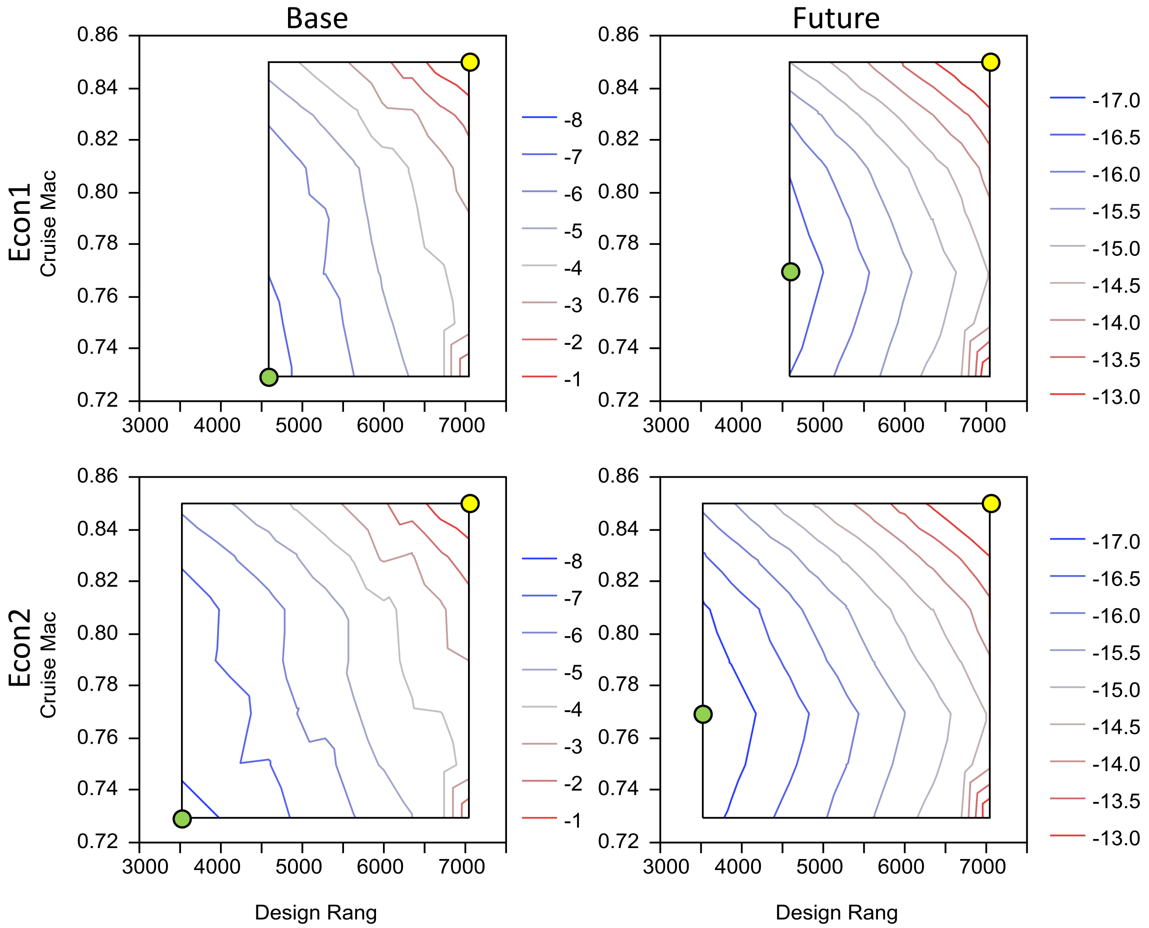


Figure 207. LQ Joint Economic Mission Operating Cost Performance

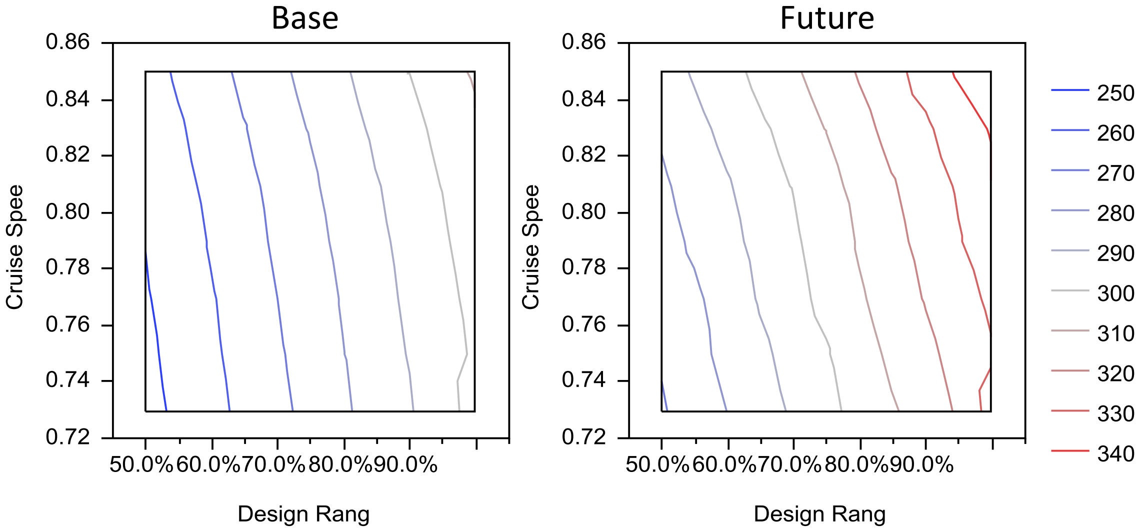


Figure 208. LQ Joint Aircraft Prices

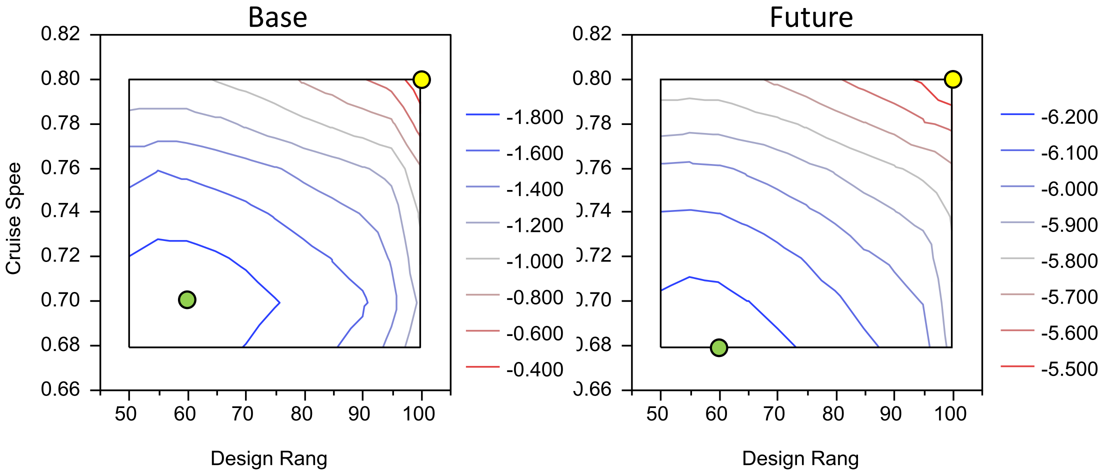


Figure 209. STA Joint Reduction Fuel Burn Fleet Impact

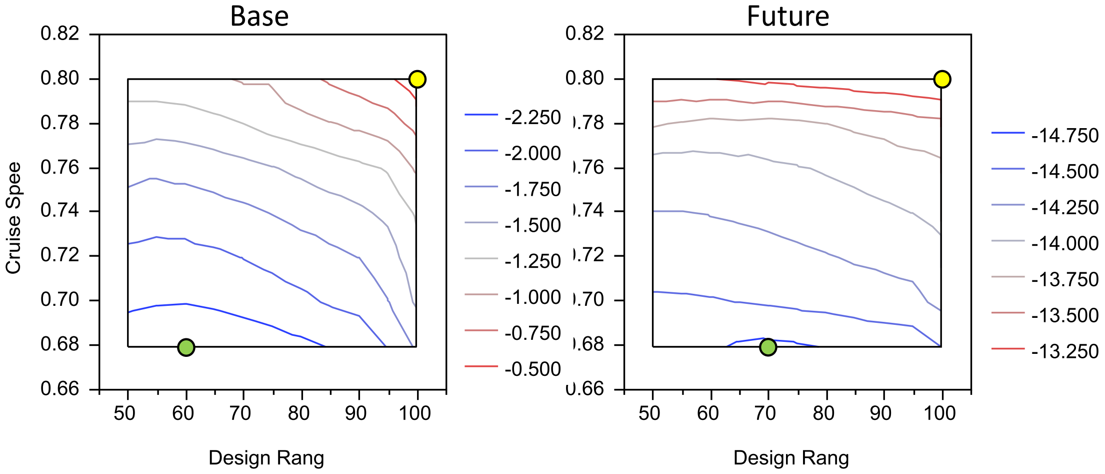


Figure 210. STA Joint Reduction NO_x Fleet Impact

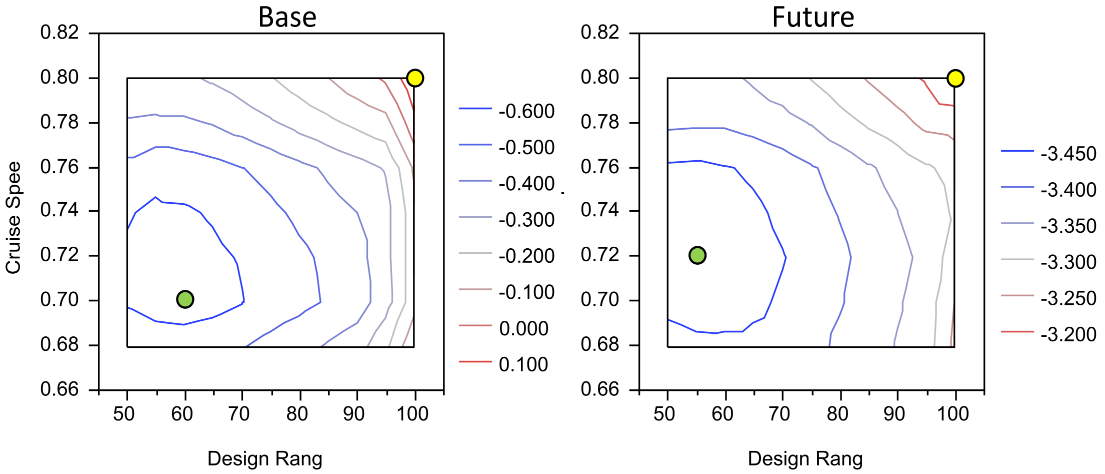


Figure 211. STA Joint Reduction Operating Cost Fleet Impact

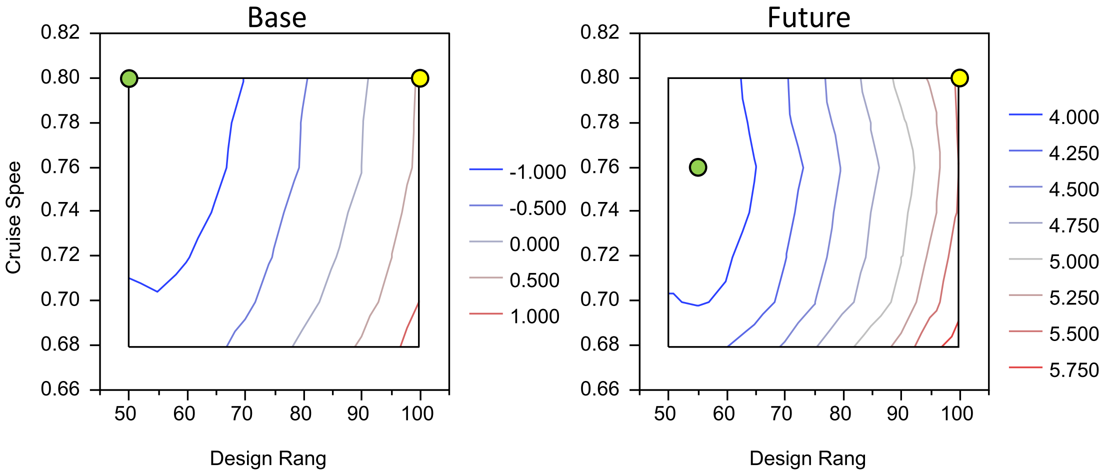


Figure 212. STA Joint Reduction Capital Cost Fleet Impact

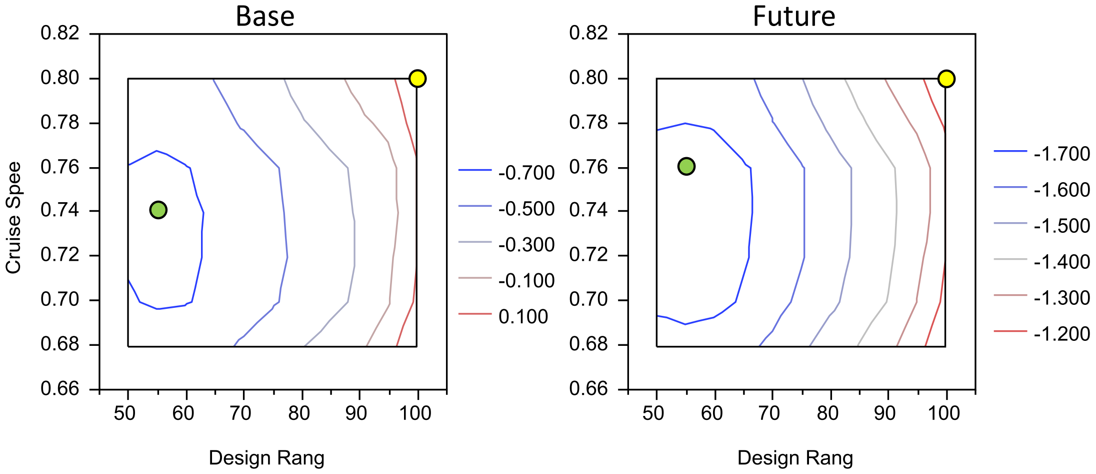


Figure 213. STA Joint Reduction Total Cost Fleet Impact

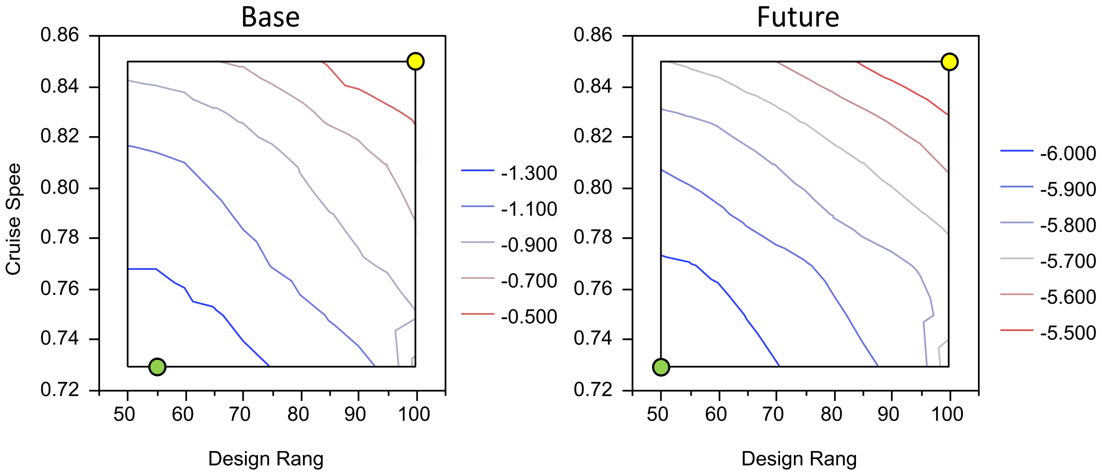


Figure 214. LQ Joint Reduction Fuel Burn Fleet Impact

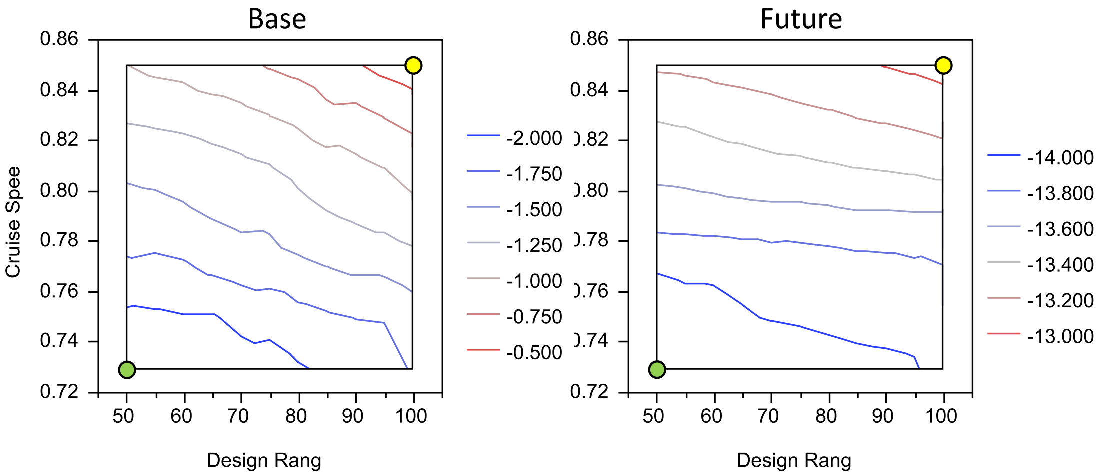


Figure 215. LQ Joint Reduction NO_x Fleet Impact

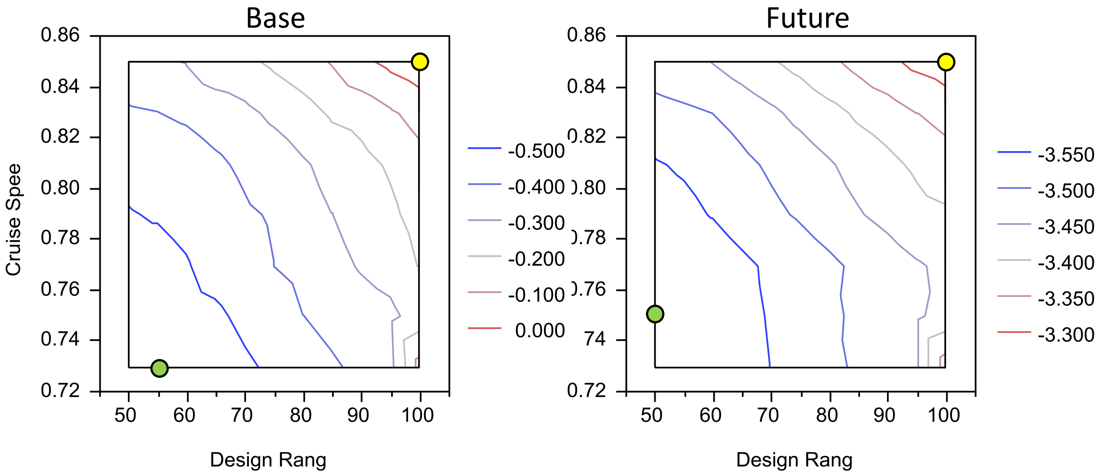


Figure 216. LQ Joint Reduction Operating Cost Fleet Impact

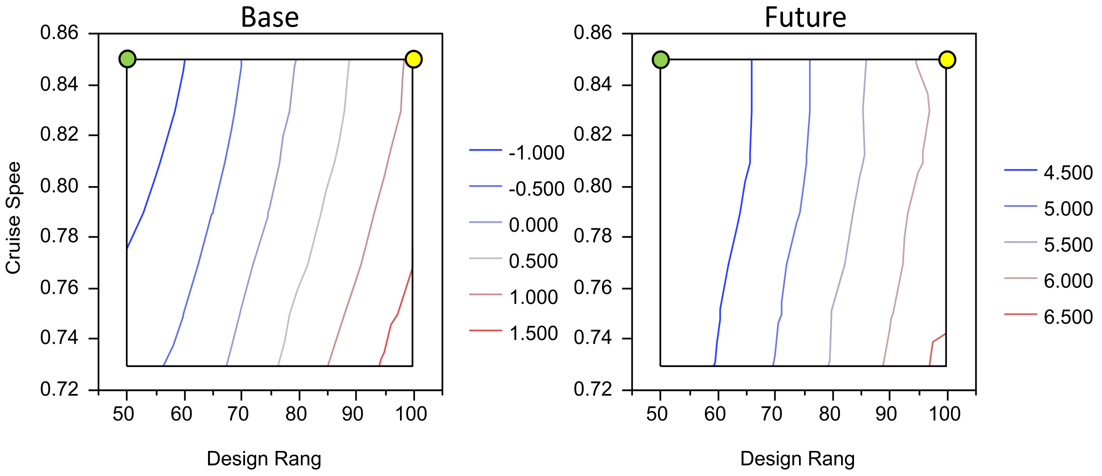


Figure 217. LQ Joint Reduction Capital Cost Fleet Impact

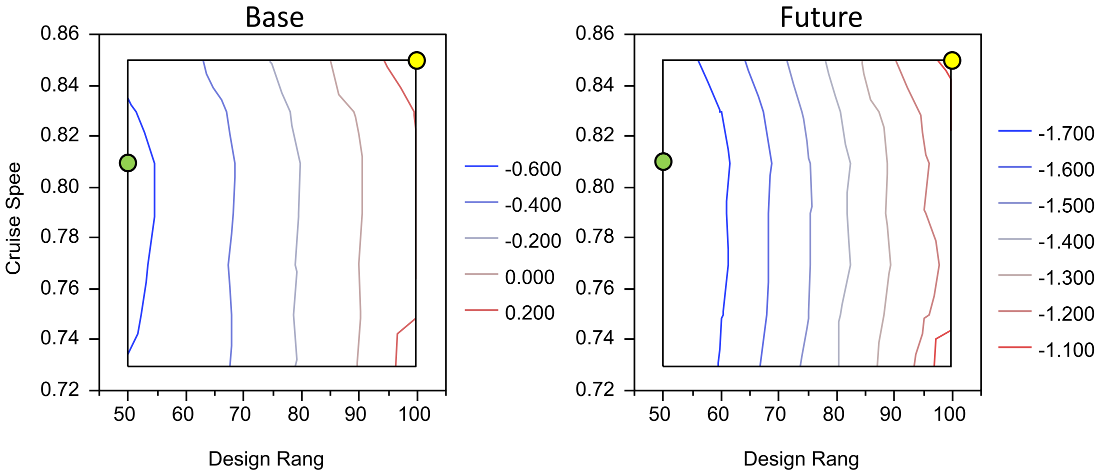


Figure 218. LQ Joint Reduction Total Cost Fleet Impact

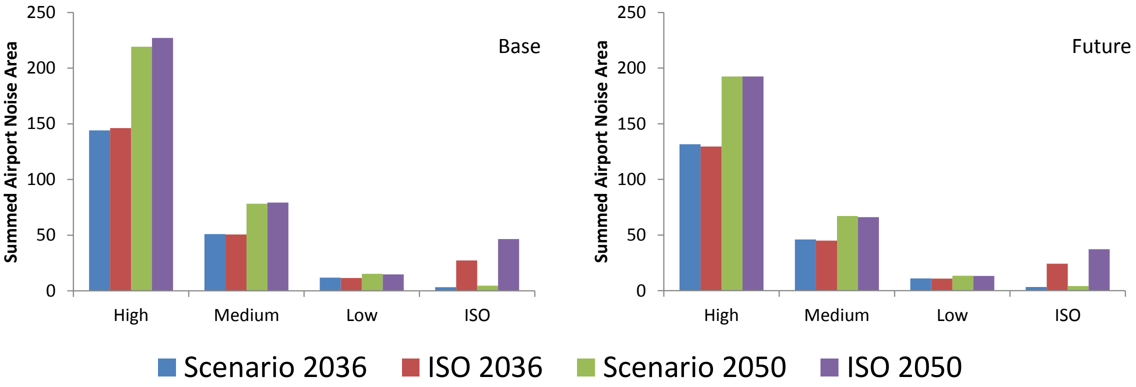


Figure 219. Noise Impact Comparison from Joint Reduction – 65 dB

APPENDIX E TRADE STUDY FIGURES

This appendix contains additional figures for utilization reduction and intermediate stop variation trade studies. The former contains the regional jet, single aisle, small twin, and large quad. The latter is the small twin and large quad.

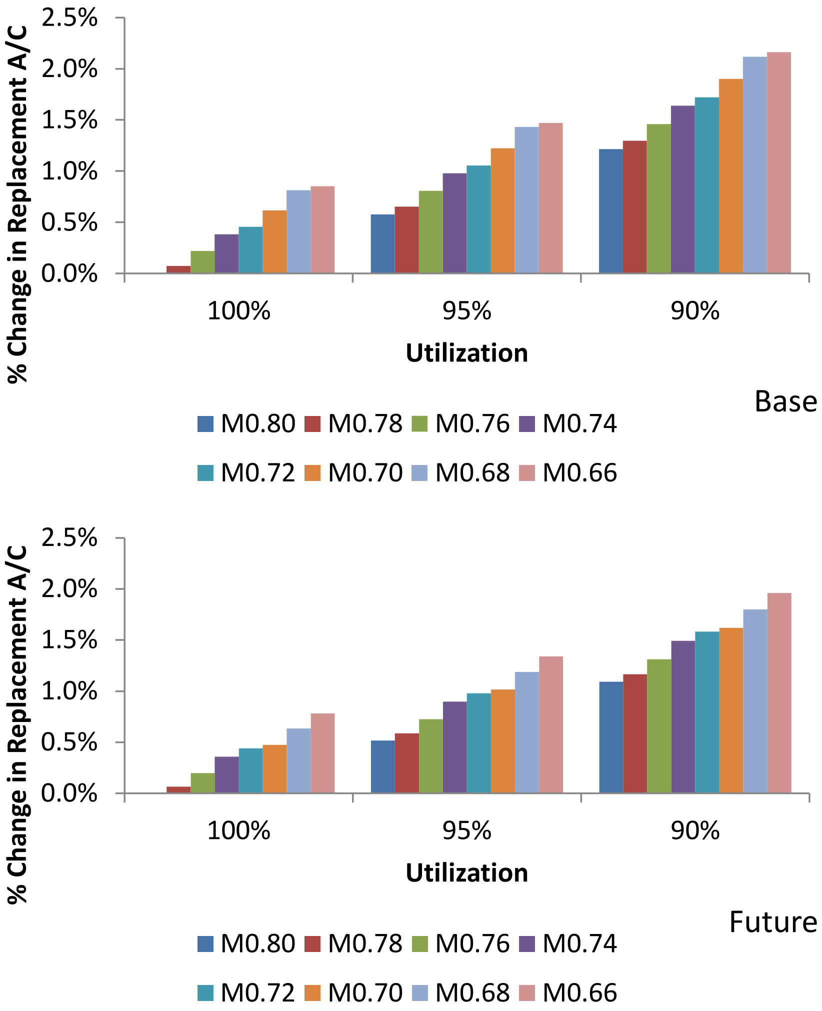


Figure 220. RJ Utilization Sensitivity for Speed Reduction on Aircraft Number

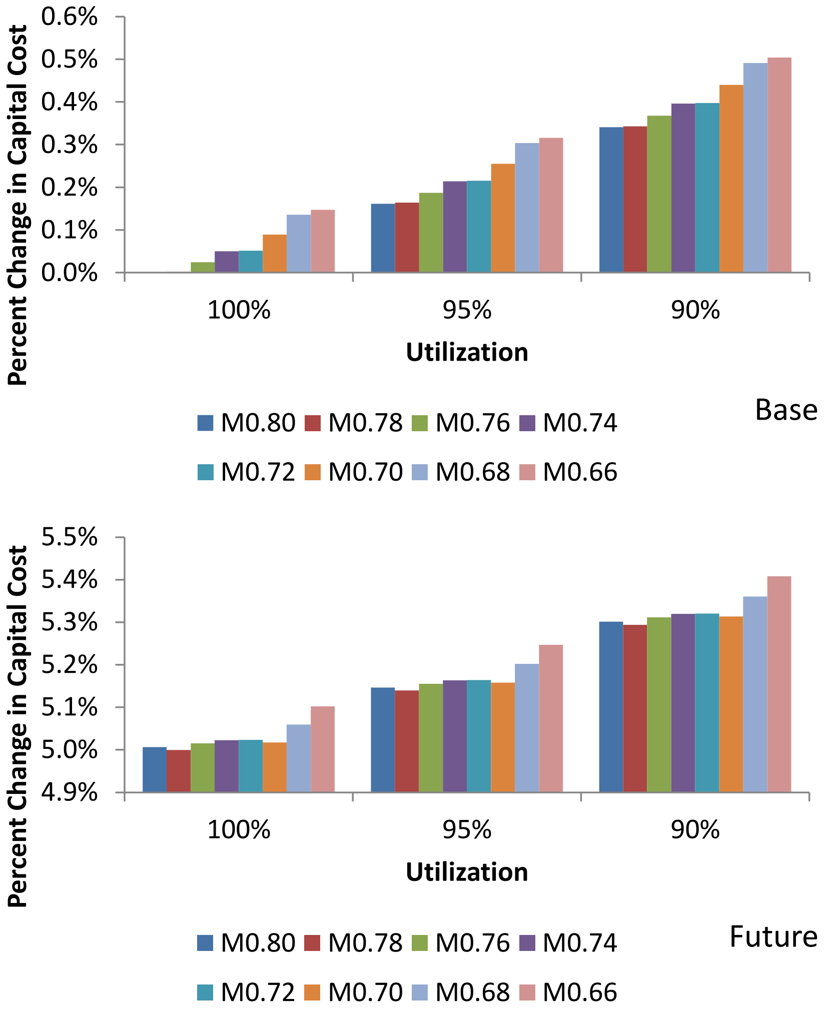


Figure 221. RJ Utilization Sensitivity for Speed Reduction on Capital Cost

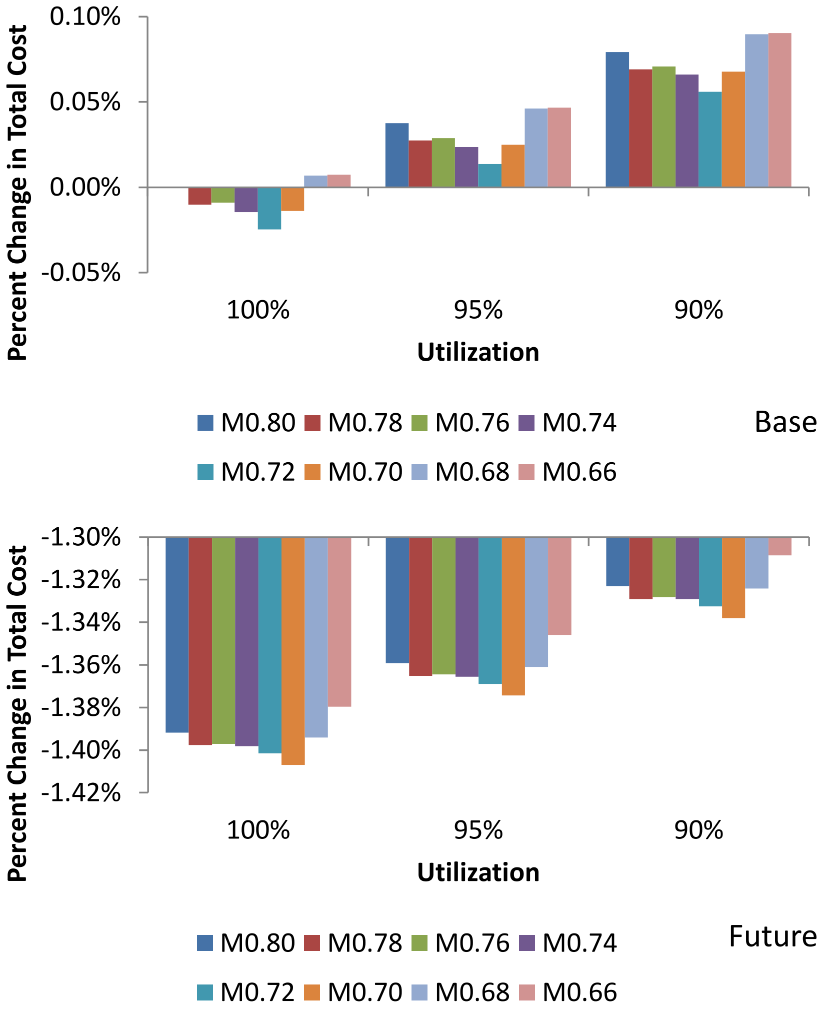


Figure 222. RJ Utilization Sensitivity for Speed Reduction on Total Cost

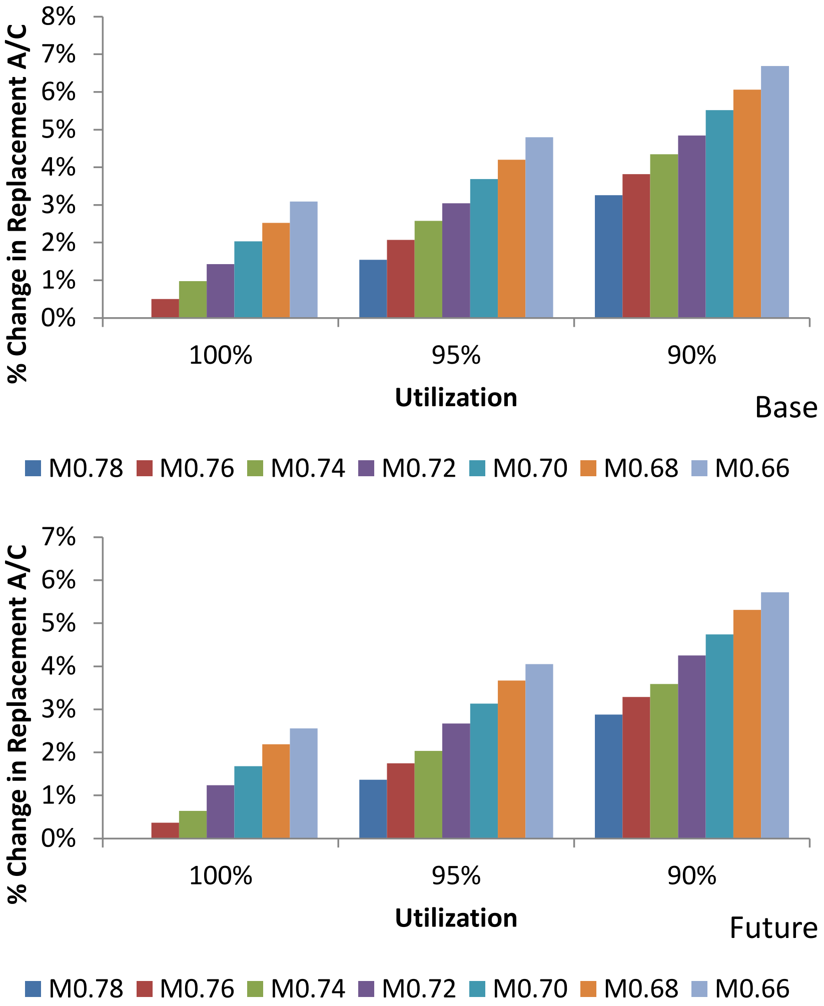


Figure 223. SA Utilization Sensitivity for Speed Reduction on Aircraft Number

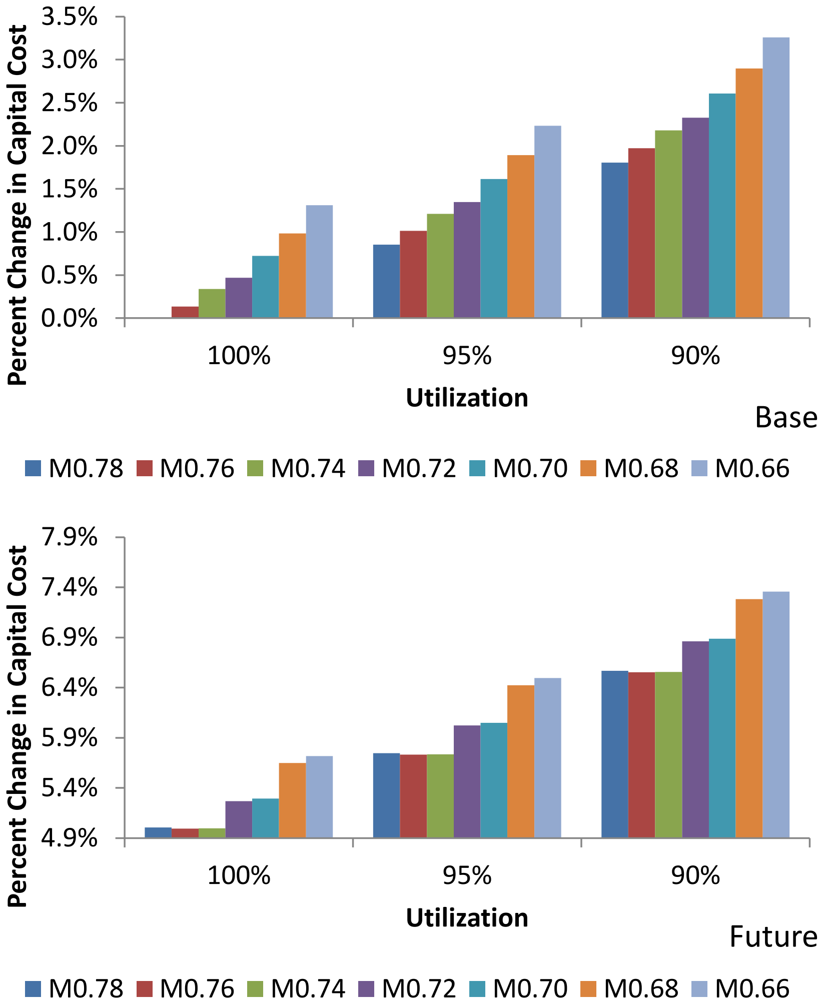


Figure 224. SA Utilization Sensitivity for Speed Reduction on Capital Cost

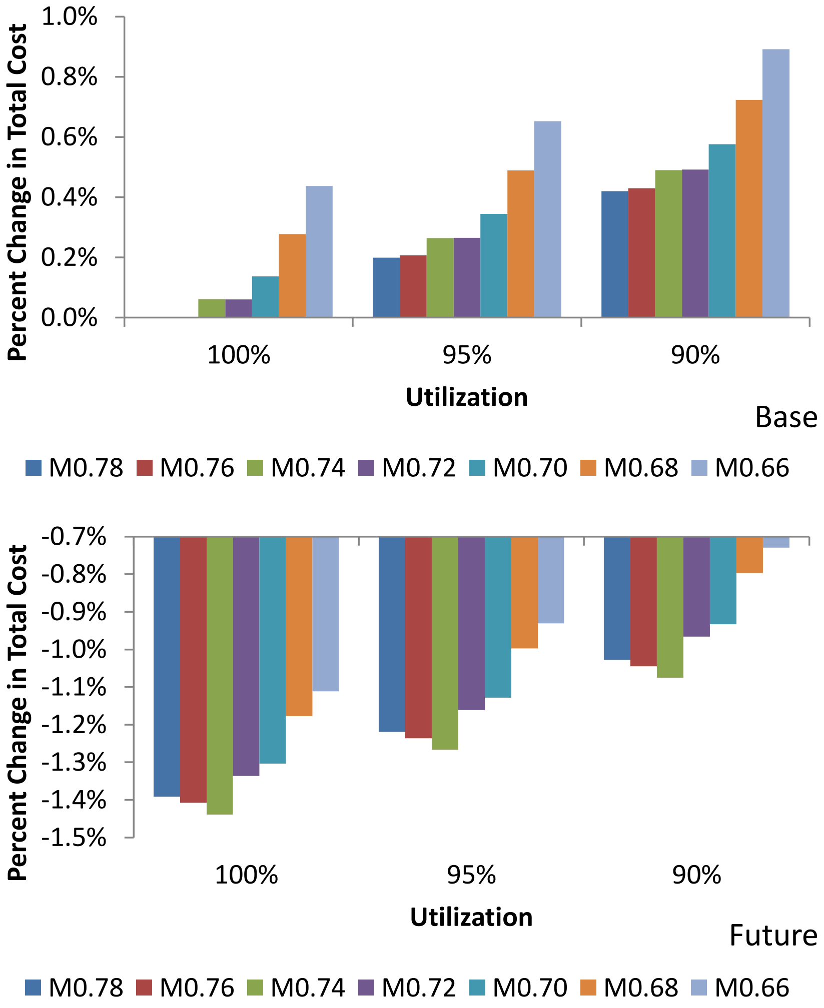


Figure 225. SA Utilization Sensitivity for Speed Reduction on Total Cost

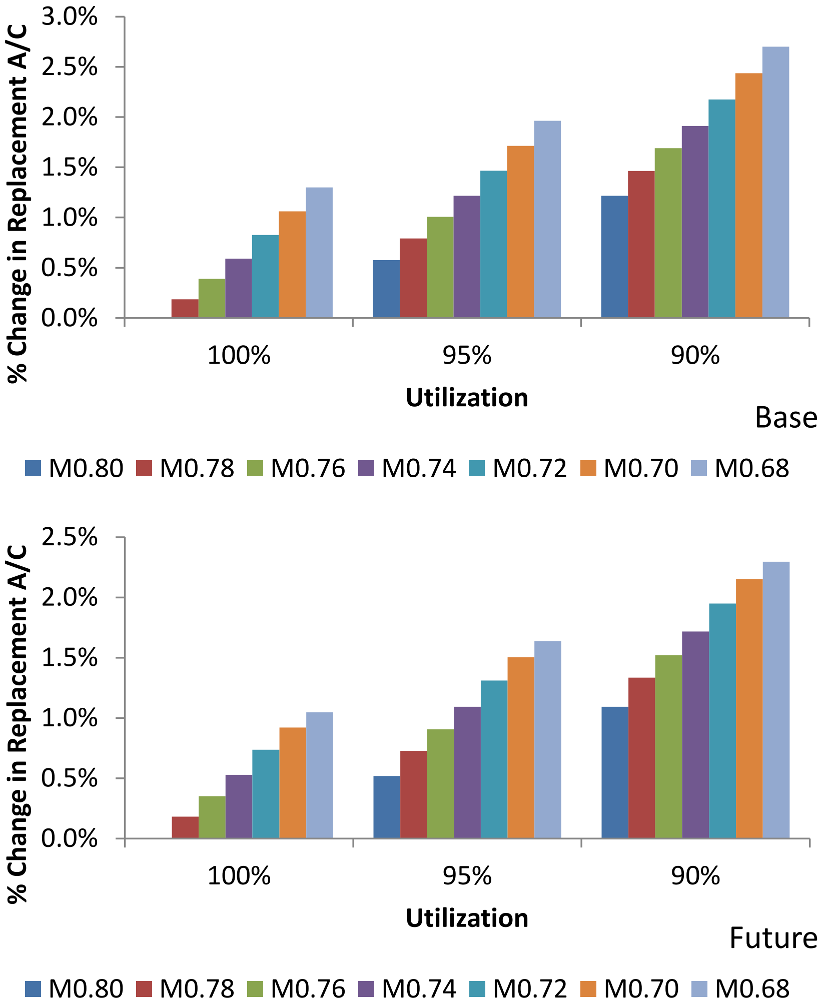


Figure 226. STA Utilization Sensitivity for Speed Reduction on Aircraft Number

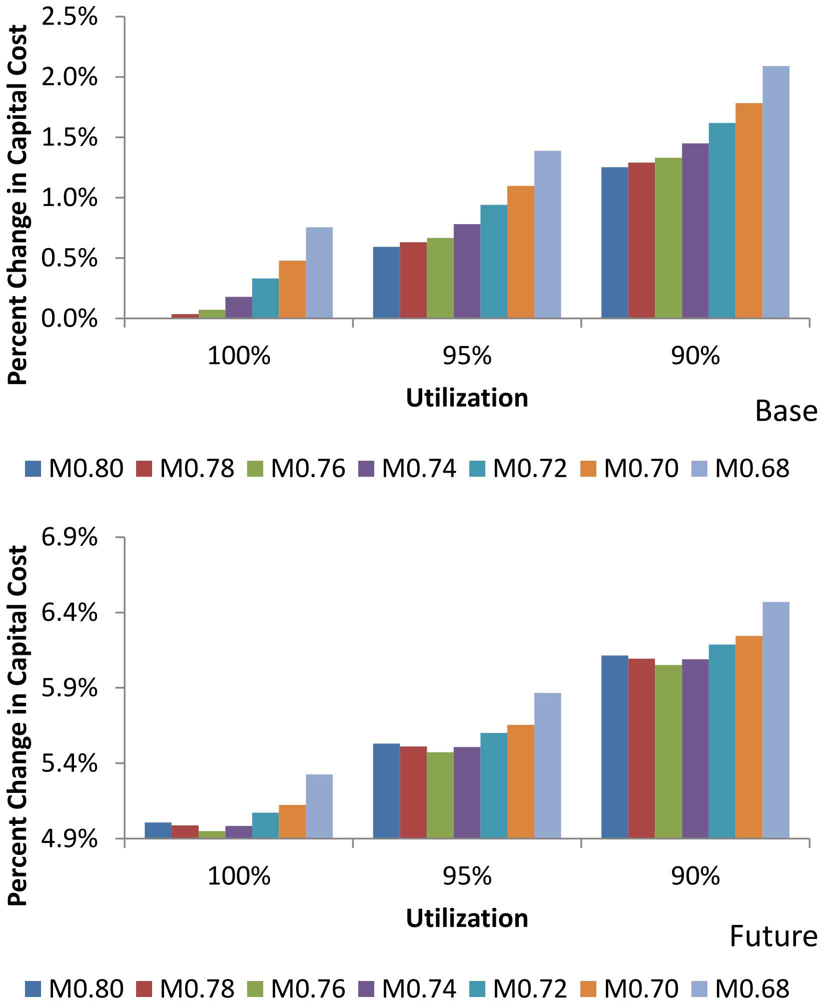


Figure 227. STA Utilization Sensitivity for Speed Reduction on Capital Cost

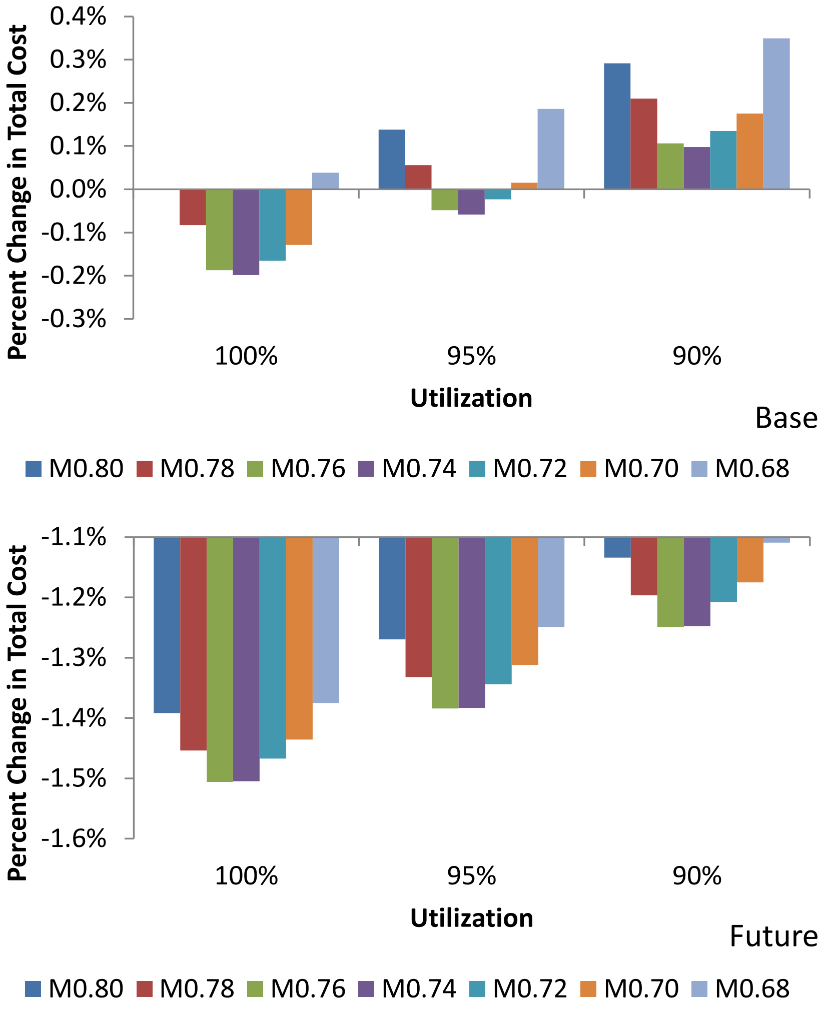


Figure 228. STA Utilization Sensitivity for Speed Reduction on Total Cost

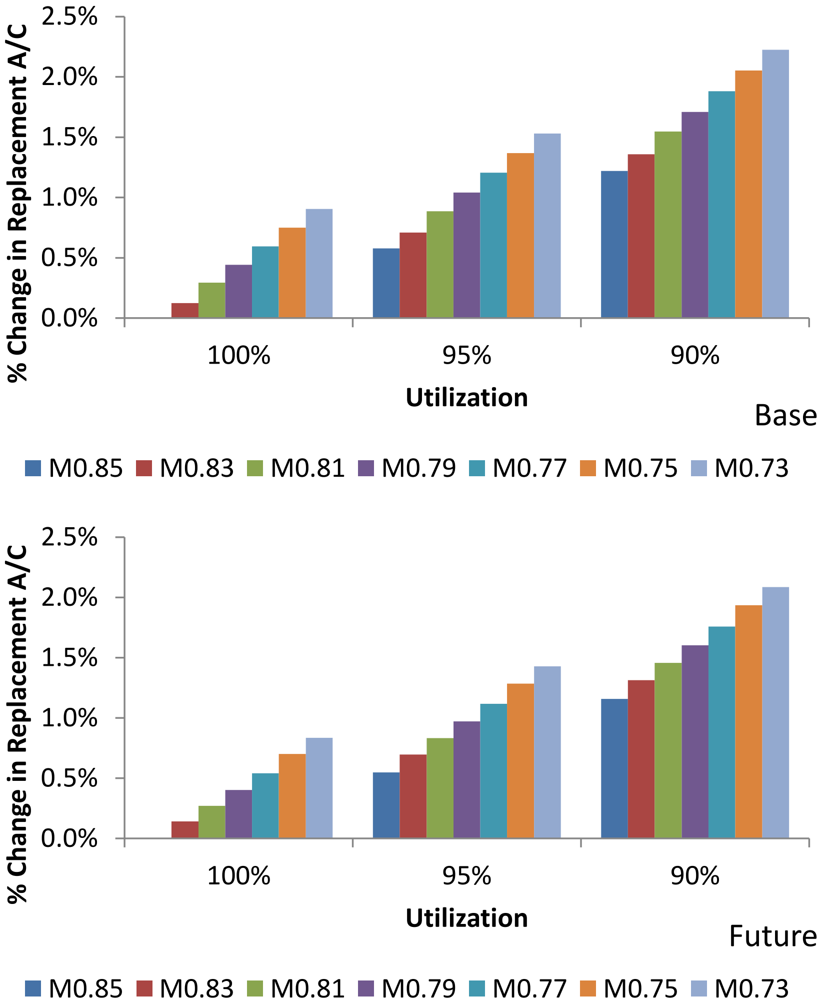


Figure 229. LQ Utilization Sensitivity for Speed Reduction on Aircraft Number

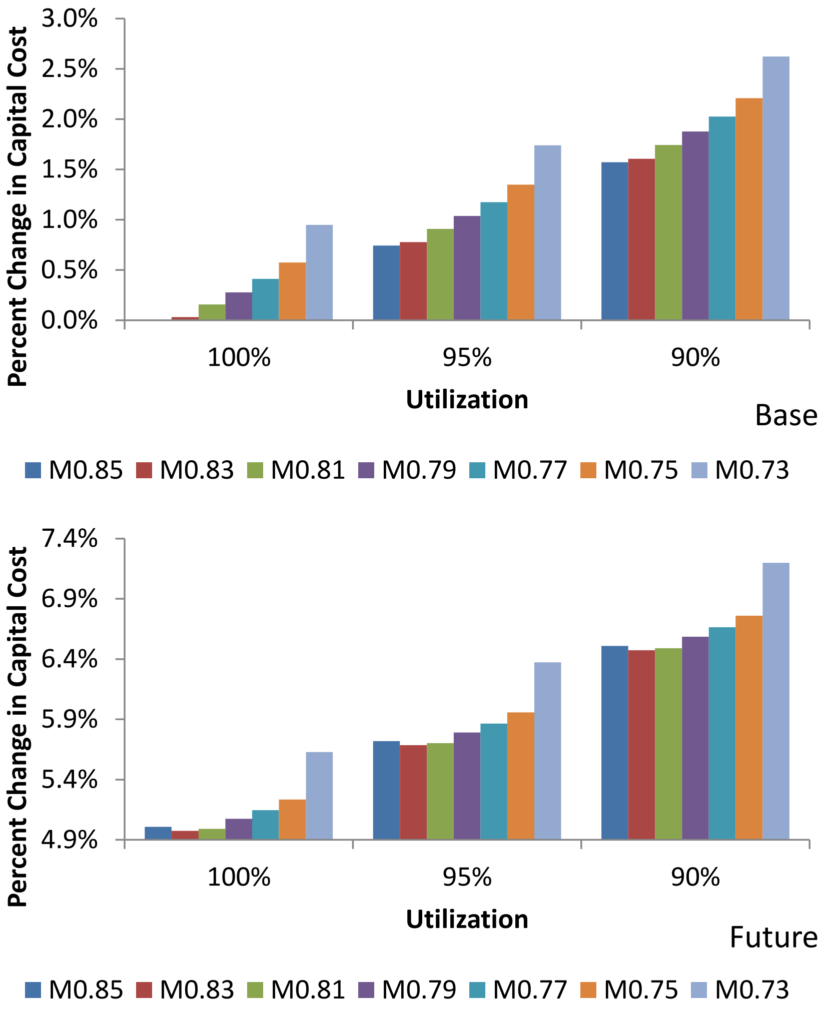


Figure 230. LQ Utilization Sensitivity for Speed Reduction on Capital Cost

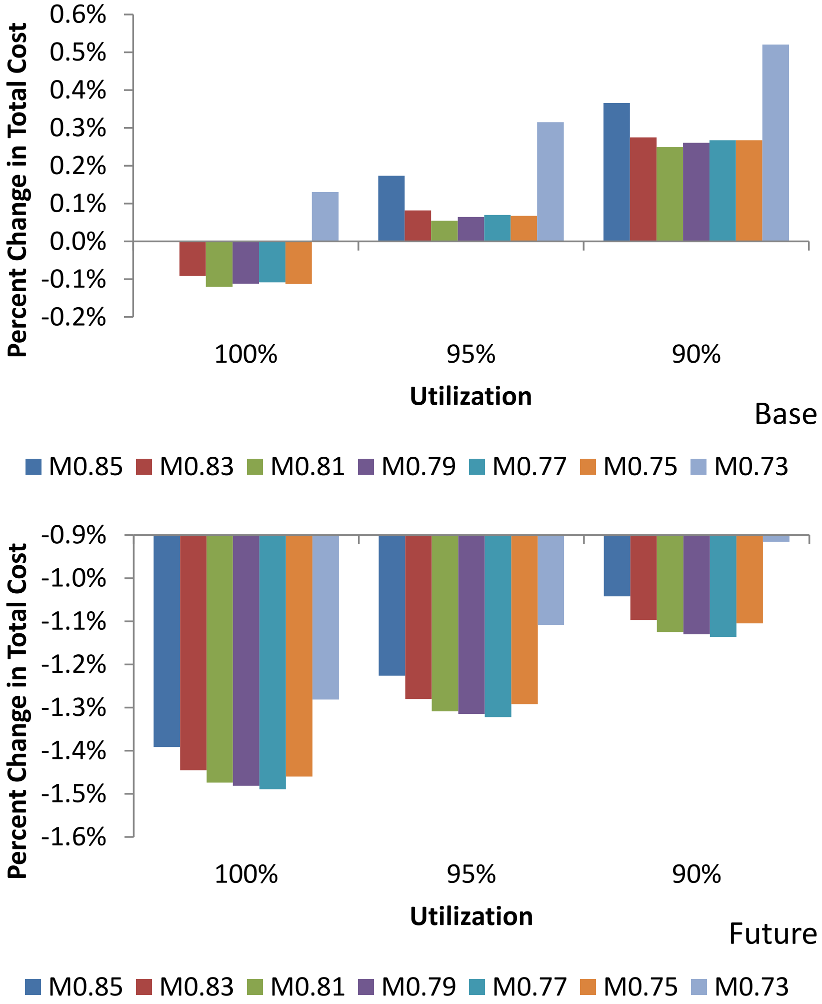


Figure 231. LQ Utilization Sensitivity for Speed Reduction on Total Cost

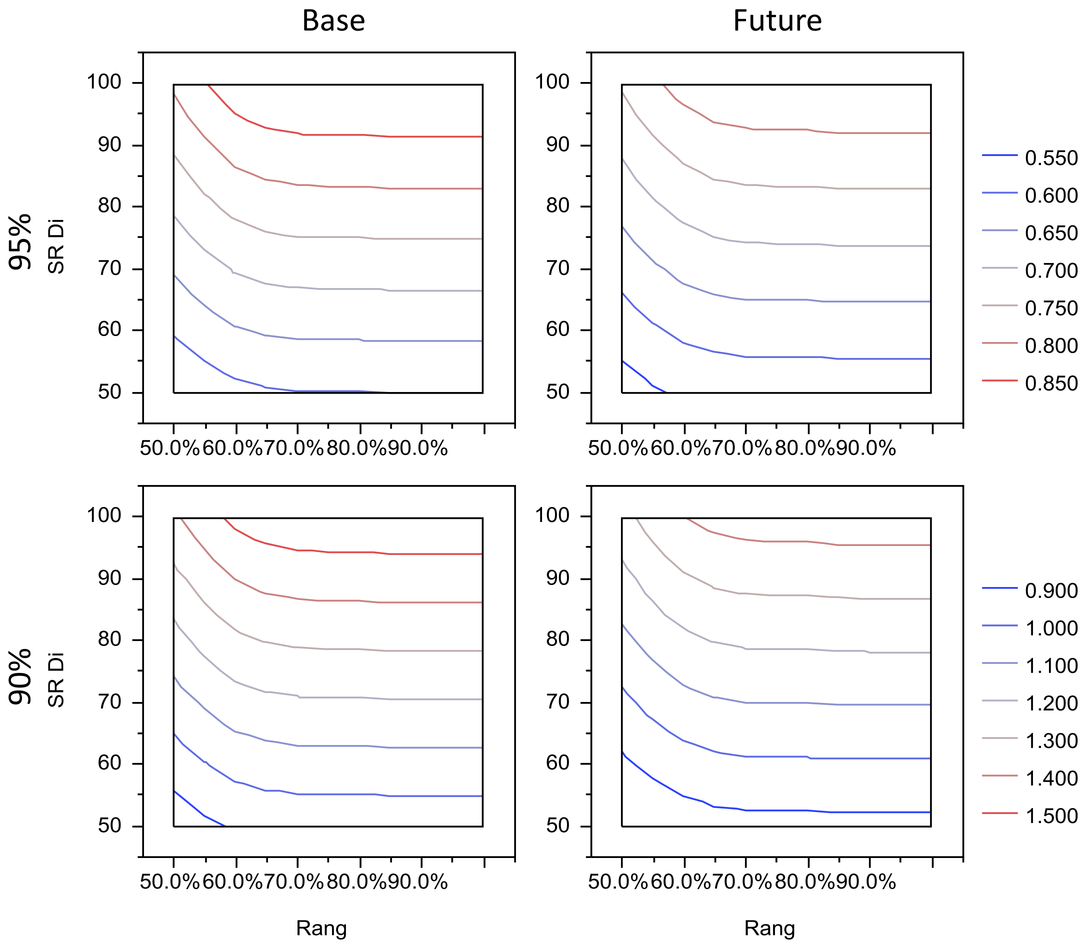


Figure 232. STA Utilization Sensitivity for Range Reduction on Aircraft Number

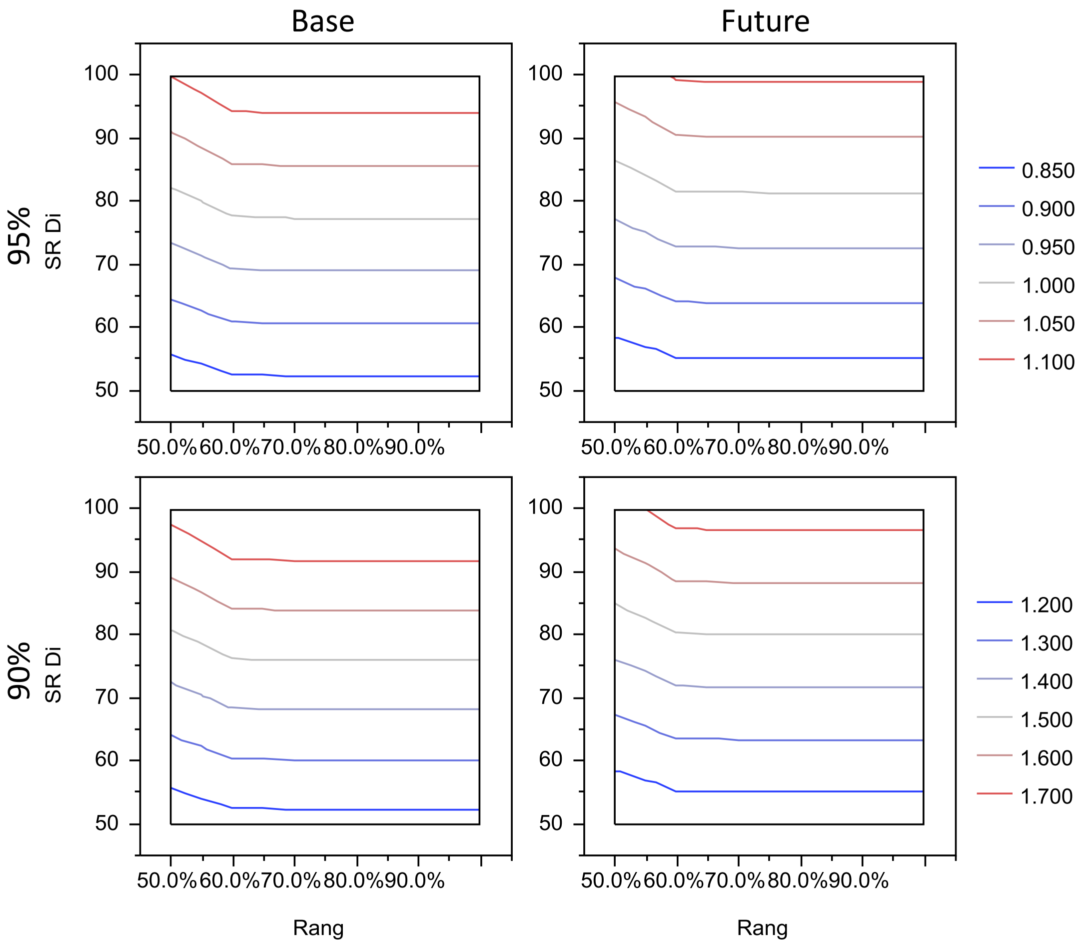


Figure 233. LQ Utilization Sensitivity for Range Reduction on Aircraft Number

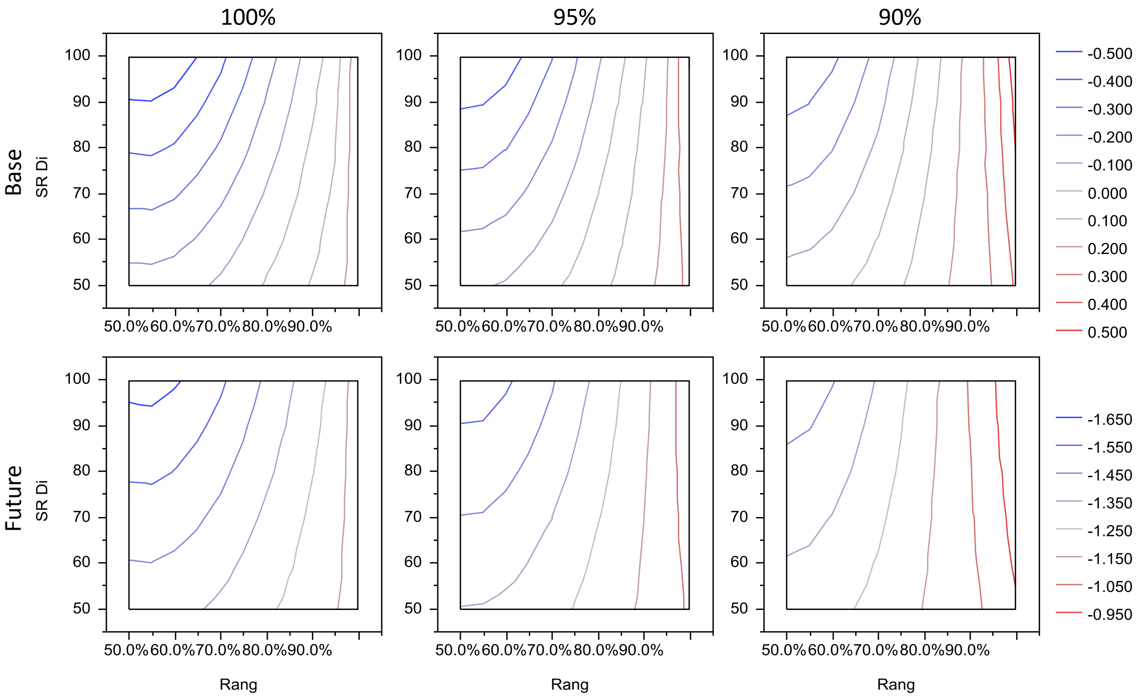


Figure 234. STA Utilization Sensitivity for Range Reduction on Total Cost

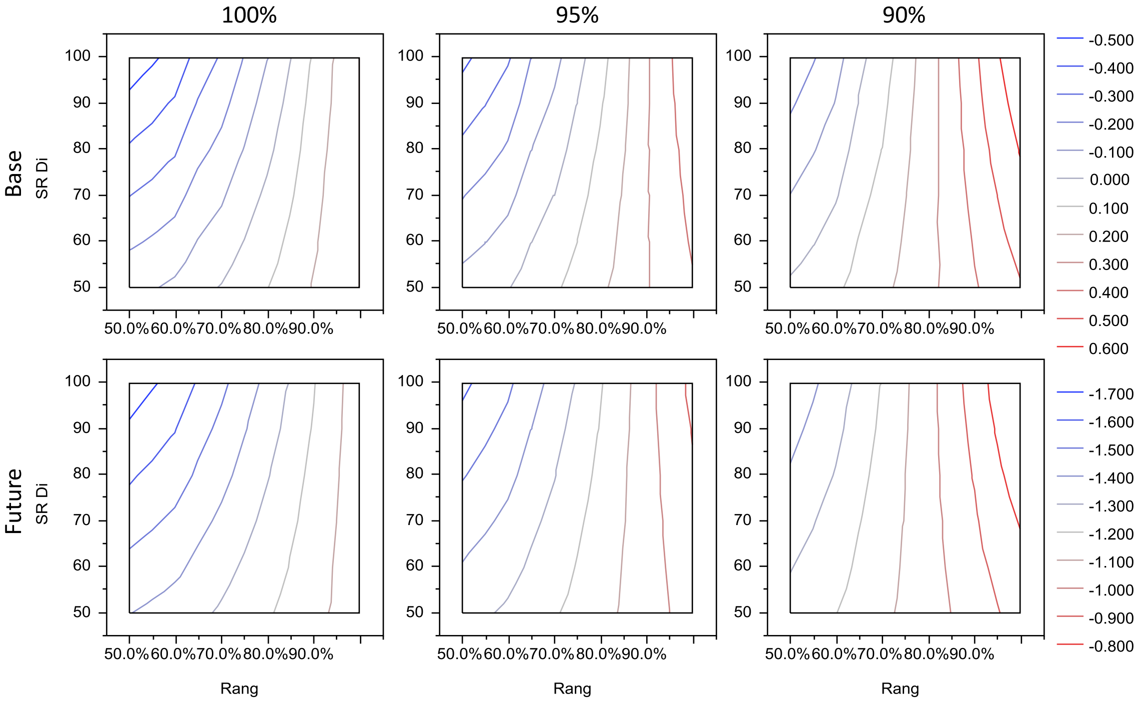


Figure 235. LQ Utilization Sensitivity for Range Reduction on Total Cost

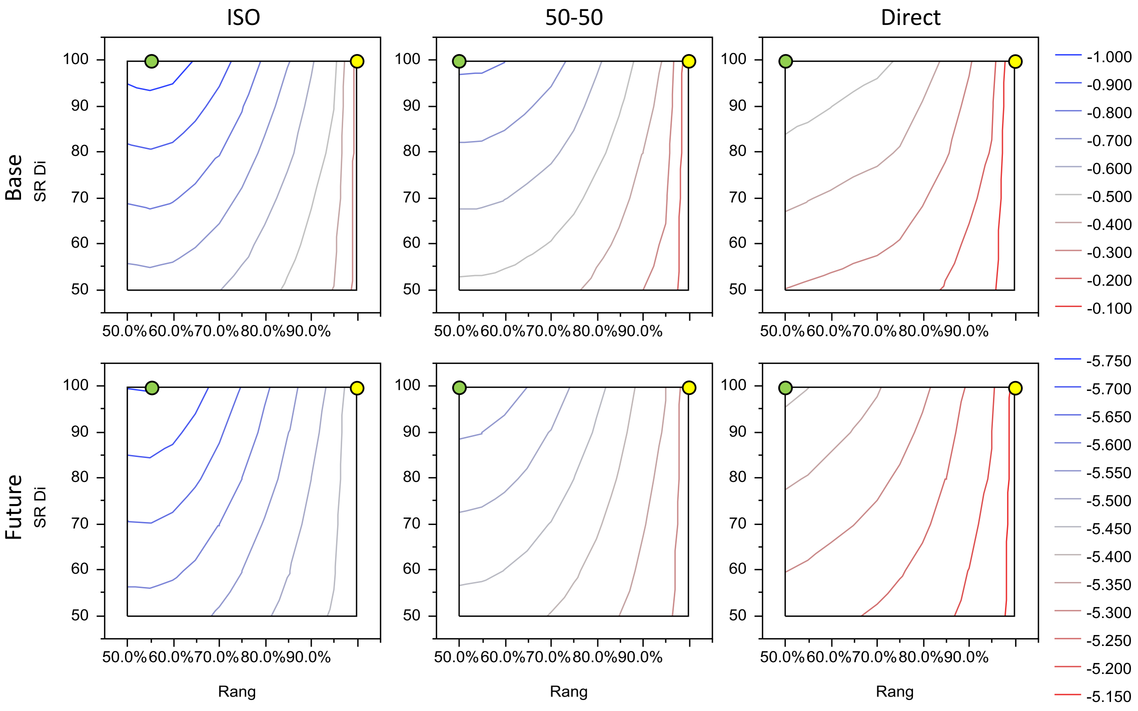


Figure 236. Sensitivity of Intermediate Stop Adoption for STA Fuel Burn

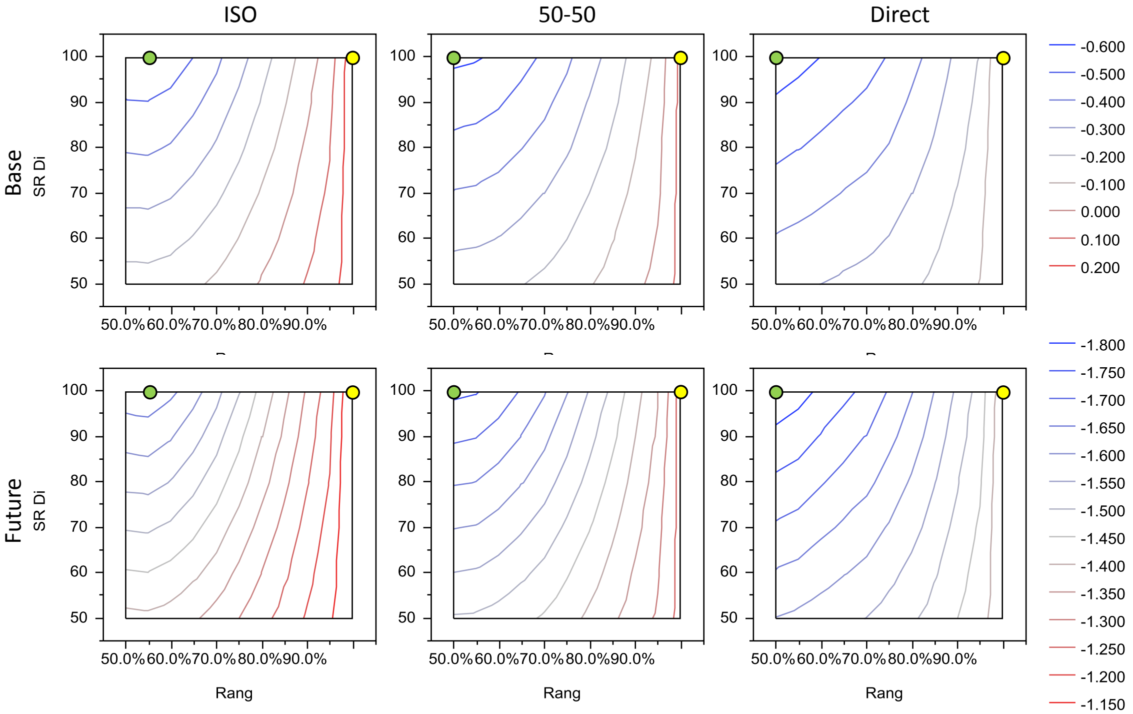


Figure 237. Sensitivity of Intermediate Stop Adoption for STA Total Cost

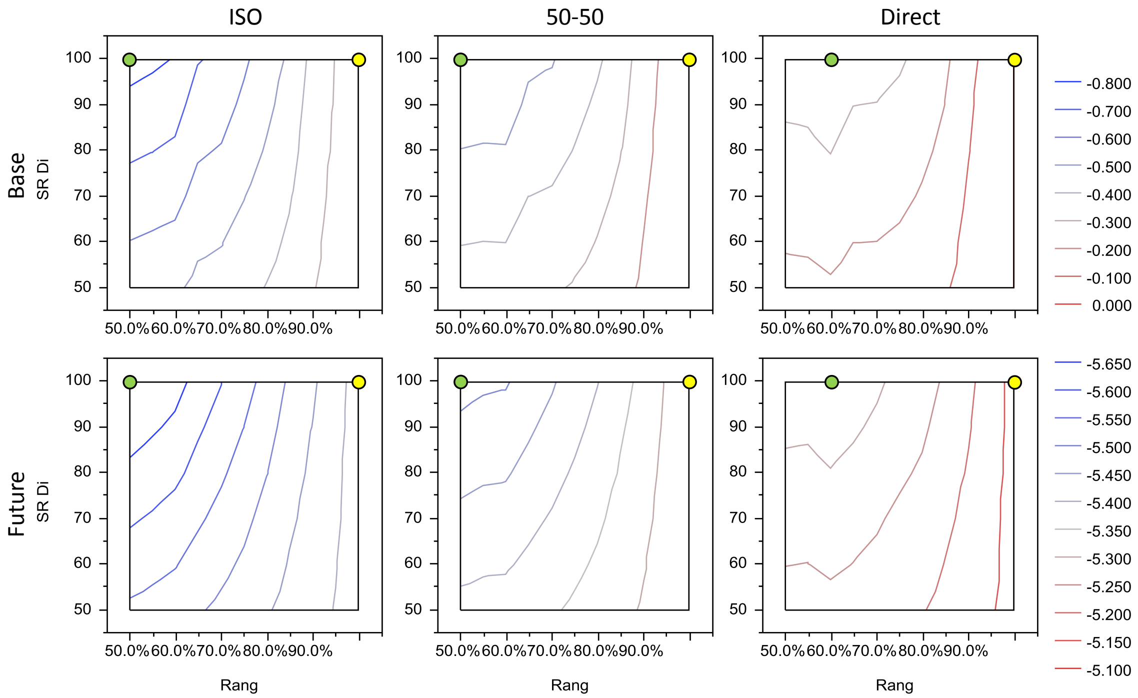


Figure 238. Sensitivity of Intermediate Stop Adoption for LQ Fuel Burn

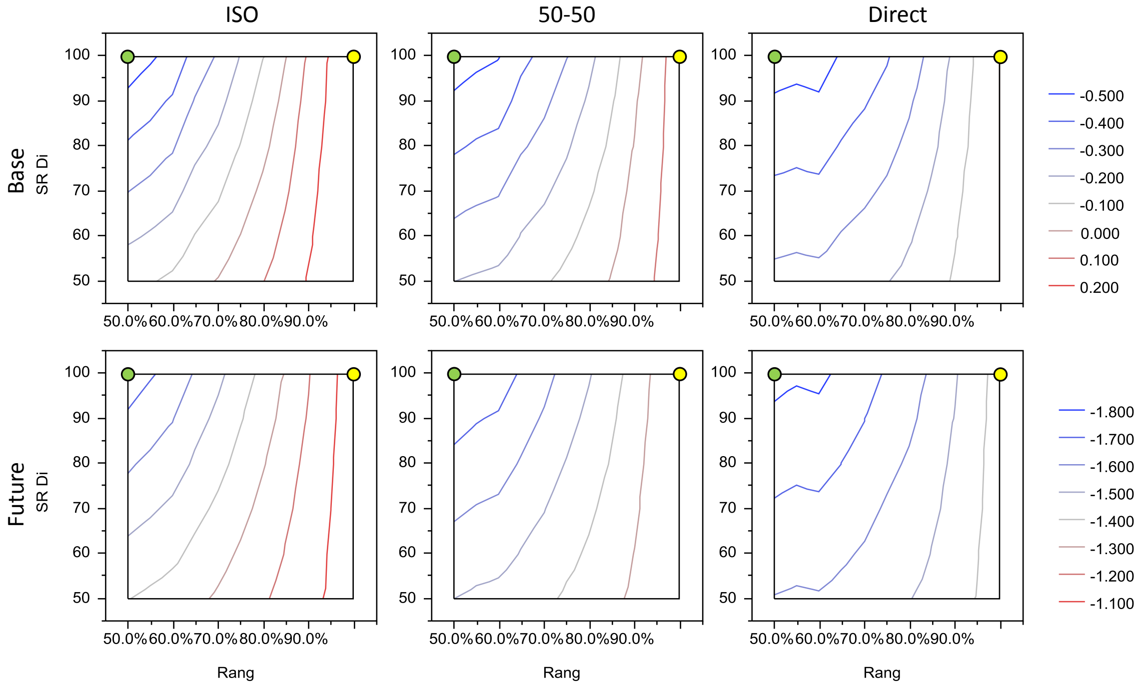


Figure 239. Sensitivity of Intermediate Stop Adoption for LQ Total Cost

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VITA

Paul Simpson Brett was born in Winston Salem, North Carolina on February 29th 1984. He grew up in the outskirts of Winston Salem in a community named Lewisville. He attended West Forsyth High School and graduated in the Spring of 2002. He entered Georgia Tech in the fall as a freshman, studying aerospace engineering. In applying for a scholarship opportunity, he was presented an opportunity to join the Aerospace Systems Design Lab as an undergraduate research assistant. He graduated with a B.S. in Aerospace Engineering in the Spring of 2006 with high honors and returned to the lab as a graduate research assistant. He earned his M.S. in Aerospace Engineering in the Fall of 2007. Paul has worked on a number of government sponsored aerospace research in the areas of aircraft design, technology forecasting, and environmental policy. Paul hopes to gain employment post-graduation and live out the rest of his days solving exciting problems.