Partnership for AiR Transportation
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Assessment of CO_2 Emission Metrics for a Commercial Aircraft Certification Requirement

PARTNER Project 30 Interim Report

prepared by
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The Partnership for AiR Transportation Noise and Emissions Reduction — PARTNER — is a cooperative aviation research organization, and an FAA/NASA/Transport Canada-sponsored Center of Excellence. PARTNER fosters breakthrough technological, operational, policy, and workforce advances for the betterment of mobility, economy, national security, and the environment. The organization's operational headquarters is at the Massachusetts Institute of Technology.

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Executive Summary

Increasing concern over the potential harmful effects of greenhouse gas emissions has motivated the consideration of an aircraft CO_2 certification requirement as one way to reduce aircraft CO_2 emissions and mitigate the impact of aviation on climate. As a first step, there is the need to identify metrics that reflect CO_2 emissions at the aircraft level. This report serves (1) to provide a summary of the ongoing study being funded by the U.S. Federal Aviation Administration (FAA) to generate and evaluate CO_2 emissions metrics, and (2) to recommend, based on quantitative and qualitative analyses completed under the study thus far, the most promising CO_2 frameworks consisting of metrics, correlating parameters (CP) and evaluation conditions for a potential aircraft CO_2 certification requirement. A metric generally captures the key performance parameters intended to be influenced (and plotted on the y-axis a graph), a correlating parameter (captured on the x-axis of plots) is generally based on fundamental physical attributes of the aircraft, and evaluation conditions are conditions at which vehicle performance is measured and reported to show compliance.

First, this report describes the problem of CO_2 emissions from commercial aviation and the rationale for generating metrics that reflect aircraft CO_2 emissions, and presents a portfolio of candidate CO_2 frameworks that were evaluated for their suitability. This portfolio of metrics was generated through systematic brainstorming sessions, literature review, interactions with industry, and interactions with the CO_2 Task Group members from the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) Working Group 3. This report then presents qualitative and quantitative criteria by which each CO_2 framework was evaluated. Evaluation tests included analyses utilizing a variety of secondary data sources[i] available to the project team, such as public-domain information, Piano-X and Piano-5 analysis tools, FAA's Environmental Design Space (EDS), ICAO's 2006 Common Operations Database, Bureau of Transportation Statistics (BTS) database, and other technical literature. Tests included the assessment of parameters that compose each metric, metric performance comparison across aircraft types and categories, sensitivity analyses of mission and flight conditions, estimation of technology influences on metric values, effects of metrics on notional future aircraft designs, and others. The insight gained from these tests directly supported the comprehensive assessment of the portfolio of metrics and the identification of a subset of most promising metrics.

From the set of over 30 metrics that were considered in this study (and many more combinations of metrics and correlation parameters), a subset of 2 metrics are believed to exhibit attributes of promising metric-CP candidates. These two metrics fall under two distinct categories, full mission and instantaneous performance;

- The full mission metric (i.e. Block Fuel / Range) measures the fuel burn of aircraft over an entire mission (i.e. across phases of flights that can include; taxi-out, takeoff, climb, cruise, descend approach and taxi-in). This metric generally requires the definition of a representative mission(s), including payload, range, taxi time, climb schedule, cruise altitude(s), diversion distances and other parameters.
- The instantaneous performance metric defined as 1/Specific Air Range (SAR). 1/SAR is analogous to 'miles-per-gallon' for automobile and represents the incremental air distance an aircraft can travel for a unit amount of fuel at a cruise condition. SAR can be

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[i] Note: For the purpose of this study, secondary data source is defined as aircraft performance data generated from third party models and tools such as Piano-5, Piano-X, EDS, as opposed to primary source data that is directly published or provided by aircraft manufacturers.

easily calculated by dividing true air speed (measured in km/s) by fuel flow (measured in kg/s). When measured in steady-level conditions, 1/SAR primarily depends only on aircraft weight, altitude, air speed, and ambient temperature. As a result, 1/SAR limits the regulatory certification burden by greatly reducing the number of assumptions required to define the measurement point(s). In addition, SAR has common use in aerospace/airline industry, which may simplify the certification process. 1/SAR also encapsulates fundamental parameters that directly influence airplane fuel efficiency including: propulsion system efficiency, aerodynamic efficiency, and airplane weight. 1/SAR does not explicitly measure performance across all phase of flight; however, research to-date suggests that 1/SAR could sufficiently capture technology improvements from all phases of flight.

The two metrics described above were assessed to be promising metrics when paired with the correlation parameter MTOW. Through substantial analysis and investigations, the resulting CO_2 frameworks were determined to be the most promising to objectively and accurately reflect CO_2 emissions at the aircraft level. These frameworks include: 1/SAR vs. MTOW and Block Fuel / Range vs. MTOW.

Acronyms & Abbreviations

Acronyms	Description
ACARS	Aircraft Communications Addressing and Reporting System
ANCA	Airport Noise and Capacity Act
ATC	Air Traffic Control
BEW	Basic Empty Weight
BF	Block Fuel
BJ	Business Jet
BTS	Bureau of Transportation Statistics
CAEP	Committee on Aviation Environmental Protection
CAFE	Corporate Average Fuel Economy
CASFE	Commercial Aircraft System Fuel Efficiency
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CP	Correlation Parameter
EASA	European Aviation Safety Agency
EDS	Environmental Design Space
EPA	Environmental Protection Agency
EPNdB	Effective Perceived Noise Level, in decibels
FAA	Federal Aviation Administration
FL	Floor Area
GHG	Greenhouse Gas
GIACC	Group on International Aviation and Climate Change
GVWR	Gross Vehicle Weight Rating
H_20	Water
HC	Hydro Carbon
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
L/D	Lift to Drag ratio
LQ	Large Quad
LRC	Long Range Cruise
LTA	Large Twin Aisle
LTO	Landing and Take-Off
MEW	Manufacturer Empty Weight
MLW	Maximum Landing Weight
MRC	Maximum Range Cruise
MSP	Maximum Structural Payload
MTOW	Maximum Takeoff Weight
MTW	Maximum Taxi Weight
MVP	Maximum Volumetric Payload
MZFW	Maximum Zero Fuel Weight
NACE	National Average Carbon Emissions (Australia)
NB	Narrow Body
NO_X	Nitrous Oxides
OEW	Operating Empty Weight
OPR	Overall Pressure Ratio
P	Payload
PARTNER	Partnership for AiR Transportation Noise and Emissions Reduction
R	Range
R_1	Payload-Range point at maximum range at MZFW
R_2	Payload-Range point at intersection of MTOW and maximum fuel volume
RJ	Regional Jet
SA	Single Aisle
SAR	Specific Air Range
SEW	Standard Empty Weight
SO_X	Sulfurous Oxides
STA	Small Twin Aisle
SUV	Sport Utility Vehicle
TCDS	Type Certificate Data Sheet

TOGW	Takeoff Gross Weight
TP	Turboprop
TSFC	Thrust Specific Fuel Consumption
UL	Useful Load
UNFCCC	United Nations Framework Convention on Climate Change
WB	Wide Body
WG3	(ICAO CAEP) Working Group 3

Glossary

Aircraft Certified Performance	The performance (e.g. fuel efficiency) of an aircraft as it is measured during an aircraft certification process
Basic Empty Weight	Standard empty weight plus optional equipment.
Block Fuel	Fuel burned by an aircraft from the gate at airport of origin to gate at the airport of destination. Block Fuel does not count reserves and contingency fuel
Manufacturer's empty weight (MEW)	The weight of an aircraft's structure, power plants, systems, furnishings, and other required items of equipment that are an integral part of a particular aircraft configuration. MEW is essentially a "dry" weight, including only those fluids (e.g., hydraulic) in closed systems.
Maximum TakeOff Weight (MTOW)	The maximum certified total aircraft weight at takeoff brake release, as limited by aircraft strength and airworthiness requirements.
Maximum Landing Weight (MLW)	The maximum certified total aircraft weight for landing, as limited by aircraft strength and airworthiness requirements.
Maximum Zero Fuel Weight (MZFW)	The maximum certified total aircraft weight allowable before usable fuel must be loaded in the aircraft, as limited by aircraft strength and airworthiness requirements.
Mission Fuel	All fuel carried by an aircraft; the sum of all fuel required to reach a destination and any reserves carried
Operating Empty Weight (OEW)	Manufacturer's Empty Weight plus Standard and Operational items. Standard Items Equipment and fluids not considered an integral part of a particular aircraft and not a variation for the same type of aircraft. These items may include, but are not limited to, the following: Unusable fuel and other unusable fluids, Engine oil, Toilet fluids and chemicals, Fire extinguishers, pyrotechnics and emergency oxygen equipment, Structure in galleys, buffets and bars, Supplementary electronic equipment, Operational Items Personnel, equipment and supplies necessary for a particular operation but not included in Manufacturing Empty Weight or Standard Items. These items may vary for a particular aircraft and may include, but are not limited to, the following: Crew and Baggage, Manuals and navigational equipment, Removable service equipment for cabin, galleys and bars, Food and beverages, including liquor, Usable fluids other than those in useful load, Life rafts, life vests and emergency transmitters, Aircraft unit load devices
Standard Empty Weight	The weight of the airframe, engines, all permanently installed equipment, and unusable fuel. Depending upon the part of the Federal regulations under which the aircraft was certificated, either the undrainable oil or full reservoir of oil is included.
Unintended Consequences	Outcomes that are not (or not limited to) the results originally intended in a particular situation

Introduction

Motivation

Growing concerns over climate change have created an impetus for reducing greenhouse gas (GHG) emissions from all sectors of the global economy. Despite the substantial historical reductions of fuel burn and pollutant emissions from commercial aviation, it is expected that further improvements will be required, especially if the global long-term demand for air transportation increases and neutral or reduced net GHG emissions are targeted.

Carbon Dioxide (CO_2) as a Contributor to Climate Change

There are many compounds that fall under the category of a greenhouse gas, but carbon dioxide (CO_2) has received much attention for its prevalence and its harmful effects. CO_2 acts as a GHG through absorption and reemission of infrared radiation, and thus is one of the most important emissions in terms of climate change. This compound becomes even more important because its emission can affect the climate for centuries [1], a trait has motivated many entities to take steps to curb CO_2 emissions.

Ambitious goals have been set for CO_2 and GHG emission targets by various countries. In the United States, the Obama administration has stated targets of 17% reductions in 2020 (from 2005 levels) and an 83% reduction target by 2050. In June 2009, the European Union (EU-27) set a 21% reduction target compared to 2005 levels, to be achieved in 2020. An International Civil Aviation Organization (ICAO) global aspirational goal is based on a fuel efficiency improvement of 2% per annum.

While commercial aviation contributed approximately 2.5% of total anthropogenic CO_2 emissions in 2005 [2], aviation's relative contribution to climate change is estimated to be higher [3], due in part to the types of emissions produced and the high altitude at which they are generated. Aviation's relative contribution to climate change is only expected to grow, as other sectors mitigate their emissions production and demand for aviation continues to increase. The identification of CO_2 as a leading contributor to climate change, coupled with concern over the potentially increasing contribution of CO_2 emissions to climate change by aviation, motivates action to mitigate aviation's CO_2 emissions in the near-term.

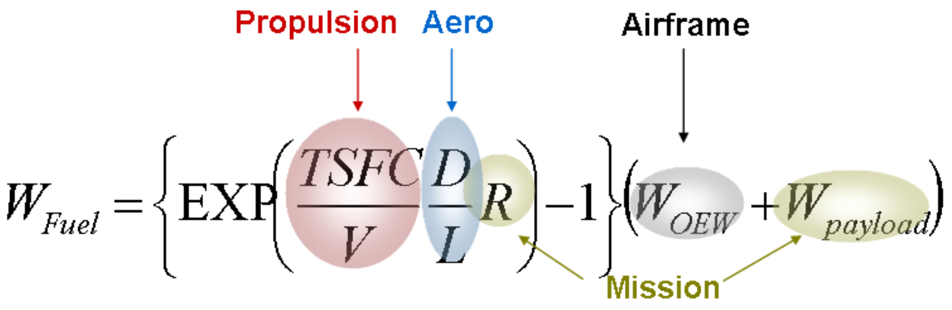
Certification Standard as an Aviation CO_2 Mitigation Measure

There are several avenues which can mitigate the influence of aviation CO_2 emissions on climate. These include technological, operational, regulatory, and market-based measures. Under the regulatory avenue, there is an ongoing effort to develop an aircraft CO_2 emissions standard under the auspices of the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP). This emissions standard, while intended to ultimately reflect aircraft CO_2 emissions, is being developed as an aircraft fuel efficiency standard, since fuel consumption and CO_2 emissions are directly proportional properties for the combustion of hydrocarbon fuel. The use of fuel efficiency concepts allows this standard to directly relate to aircraft performance and ensures a degree of transparency demonstrating the practical benefit of this regulation.

An aircraft CO_2 emissions standard is a mechanism that could provide incentives for industry stakeholders to improve aircraft fuel efficiency through the implementation of new airframe and engine technology. A standard is generally composed of three elements; (1) a metric, a correlating parameter and evaluation conditions, (2) a scope of applicability and (3) a regulatory level. Note that a certification requirement is generally composed of the first two elements. According to the ICAO CAEP Working Group 3 (WG3) meeting in London 1-3 April 2009, “the development of appropriate metric(s) is a key issue that must be addressed as a first step [4]”.

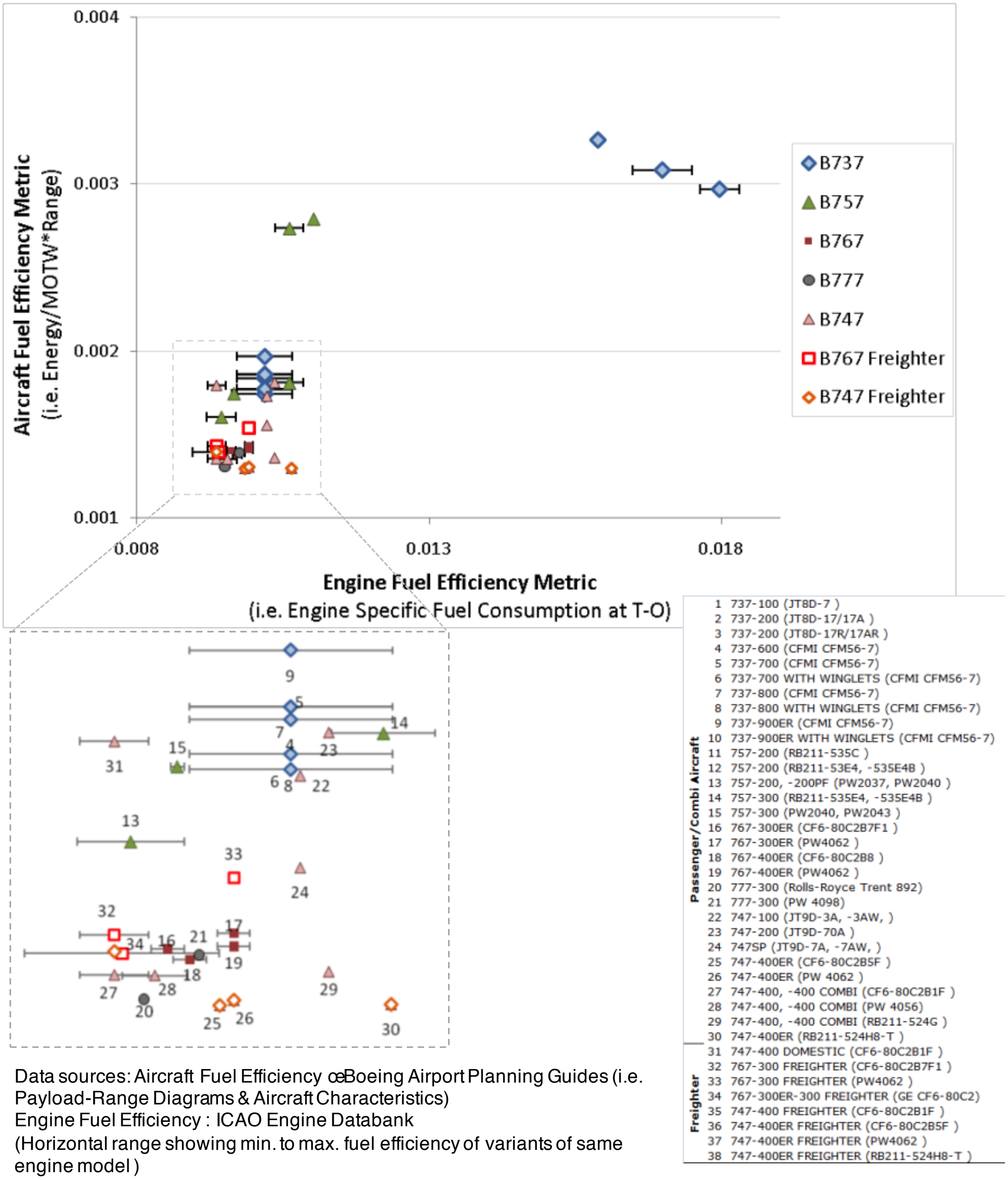
This research project focuses on providing scientific and technical input into the advantages and disadvantages of commercial aircraft CO_2 emission metrics, correlating parameters and associated evaluation conditions, i.e. a certification framework.

Unlike other emission certification requirements for aviation that are defined and performed at the engine level (e.g. Dp/Foo which measures the quantity of pollutants emitted per unit of thrust), the proposed CO_2 certification requirement or fuel efficiency certification requirement is intended to be defined at the aircraft level. This is motivated by the multiple factors that influence aircraft fuel burn. As shown below, the Breguet-Range equation depicts, total fuel burn is influenced by thrust specific fuel consumption (i.e. TSFC), aerodynamics (i.e. lift-to-drag ratio or L/D), airframe operating empty weight (OEW), and design trades (e.g. Cruise Speed, Range and Payload). All these factors contribute to the total fuel efficiency of the vehicle and need to be taken into account in the assessment of aircraft CO_2 emission metrics.



$$W_{Fuel} = \left\{ \mathrm{EXP}\left(\frac{TSFC}{V} \frac{D}{L} R \right) - 1 \right\} \left(W_{OEW} + W_{payload} \right)$$

The need to consider a CO_2 certification at the aircraft level as opposed to the engine level is further demonstrated by the comparative analysis of the correlation between the aircraft fuel efficiency and engine fuel efficiency (Figure 1). As shown, there is no strong correlation between aircraft and engine level efficiency. For a given engine fuel efficiency the aircraft fuel efficiency can vary by a factor of 3. This significant variation suggests engine level fuel efficiency metrics are not suitable surrogates for total aircraft fuel efficiency.



Data sources: Aircraft Fuel Efficiency œBoeing Airport Planning Guides (i.e. Payload-Range Diagrams & Aircraft Characteristics)
Engine Fuel Efficiency : ICAO Engine Databank
(Horizontal range showing min. to max. fuel efficiency of variants of same engine model)

Figure 1: Aircraft Fuel Efficiency vs. Engine Fuel Efficiency

Objective

The objective of this research is to identify robust metrics, correlating parameters, and evaluation conditions (i.e., a CO_2 certification framework) that objectively and accurately reflect CO_2 emissions at the aircraft level. This effort aims to inform the national and international decision-making processes with regards to the development of an aircraft CO_2 certification requirement by (1) identifying a set of CO_2 frameworks consisting of metrics, correlation parameters, and evaluation conditions that could be used as a basis for the aircraft certification requirement, (2) evaluating the advantages and disadvantages of each CO_2 framework, (3) examining the ways in which each metric would be measured in a certification requirement, and (4) providing a comprehensive assessment to aid decision makers and stakeholders.

Overview of Research Approach

A multi-prong approach was used for the assessment of metrics that objectively and accurately reflect CO_2 emission at the aircraft level. This approach includes the following steps;

- Identification of key issues, challenges, and methods in existing environmental standards
- Generation of a portfolio of candidate metrics, correlation parameters, and evaluation conditions
- Identification of the relationship of the current fleet to the metrics, correlation parameters and evaluation conditions
- Assessment of the possible impacts that certification requirements based on these metrics would have on the future vehicle development
- Working with industry stakeholders to identify equity issues and potential gaming dynamics
- Providing a comprehensive assessment of the metrics considered

Review of Existing Environmental Standards

A literature review was conducted for non-CO_2 standards in the commercial aviation industry and GHG emissions standards in non-aviation industry sectors to better understand the role of standards and issues that historically arose with their development, construction, and implementation.

Non-CO_2 Emission Standards in Commercial Aviation

Non-CO_2 emission standards in the commercial aviation industry focus primarily on engine design and certification. The ICAO Annex 16 document governs the standards that are related to engine emissions during the Landing and Take-Off (LTO) cycle. ICAO standards define emissions levels for engine smoke, unburned Hydro Carbon (HC), Carbon Monoxide (CO), and Nitrous Oxides (NO_X).

Engine Smoke Standard

This standard was established in 1974 and revised several times [5].

Unburned HC Standard

In 1984, the Environmental Protection Agency (EPA) had hydrocarbon (HC) emission standards for newly manufactured aircraft gas turbine engines with a thrust greater than 26.7 kN. EPA regulations for smoke and HC emissions have been in effect since 1984.

CO Standard

The CO emission standard applies to newly manufactured aircraft gas turbine engines (turbofan and turbojet engines).

NO_X Standard

The NO_X emission standards were established on the recommendation of CAEP/2. This NO_X framework contained a metric, correlating parameter, and evaluation conditions, which are defined as:

Metric: The general metric used to regulate aircraft engine emissions is D_P/F_{00}, where DP is the mass of pollutants emitted and F_{00} is the engine's sea-level static maximum rated thrust. This metric was chosen in part because it succinctly relates emissions performance to the useful capability of the engine.

Correlation Parameter: In the associated regulation, the metric is expressed as a function of overall pressure ratio (OPR) in order to normalize the effect of the choice of OPR in an engine architecture. This regulatory basis has the benefit of generally providing the incentive to reduce pollutants emitted for a given engine capability, without proscribing a specific method to control emissions. This provides to manufacturers the flexibility to comply with a standard [6].

Evaluation Conditions: Engine emissions are certified for a representative landing and takeoff (LTO) cycle, which relates pollutant emitted in the vicinity of airports, the region of interest for emissions affecting local air quality. This LTO cycle, depicted in Figure 2, contains assumptions for time spent in each of taxi, takeoff, approach, and idle conditions. The reference LTO cycle used for certification, while originally derived from traffic surveys from major metropolitan airports in peak traffic conditions, is an artificial model that may not relate to any actual operation. Instead, this representative cycle is intended to provide a constant frame of reference to measure differences in engine emissions performance [6]. The lack of horsepower extraction or other power requirements off an aircraft engine in the test conditions for NO_X implies that the NO_X certification reported values are a worst case scenario.

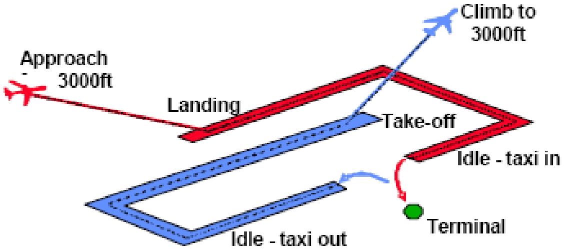


Figure 2: Representative LTO Cycle for Aircraft Engine Certification [6]

Noise Standards in Commercial Aviation

The introduction of the jet engine into commercial aviation in the 1960's, motivated measures to mitigate the impacts of significant aviation noise exposure. In the United States, the first regulations were enacted in 1969 and set limits on noise emission of new aircraft [7]. The noise emission limits regulated source noise production, measured in decibels in effective perceived noise level (EPNdB), at separate points, and specified specific conditions, configurations, and procedures required to show compliance. ICAO is responsible for the control of, technical issues associated with, and update of aircraft noise certification limits, and goes to great lengths to publish specific guidelines for test procedures, proper equipment, and processing of collected data. The framework established for noise certification is:

Metric: Of the many metrics available for measuring noise levels, the EPNdB metric was chosen for noise standards since it "provides the best known basis for objectively measuring the qualities of aircraft noise that are most offensive to persons on the ground." Because it accounts for tones and other factors specifically related to the human perception of noise, this metric was chosen as a technically superior way to measure the impact of noise exposure to people [7].

Correlation Parameter: Aircraft noise in EPNdB was chosen to be measured as a function of aircraft takeoff weight in the regulation. Even though the weight of an aircraft does not directly affect the annoyance of persons on the ground, the weight parameter was included in the regulation because it is "… directly related to the amount of power or thrust needed by the airplane, and this factor is directly related to the amount of noise reduction that can be required." The weight parameter not only represents a physical characteristic of the aircraft system as it relates to noise production, but also the magnitude of mitigation that can be accomplished for a particular system. Thus, the noise certification standard was constructed from its inception to incentivize and promote technology introduction to the maximum extent possible: "… the purpose of the weight parameter in Part 36 is to ensure that all reasonable noise abatement technology is applied for each weight [7]."

Evaluation Conditions: The procedure for aircraft noise certification consists of measurements at three locations intended to be representative of actual aircraft operations at an airport. Flyover, lateral, and approach locations are well-specified in the regulatory procedures as shown in Figure 3, and are the same for any aircraft. While this consistent procedure means these measurement locations may not perfectly correspond to any single aircraft operation, "… the prescribed measuring points in fact measure the capability of the aircraft to achieve maximum reasonable noise reductions at points representative of frequently occurring distances between the aircraft and the airport neighborhoods [7]." The noise certification was constructed as a whole to encourage noise reduction at conditions representative of real-world situations. However, even at these representative points the test conditions represent the worst case scenario in terms of noise exposure because aircraft are not in a "clean" configuration, but rather in a louder "dirty" configuration with landing gear, flaps, and other surfaces exposed.

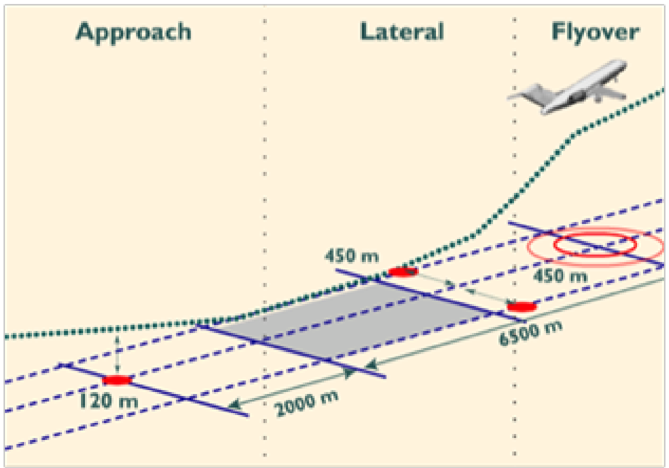


Figure 3: Aircraft Noise Certification Locations [8]

Sample of CO_2 Emission Standards in Non-air Transportation Sectors

In response to the growing concerns over the impact of anthropogenic emission on climate, several governments around the world have started to regulate CO_2 emissions using standards. These standards have been mostly for focusing on the automobile and shipping industries: The U.K. Department for Transport uses a metric measuring gCO_2/km to set targets for CO_2 emission reductions.

- In Australia, the National Average Carbon Emissions (NACE), measured in g CO_2/km, is used to track fleet performance. All new vehicles sold in Australia are required to report emissions in terms of grams of CO_2/km. The NACE is calculated using emissions data and new vehicle sales data (VFACTS). Simply, the NACE is the average grams of CO_2 emitted per kilometer of all new light vehicles sold in Australia. In 2007, the NACE was 226.1gCO_2/km and a 222 gCO_2/km target has been set for 2010.
- On January 1st 2008, the French government started using CO_2 emission standards, measured in g CO_2/km, in a fee-bate regulation scheme.
- Within the U.S., the Corporate Average Fuel Economy (CAFE) standard aims at regulating automobile fuel efficiency, which also measures emissions on terms of emission per unit distance traveled. The Corporate Average Fuel Economy (CAFE) standard aims at regulating automobile fuel efficiency in the United States. This certification requirement is based on a metric that fuel economy using miles per gallon (mpg). Through 2011, there was no correlating parameter in this certification requirement (i.e. solely based on fuel economy metric expressed in mpg). However, beginning in 2008 the vehicle footprint (i.e. the area defined as the product of the wheelbase and wheel track) was used as correlating parameter to comply with the recommendation of the National Academy of Sciences report evaluating the effectiveness of the CAFE standards, which found the CAFE program “might be improved significantly by converting it to a system in which fuel targets depend on vehicle attributes [9].” The evaluation conditions used in the CAFE standard is achieved with the use of a set of “test cycles”. Various parameters such as engine run-in time before testing, track conditions, maximum speed, repeatability of results, and weather conditions are all prescribed by the respective governing bodies. These conditions are meant to create consistent results along with mimic normal driving conditions the vehicle will typically operate at during its lifetime. Potential unintended consequences identified from the review of this certification requirement included; “cycle beating” where manufacturers potentially developing their cars and engines to perform better on the test cycle than they would in day-to-day operations [10], emergence of sport utility vehicle (SUV) class of vehicle as a result of a scope of applicability decisions.

These findings suggest that for the automobile industry, the metrics for CO_2 emissions are generally measured in gCO_2/km. This metric uses quantities of CO_2 emitted in the numerator and distance traveled in the denominator.

Summary of Lesson Learned

Several lessons can be taken from the literature search on existing standards, particularly relating to the components of standards:

- A metric, generally plotted on the y-axis of graphs, captures the key performance parameter intended to be influenced (e.g. EPNdB for noise, quantity of NO_X i.e. D_P for the NO_X standard). This key performance parameter can be normalized in the metric (e.g. inclusion of F_{00} for the NO_X standard). This key parameter can also be normalized through the use of a correlating parameter.
- A correlating parameter, generally captured on the x-axis of plots, based on fundamental physical attributes of the aircraft. For aircraft engine NO_X emissions, NO_X is measured with respect to OPR and sea level static thrust. For aircraft noise emissions, noise is measured with respect to takeoff gross weight (TOGW) for categories related to the number of engines. These attributes are highlighted in Figure 4.

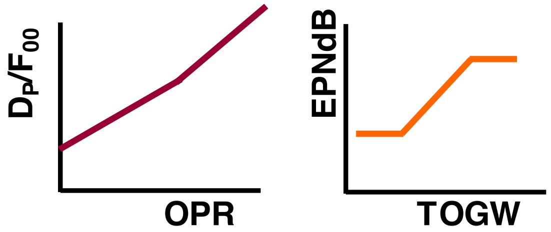


Figure 4: Existing civil aviation NO_X and noise regulations

- Evaluation conditions are measurements of vehicle performance and are reported to show compliance. These measurement conditions are intended to be representative of actual conditions, but may not precisely reflect any actual vehicle in day-to-day operations. An aircraft CO_2 metric used for aircraft certification thus should have a very specific set of conditions associated with it to test for compliance. In addition, the test conditions represent the "worst case" scenario of the environmental impacts which are typically not seen in real world operations.
- A regulatory level that sets the performance goals (y-axis) to be achieved for a product with a given capability (i.e. value of correlating parameter) (x-axis). This regulatory level function generally captures the physics based relationship between the metric and the CP. Subsequent regulatory levels are generally set by sliding down.

It was also found that existing standards have been intentionally constructed to encourage the introduction of technology to the maximum extent practicable. These standards have also been constructed to not incentivize the development and introduction of a specific type of technology that should be applied, but instead allow freedom in a design to comply with regulations, including freedom in not only technology introduction but also the capability of the aircraft.

Research Approach

Generate Candidate Metrics for an Aircraft Certification Requirement

Rationale for Generating Candidate Metrics

From first principles, it was determined that total fleet-wide CO_2 emissions from commercial aviation are a function of three key parameters (1) **fuel CO_2 content** (i.e. emissions generated by the use of one unit of energy of fuels or a blend of fuels), (2) **aircraft fuel energy intensity** (i.e. energy required to generate one unit of output of air transportation services, (3) **operational factors** (i.e. Airline business Constraints & Operational Inefficiencies)[ii]. These operational factors are composed of (a) a generic load factor measure, (b) inefficiency of air traffic control system and (c) inefficiency of airline. The product of these factors is summed over the total actual air transportation output.

[ii] Note: For purposes of Project 30 research, the decomposition above uses "fuel energy" due to the potential future introduction of alternative fuels for aviation that could exhibit varying fuel CO_2 content. However, under the assumption of a common reference fuel (e.g. ICAO Annex 6), CO_2 metrics could be expressed as:gCO_2 / AT Output, for reporting purposes.

$$CO_2Emissions = \sum_{AT\_Output_{As\_operated}} \underbrace{\left(\frac{CO_2Emissions}{Fuel\_Energy}\right)_{"As\_designed"}}_{\substack{\textbf{Fuel CO}_2\textbf{ Content} \\ \text{(measures fuel performance} \\ \text{in terms of CO}_2\text{ emitted per} \\ \text{unit fuel energy)}}} * \underbrace{\left(\frac{Fuel\_Energy}{AT\_Output}\right)_{"As\_designed"}}_{\substack{\textbf{Aircraft Fuel} \\ \textbf{Energy Intensity} \\ \text{(measures aircraft fuel burn} \\ \text{per unit of air transp. output)}}} * \underbrace{\left(\frac{AT\_Output_{"As\_designed"}}{AT\_Output_{"As\_operated"}}\right) * \left(\frac{1}{\eta_{ATC} * \eta_{airlines}}\right)}_{\substack{\textbf{Airline Business Constraints \&} \\ \textbf{Operational Inefficiencies} \\ \text{(i.e. load factor, ATC and airlines} \\ \text{efficiencies)}}}$$

Figure 5 shows the schematic representation of aircraft and system input and output. This project aims at identifying ways by which these parameters can be characterized and measured in order to isolate a metric or a set of metrics to accurately reflect aircraft level CO_2 emissions.

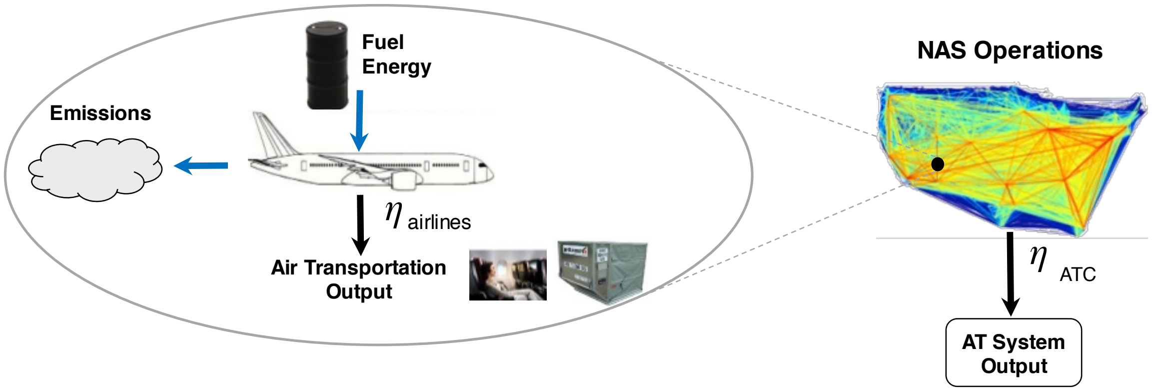


Figure 5 representation of aircraft and system input and output

To ensure accurate measurement of aircraft fuel efficiency performance and limit unintended consequences, fuel performance and aircraft certified fuel intensity performance should be decoupled. This was motivated by the potential future introduction of alternative fuels. Since the selection of a drop-in fuel is an operator (i.e. airline) decision, this fuel CO_2 content needed to be decoupled from the aircraft certification performance, which is controlled by aircraft manufacturers. The objective of identifying aircraft certification metrics therefore focuses on aircraft fuel energy intensity. There are two critical aspects to consider in the definition of fuel intensity: an appropriate measurement of fuel consumption (i.e. numerator), and the definition of productivity (i.e. denominator).

Fuel Consumption Measure

There are two types of measurement of aircraft performance and fuel consumption, which can be used in the definition of candidate metrics:

- Full mission performance; the performance of the aircraft is measured for the entire mission (i.e. block to block); from the time the aircraft starts to move from the departure airport gate to arrival at the destination gate.
- Instantaneous performance; the aircraft performance can be measured at one point in time. For this research, performance at a steady-level cruise condition was the only type of instantaneous performance considered.

Air Transportation Productivity

The second major consideration in the definition of candidate fuel intensity metrics is how to define productivity or "Air Transportation Output". Air transportation output can be constructed using one or a combination of the following high-level parameters: "measure of distance traveled", "measure (or proxy) of what can be transported", or "measure of speed (or time)".

Through brainstorming sessions, a literature review of work on fuel efficiency in commercial aviation and interviews with stakeholders and aviation stakeholders, a number of measures of these parameters were identified:

- "Measure of distance traveled"
  - Range (i.e. distance)
- "Measure (or proxy) of what can be transported"
  - Payload = Maximum Zero Fuel Weight – Operating Empty Weight = MZFW – OEW[iii] (see Appendix for definitions and aircraft weight breakdown)
  - Useful load = Maximum Takeoff Weight - Operating Empty Weight = MTOW – OEW[iv]
  - Maximum Takeoff Weight (MTOW)
  - Floor Area
  - Number of Available Seats
- "Measure of speed" (or time)
  - Speed: Maximum Range Cruise (MRC), Long Range Cruise (LRC), other appropriate measurement of speed.
  - Time (e.g. Block time, Air time)

Candidate metrics were constructed with fuel in the numerator and were normalized by a measure of productivity in the denominator. Taking a systematic approach to their generation, metrics with one, two and three productivity parameters were evaluated. A summary of the portfolio of metrics that were considered in this research are shown in

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[iii] Note: Alternatively, Payload can be defined using Manufacturer Empty Weight (MEW) i.e. MZFW – MEW, in order to limit the inclusion of operational equipment.

[iv] Note: Alternatively, Useful Load could be measured as MTOW – MEW where MEW is the Manufacturer's Empty Weight

Table 1.

Table 1: Summary of candidate metrics

	Full Mission Metrics				
Single parameter metric	Block Fuel ----------------- Range				
Two parameter metric	Block Fuel ----------------- **Payload** * Range	Block Fuel ----------------- **Useful Load** * R	Block Fuel ----------------- **MTOW** * Range	Block Fuel ----------------- **Floor Area** * R	Block Fuel ----------------- **Av. Seats** * R
Three parameter metric	Block Fuel ----------------- **Payload** * R.*Speed	Block Fuel ----------------- **Useful Load** * R.*Speed	Block Fuel ----------------- **MTOW** * R. *Speed	Block Fuel ----------------- **Floor Area***R.*Speed	Block Fuel ----------------- **Av. Seats** * R. *Speed
	Block Fuel ----------------- **Payload** * R./Time	Block Fuel ----------------- **Useful Load***R./Time	Block Fuel ----------------- **MTOW** * R./Time	Block Fuel ----------------- **Floor Area***R./Time	Block Fuel ----------------- **Av. Seats** * R./Time
	Instantaneous Performance Metrics				
Single parameter metric	1 ----------------- **Specific Air Range** = 1 ----- **SAR**				
Two parameter metric	1 ----------------- SAR * **Payload**	1 ----------------- SAR * **Useful Load**	1 ----------------- SAR * **MTOW**	1 ----------------- SAR * **Floor Area**	1 ----------------- SAR * **Av. Seats**
Three parameter metric	1 ----------------- SAR * **Payload** * Speed	1 ----------------- SAR * **Useful Load** * Speed	1 ----------------- SAR * **MTOW** *Speed	1 ----------------- SAR * **Floor Area*** Speed	1 ----------------- SAR * **Av. Seats** * Speed

Note: R = Range

Desired Attributes of Metrics

In order to evaluate the candidate metrics presented in Table 1, a set of quantitative and qualitative criteria were defined. Ideally, the metrics and frameworks should:

- ***Decouple effects of fuel performance from aircraft performance*** - From first principles, CO_2 emitted by an aircraft is a function of (1) fuel CO_2 content, and (2) aircraft energy intensity. Because of the use of a single type of fuel for commercial aviation (i.e. Jet A), the fuel CO_2 content has historically been constant over time. However, the potential future introduction of alternative fuels and blends of fuels is likely to change the value of this fuel CO_2 content factor.
- ***Include a measure of transport capability*** - a CO_2 framework should include a measure or proxy of what is transported and distance traveled
- ***Exhibit independence of purpose or utilization*** - A metric and CP system should not discriminate between the performance of aircraft intended for different purposes in use
- ***Account for fundamental airplane design elements and capabilities*** - A metric and CP system should capture fundamental elements of aircraft performance to appropriately reflect fuel efficiency

- ***Not require inappropriate amount of resources to implement*** - The parameters in the metric, CP, and evaluation condition should limit the burden on the authorities if considered appropriate to implement as part of a certification requirement
- ***Explainable to the general public*** - The parameters in the framework should be simple and easily understood by the layman
- ***Be easily measurable*** - The metric(s) should be based upon certified parameters to ensure commonality between different manufacturers. The parameters that compose the metric should be easily measurable at the certification stage, or derived from engineering data, and should consider the industry certification requirement practices of measurement and adjustment,
- ***Differentiate generations of CO_2 reduction technologies*** - a CO_2 framework should clearly distinguish between inherent aircraft technology levels, so as to best encourage the introduction of fuel efficient technologies in the future
- ***Accurately reflect CO_2 emissions and fuel burn at aircraft level*** - Improvements observed via the CO_2 certification requirement should correlate with reduction of CO_2 emissions at the aircraft level as demonstrated by procedures which are relevant to day-to-day operations
- ***Be fair (equitable) across set of stakeholders*** - To the extent practicable, the metric should be fair across the set of stakeholders covered by the CO_2 certification requirement, including the distribution of cost and benefits, when initially applied and with respect to the future,
- ***Limit unintended consequences*** - The use of poorly defined metrics can create equity issues and can result in the emergence of opportunities to influence the system in a way that may reduce their effectiveness and have the potential to drive the system to a different operating point than the one originally intended
- ***Contribute positively to system level environmental benefits*** - The metric (when adopted as part of a certification requirement) should contribute to achieving reductions in CO_2 emissions both at the vehicle-level and at a system-wide aggregate level[v].

Quantitative and Qualitative Evaluation Criteria

Using high level metric attributes defined in the previous section, qualitative and quantitative criteria were defined. The criteria along with the evaluation processes that were used to evaluate and judge the different metrics are summarized in

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[v] While an important consideration, system-wide assessment of effectiveness was not addressed to date in this research. Instead, an approach for evaluating aggregate environmental benefit is suggested in a later section.

Table 2.

Table 2: Summary of CO_2 Framework qualitative and quantitative criteria

Metric Attributes	Criteria (type)	Evaluation measurements	Evaluation Process
Decouple effects of fuel performance from aircraft performance	Definition / formulation	Yes / No	- Definition of the metric and certification process (e.g. cert. constraints such as fuel CO_2 content)
Include a measure of transport capability	Definition / formulation	Yes / Proxy / No	- Assess parameters for inclusion of distance traveled and what is transported
Exhibit independence of purpose or utilization	Differentiation of performance	Relative ability to differentiate aircraft purpose	- Assess degree of differentiation of similar products intended for different purposes, e.g. passenger vs. freighter
Account for fundamental airplane design elements and capabilities	Reflect basic aircraft performance measures	Yes / No	- Assess whether metrics account for typical measures of aircraft design performance
Not require an inappropriate level of resources from aviation authorities to implement	Degree of difficulty, level of resources	Appropriate / Inappropriate	- Estimate difficulty and level of resources required to implement certification procedure for parameters in metric, CP, and evaluation condition
Explainable to the general public	Ease of understanding	Ability of general public to understand	- Assess simplicity of metrics, or degree of similarity to accepted efficiency measurements
Be easily measurable	Measurability (Assessment of measurability of individual parameters composing a metric)	- Already certified parameter - Barriers to measuring non-certified parameters	- Decomposition of metrics into measurable parameters - Review of literature on aircraft certification - Interview with stakeholders
Differentiate generations of CO_2 reduction technologies	Differentiation of distinct technology levels	Relative ability to differentiate technological improvement from other factors	- Investigate differentiation of EDS generated aircraft designs with technology infusion - Investigate separation of technology generations of existing aircraft
Accurately reflect CO_2 emissions and fuel burn at aircraft level (i.e. relevance to day-to-day operations)	- Robustness to configuration changes - Robustness of metric measurement to operational deviation	Yes/No % deviation across type of aircraft (given current operating patterns)	- Decompose metric into measurable parameters - Analyses current fleet - Conduct interview with stakeholders
Be fair (equitable) across set of stakeholders	Fairness across aircraft categories,	"Performance spread" across aircraft categories	- Fairness evaluated using certification requirement deviation from trend line of generational grouping of aircraft
Limit unintended consequences	Potential outcomes (i.e. system behaviors)	Potential impact of identified outcomes (evaluated through the effectiveness for set of scenarios)	- Interview with stakeholders - Infer potential behaviors from analyses of current and future aircraft and fleet characteristics
Contribute positively to system level environmental benefits	Aircraft level analysis: Co-linearity with design objectives	Directions of vectors of performance improvements	- Analysis of optimization gradients with and without certification requirements (i.e. for each metric)

* Note: Fairness is dependent on productivity definition and policy maker value judgment. For the purpose of this analysis potential for fairness issues is evaluated through "performance spread" across sets of stakeholders.

Also listed are the types of evaluation measurements that will be used to assess whether a framework meets a criteria. As listed in

Table 2, some of these evaluation measurements are binary (e.g. Yes/No); while other are expected to be measured on a continuous scale and could be used to rank metrics along the evaluation dimension.

Evaluation of Current Fleet Performance

The performance of the current fleet with respect to the metrics listed in

Table 1 was then analyzed. Investigating in- and out-of-production aircraft provided benefits in several areas. First, a good understanding of fuel efficiency variations between aircraft of disparate size and capability was gained. Second, investigating existing aircraft highlighted fuel efficiency trends consistent across aircraft age and size that could be related to potential future aircraft. Finally, exploring the change of fuel efficiency over time from older technology aircraft to modern aircraft provided insight into how various metric-CP-evaluation conditions frameworks were capturing technology improvements.

Data sources and Modeling Tools Used

Several analysis tools and data sources were used in the evaluation of current fleet performance. These tools ranged from publically available published performance data, to commercially available aircraft design and analysis software, to aircraft design and analysis tools developed by research organizations, and included:

- Publically available performance data, as found on manufacturer websites and in airport planning documents
- Piano-X [11] and Piano 5 [12] aircraft design and performance analysis software. This software was used to great extent to investigate different portions of the research and was especially useful for their extensive library of aircraft performance models.
- The Environmental Design Space (EDS), a PARTNER sponsored conceptual aircraft design tool [13]. EDS representations of in-production vehicles were used to complement investigation of metric performance across the operating envelope, and to investigate potential future aircraft design implications.

Scope of Aircraft Types Considered in Fleet Analysis

One early objective of this research was to identify the performance of a wide variety of aircraft with respect to the candidate frameworks. To this end, a wide spectrum of aircraft were included in the analyses. Third party performance models for over 200 individual aircraft were utilized [11], [12]. Broad classification schemes were also used to place the aircraft models into general categories, based on general type and capability. Grouping aircraft into equivalent bins facilitated observation of how metrics treated different classes of aircraft. Several different categorizations were used in this research, two of which are depicted in

Table 3 along with their abbreviations. Using different groupings of aircraft types into categories was found to be insightful to compare and contrast trends and observations from various investigations. The inclusion of a large number and variety of aircraft types in the ensuing analyses, however, was invaluable for discerning meaningful trends of metric behavior.

Table 3: Aircraft Categories Utilized [images from www.airliners.net]

Categorization 1	**Turboprop (TP)**	**Business Jet (BJ)**	**Regional Jet (RJ)**	**Narrow Body (NB)**		**Widebody (WB)**	
							
Categorization 2	**Turboprop (TP)**	**Business Jet (BJ)**	**Regional Jet (RJ)**	**Single Aisle (SA)**	**Small Twin Aisle (STA)**	**Large Twin Aisle (LTA)**	**Large Quad (LQ)**

Evaluation of the existing aircraft performance, with respect to the portfolio of candidate metrics, consisted of calculating fuel consumption for the appropriate condition, and combining this with other aircraft performance terms to produce the defined metrics. This analysis proceeded on two tracks, differing by the type of metric considered: evaluation of mission fuel metrics and evaluation of instantaneous metrics. The evaluation of full mission metrics required the calculation of mission fuel for each aircraft type for any mission considered. The estimation of full mission fuel consumption was greatly facilitated by the performance tools available. In fact, fuel consumption and metric performance could easily be estimated for a single aircraft across a variety of missions. An example of metric performance across an aircraft's payload-range envelope is shown in Figure 6. Here, the metric score is color-coded, with blue areas reflecting better (more fuel-efficient) performance and red areas reflecting poorer performance. It was observed that the fuel efficiency, as measured by two example metrics, varies not only with the mission, but also with the selected metric. In this way, performance of a single aircraft was established for the portfolio of candidate metrics.

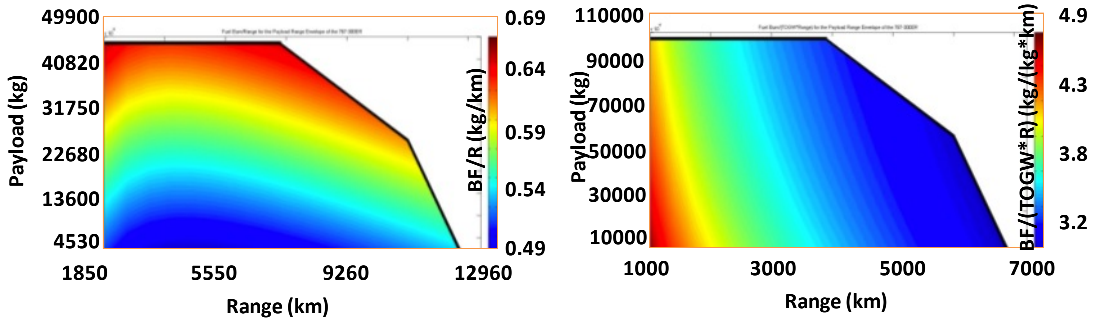


Figure 6: Comparison of Metric Performance across Payload-Range Envelope for EDS Small Twin Aisle Aircraft [Left: Fuel / (Range), Right: Fuel / (TOGW * Range)]

Given that potentially large variations in metric performance were observed over a vehicle's payload-range envelope, comparing metric performance across aircraft was more challenging. For an effective comparison of fuel efficiency performance across aircraft types, a similar mission had to be used across aircraft. This was difficult due to the wide disparity in capability of aircraft in the existing fleet. However, there were a few similar conditions identified that could be used for an initial investigation. These conditions were identified as having similar constraints on a typical aircraft payload-range diagram, which describes the maximum payload and range capability of an aircraft. A notional payload-range diagram is shown in Figure 7. While the payload-range diagram is different for each aircraft, the points labeled R_1 and R_2 are similar because of constraints placed on them;

- R_1 is the range at the intersection of maximum structural payload and maximum takeoff weight,
- R_2 is the range at the intersection of maximum takeoff weight and maximum fuel capacity.

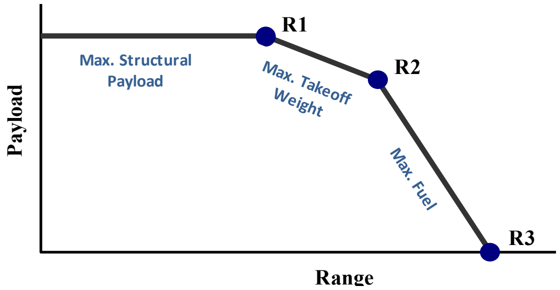


Figure 7: Notional Payload Range Envelope

The identification of similar mission conditions across aircraft, combined with the performance characterization of a large number of aircraft, enabled the evaluation of a fleet of aircraft with respect to candidate fuel efficiency metrics. An example of a comparison of 217 aircraft types from Piano-X is shown in Figure 8. Here, performance is shown with respect to a payload-based mission fuel metric, at the R_1 measurement condition. This type of evaluation greatly facilitated the observation of metric behavior and trends, as well as the performance of different aircraft categories.

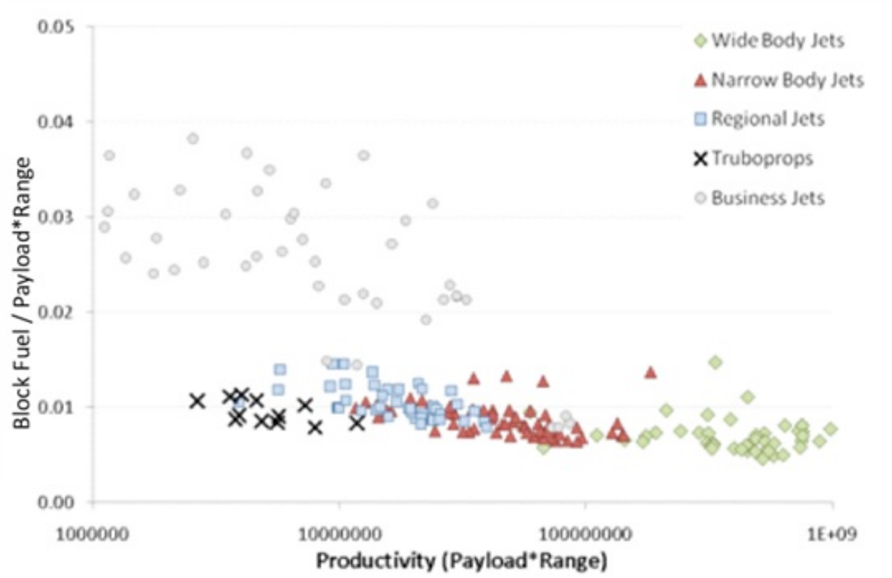


Figure 8: Aircraft Fuel Intensity Measured using Payload based metric at Max. Structural Payload – R_1 for 217 aircraft types [11]

Many other assumptions had to be made for any evaluation of mission fuel based metrics (including but not limited to taxi time, climb profile, cruise speed and altitude, and fuel reserve allowances), and it was found in later investigations that the measurement conditions were an extremely important consideration, and sometimes had a significant impact on the results. Metric evaluation conditions are discussed in much more detail in later sections.

The evaluation of full mission metrics was accomplished by measuring block fuel, or the fuel consumed between departure from a gate at the origin airport and arrival at a gate at the destination airport. In this report, block fuel is referred to by the abbreviation BF. Metrics are also often referred to by abbreviations; for example, Block Fuel / (Payload * Range) is noted as BF/(P*R). Since a metric value is always associated with an evaluation condition, sometimes in this paper the evaluation condition is appended to the metric name for clarity. For instance the BF/(P*R) metric, when evaluated at the R_1 condition, would be named BF/(P*R)_R1.

The evaluation of instantaneous metrics proceeded in a similar fashion, but was simpler overall due to the simple nature of instantaneous metrics. Since instantaneous metrics are not directly linked to any particular mission, a specific mission did not have to be chosen for a comparison point. All that was required for evaluation of the existing fleet was performance at a specific aircraft gross weight, altitude, speed and standard atmospheric conditions (e.g. temperature, pressure). Once appropriate conditions were specified, performance of a fleet of aircraft was also characterized for instantaneous metrics.

Concurrent Assessment of Metric, Correlating Parameter, and Evaluation Conditions

The successful characterization of the performance of the existing aircraft fleet, with respect to the established portfolio of candidate metrics, enabled the evaluation of the metrics against the evaluation criteria. The proper assessment of the metrics against all evaluation criteria was greatly facilitated by the simultaneous consideration of a metric and correlation parameter. Similarly, evaluation conditions have a significant impact on the assessment of the metrics against the evaluation criteria.

Importance of correlating parameters

One important observation in this research was that the successful evaluation of aircraft fuel efficiency metrics was very challenging when considering a metric in isolation. Ideally, fuel efficiency metrics could be used in isolation to effectively compare the efficiency of all aircraft in the fleet. In practice, however, this is extremely challenging, due to the disparity in aircraft capability in the existing fleet. An example of the behavior of the fleet against two example metrics is shown in Figure 9. Here, aircraft are separated into categories, in-production aircraft are shown in blue, and out-of-production aircraft are shown in red. Freighter (F) aircraft are shown as diamonds, Business Jets as triangles, Turboprops as open circles, and all other passenger aircraft as filled circles.

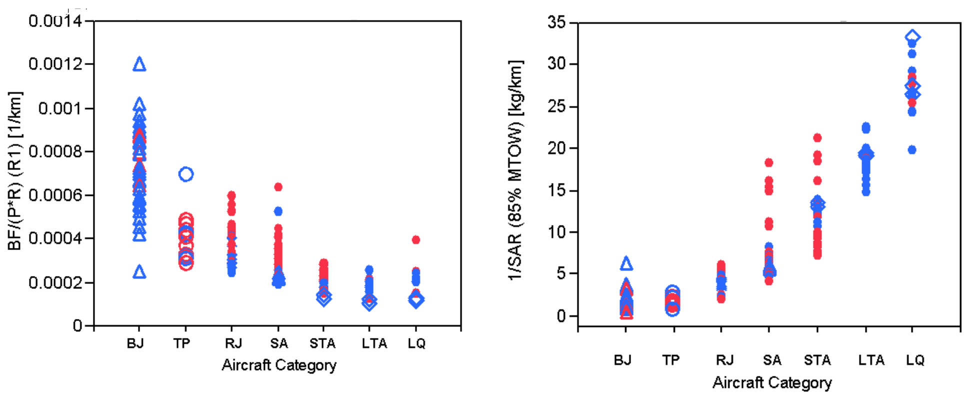


Figure 9: / (P*R) and 1/SAR Performance across Multiple Aircraft Categories [12]

For both example metrics in Figure 9 it can be observed that metric performance varies widely between aircraft categories as well as within each category. This disparity may be due to several factors, including but not limited to aircraft introduction year (roughly representative of inherent technology level), purpose, or capability (payload capacity, passenger complement, range, fuel volume, etc.). More concerning than performance variation, however, is the lack of identifiable trends relating to any of these driving factors, some of which provide the basis for evaluation criteria established for metric assessment. The lack of an identifiable trend suggests that the assessment of either metric in isolation may be inconclusive at best. The observations for the metrics shown in Figure 9 were consistent across all metrics. These observations suggest evaluation of metrics in isolation may be extremely challenging, and potentially ineffective.

One way to overcome this challenge is to adopt a correlation parameter along with a metric when assessing aircraft fuel efficiency. A correlation parameter (CP) is, in essence, an additional dimension used in combination with a metric to define a basic relationship between capability-related attributes and the impact of interest. Examples of the use of correlation parameters in existing certification requirements were discussed previously, specifically takeoff weight is the CP for aircraft noise standards, and overall pressure ratio is the CP for engine emissions standards. Each CP is the x-axis and is combined with a metric on the y-axis. A CP for aircraft fuel efficiency would likely be an attribute that would serve to differentiate aircraft products based on capability.

The use of a CP in conjunction with a metric can greatly aid the evaluation of fuel efficiency metrics with respect to established criteria. As outlined in earlier sections, many candidate metrics were constructed to normalize fuel consumption by a measure of aircraft size or capability. The intent of this normalization was that effects related to aircraft size would be minimized, and an equitable basis for fuel efficiency comparison could be established. However, as discussed above, even when several attributes relating to size or capability are included in the metric, there still persists a trend across aircraft categories, evidenced in Figure 9. By adopting a correlation parameter, aircraft attributes related to size or capability can be included in another dimension, and not necessarily explicitly in the metric. The resulting trend identified by the combination of a metric and CP can be used to compare fuel efficiency across the aircraft fleet.

However, the choice of the best parameters in the metric and CP, as well as their arrangement, can significantly impact the assessment of the portfolio of metrics against established evaluation criteria. As an example, consider the criterion that recognizes that a metric should effectively differentiate generations of CO_2 reduction technologies. Aircraft production status is a rough surrogate for inherent aircraft technology level, and the separation of in-production and out-of-production groups can be observed easily using performance data. As an illustration, Figure 10 shows two plots comparing the BF/R metric against 2 CPs for the SA aircraft class and consists of the same performance data, but highlight two different CPs reflecting aircraft load; maximum useful load (MUL) and MTOW. Out-of-production aircraft are shown in red and in-production are shown in blue. The metric is measured at maximum range at 60% maximum structural payload, referenced here as P60.

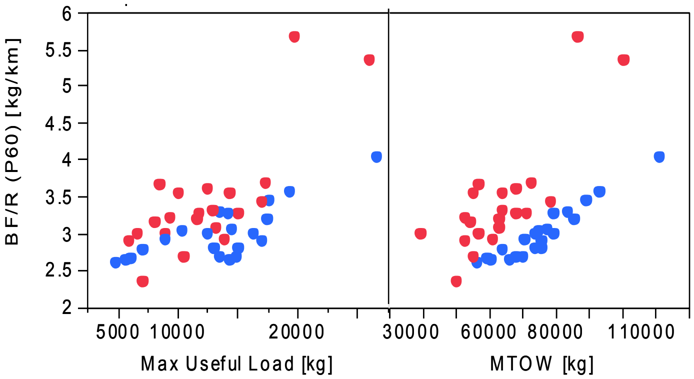


Figure 10: BF/R Performance with two CPs for the Single Aisle (SA) Aircraft Category [12]

Although the two plots in Figure 10 show the same aircraft and utilize the same performance data, the two metric-CP pairs show substantially different abilities to satisfy the technology differentiation criterion. On the left, BF/R paired with the maximum useful load CP does not show satisfactory ability to differentiate in and out-of-production aircraft; several in-production aircraft show very similar performance as some out-of-production aircraft, and vice versa. Thus the metric-CP pair on the left does not satisfy technology differentiation criterion. On the right, however, the metric-CP pair shows a very clear distinction between production status, separating the two groups very well. Because production status is not a perfect indicator of inherent technology level, there are some exceptions which are explored later, but the example clearly illustrates the conclusion. The difference in ability of one metric paired with two CPs to satisfy an example evaluation criterion highlights the importance of the selection of a CP when assessing metrics against evaluation criteria. Therefore, metric assessment in this research also concurrently considered a CP when evaluating against criteria.

Importance of Evaluation Conditions (EC)

Another critical observation from this research was that the metric evaluation condition is also a key driver to the behavior of the metric-CP pair. Specifically, the metric performance against some evaluation criteria significantly differed with the selection evaluation conditions. An illustration of this is given in Figure 11, which shows the BF/R metric against MTOW for two different evaluation conditions, R_1 and P60. These are the same aircraft that was discussed above, with the same production status categories.

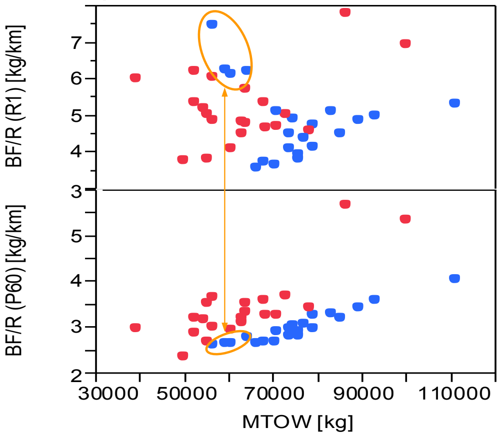


Figure 11: BF/R vs. MTOW Performance with two Evaluation Conditions for the SA Aircraft Category [12]

Using the example of technology differentiation criterion, approximated by production status, Figure 11 illustrates that the same metric-CP combination has different abilities to meet this criterion due for different evaluation points. For the top plot, the R_1 condition shows more variability with respect to differentiating production status, while the P60 condition on the bottom shows very clear distinction. In fact, the R_1 condition seems to penalize the metric especially a few aircraft types, highlighted in the gold circle. Upon further investigation, it was found that these four aircraft were discriminated for the R_1 condition due to their extremely short R_1 range. Because of the significant influence of an evaluation condition on assessment of metrics against evaluation criteria, this research emphasizes simultaneous consideration of metrics, correlations parameters, and evaluation conditions in order to conduct a proper assessment of metrics against evaluation criteria.

Assessment of Possible Impacts of Metrics on Future Vehicle Development

The choice of an aircraft fuel efficiency metric may have consequences on vehicle development in the long-term. These consequences stem from how parameters in the metric might relate to the design philosophies of different aircraft manufacturers and their products, and what design decisions might be made in the future in order to improve a product's fuel efficiency based on the elements of a particular metric. It was anticipated that improving fuel efficiency would be viewed by a manufacturer as an additional competing design constraint, which would have to be met to achieve a feasible product. The specific aircraft fuel efficiency metric selected could therefore significantly influence future product design if the additional constraint incentivized trends very different from traditional objectives. Thus, proposed metrics were analyzed for their relation to traditional design objectives, to see how future trends might shift as a result of the adoption of particular aircraft fuel efficiency metric.

A three-fold approach was taken to understanding the relationship between traditional objectives and trends incentivized by specific metrics. These three approaches are shown in Figure 12. All three approaches utilized EDS to investigate the design space surrounding a reference aircraft, which estimated the performance of aircraft resulting from slight changes in design.

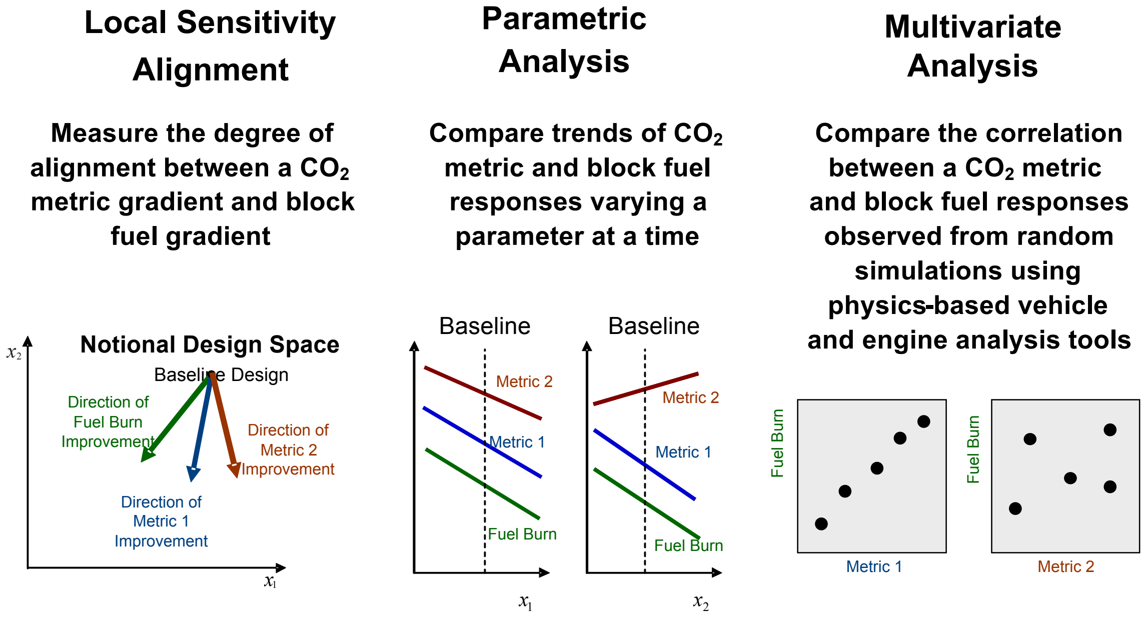


Figure 12: Overview of Vehicle Design Impacts Evaluation Methods

- The first method, the Local Sensitivity Assessment, measured the degree of alignment between block fuel and a particular metric, with respect to very small changes in input design parameters near the baseline design.
- The second method, a Parametric Analysis, similarly compared trends of block fuel and metric improvement, but for larger variations in input design parameters, varied one at a time.
- The third method, the Multivariate Analysis, compared the correlation between block fuel and metric responses, using input design parameters selected randomly.

In all cases, a high degree of alignment suggested that design trends incentivized by the metrics were similar to traditional objectives. By using three different but related approaches, it was expected that the best possible comprehensive view of potential implications of metric selection on future vehicle design could be obtained.

Investigation of Potential Unintended Consequences

As highlighted in the section on the review of existing certification requirements for aviation and non-aviation sectors, the implementation of a standard has the potential to generate unintended consequences. One illustration was the emergence, in the automobile industry, of the SUV class of vehicle that was not covered by the CAFE standards. In order to limit potential unintended consequences to an aviation CO_2 certification requirement, an attempt to foresee possible potential consequences resulting from the implementation of a certification and examined concurrently with the metric-CP analysis. For the purpose of this project, the potential unintended consequences resulting from the implementation of a CO_2 certification requirement were identified through a set of methods:

- Analyses of potential impacts of the metrics (and associated certification requirements) on future aircraft designs using tools such as EDS, Piano-5 and other sources of aircraft performance data
- Analyses of potential impacts of the metrics and scope of applicability on the future evolution of the fleet

- Interview with aerospace and airline industry stakeholders

Assessment of Candidate Metric Portfolio

This section presents results of the evaluation of aircraft fuel efficiency metrics. Presentation of results is structured around the list of metric attributes presented in

Table 2. For the purpose of this evaluation a number of analyses were conducted:

- Evaluation of the aircraft certified performance of the current fleet using the Piano-X, Piano-5 and EDS aircraft performance models and databases.
- Analysis of operational databases (i.e. ICAO 2006 Common Operations Database and U.S. Bureau of Transportation Statistics (BTS) databases)
- Evaluation of correlation parameters using EDS, Piano-X and Piano-5 aircraft databases
- Review of FAA Certification procedures
- Interviews with stakeholders.

Decoupling Fuel Performance from Aircraft Performance

In order to accurately reflect fuel efficiency at the aircraft level and limit unintended consequences, the metric should decouple the effects of fuel performance from aircraft performance. This was motivated by the potential future introduction of alternative fuels with varying life cycle fuel CO_2 content (see Figure 13). The cumulative GHG emissions are given by the summation of the positive and negative contribution for a subset of potential future alternative jet fuel options [14].

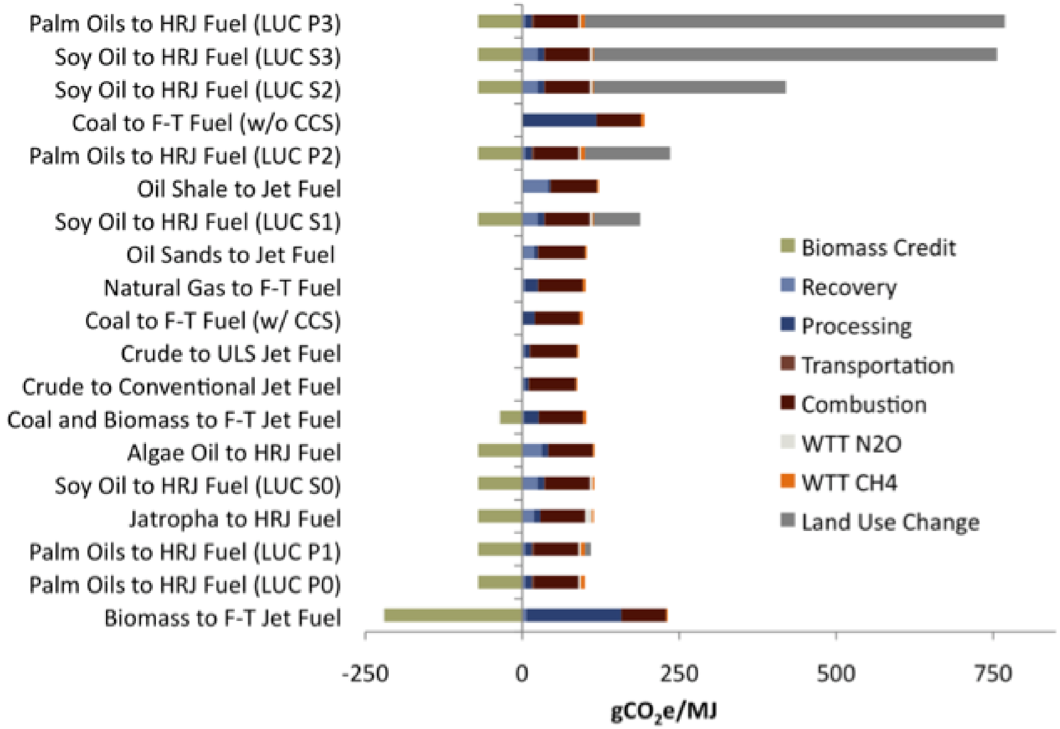


Figure 13: Comparison of the fuel CO_2 content (i.e. life cycle GHG emissions) from a wide range of alternative fuel pathways.

The selection of a drop-in fuel is an operator's decision, as a result this fuel CO_2 content must be decoupled from the aircraft certification performance which is controlled by aircraft manufacturers. For the purpose of this project, it was agreed upon that the metric would be an "Aircraft CO_2 Intensity metric" based on "Aircraft Fuel Intensity" metric. Aircraft fuel intensity is used to certify aircraft fuel intensity performance using a reference fuel. The aircraft CO_2 intensity –computed as the product of the aircraft fuel intensity and fuel CO_2 content of a reference fuel- is expected to be reported for industry communications purposes, as depicted in Figure 14.

$$\underbrace{\frac{gCO_2}{AT\ Output}}_{\substack{\textbf{Aircraft } \mathbf{CO_2} \textbf{ Intensity} \\ \text{(measure reported for industry} \\ \text{communications purposes)}}} = \underbrace{\frac{gCO_2}{kg\ fuel}_{reference\ fuel}}_{\substack{\textbf{Fuel } \mathbf{CO_2} \textbf{ Content of} \\ \textbf{Reference Fuel} \\ \text{(constant fuel } CO_2 \text{ content of a} \\ \text{reference fuel used for certification)}}} * \underbrace{\frac{kg\ fuel\ burnt}{AT\ Output}}_{\substack{\textbf{Aircraft Fuel Intensity} \\ \text{(measured during aircraft} \\ \text{certification process)}}}$$

Figure 14: Relation between aircraft CO_2 intensity, fuel CO_2 content and aircraft fuel intensity.

All metrics satisfactorily decouple fuel performance from aircraft performance.

Measure of Transport Capability

Single Parameter Metrics

Full Mission Performance

Based on the literature review of standards on fuel efficiency and CO_2 emissions, it is believed that a metric applied to transportation has to include, at least, a measurement of distance. Single parameter metrics including only a measure of distance are used in the automobile industry (e.g. fuel economy standards in the United States use mile per gallon, CO_2 emission standards in Europe use gCO_2 per km) because the "measure of what can be transported" does not significantly vary and most cars have approximately the same speed capabilities. Most cars have a 5-seat capacity and speed limit is often bounded by operational speed limits.

If measured using a single parameter metric, the fuel intensity of aircraft used in commercial aviation varies significantly due to the large variations of vehicle sizes (i.e. from a few seats to 800+ seats or MTOW from a few thousands kg to over 500 tons). Figure 15 shows Range / Block Fuel similar to mileage per gallon (mpg) for aircraft types ranging from small business jets (i.e. very light jets) to the largest wide body jets (i.e. Airbus A380) as a function of MTOW (used here as a proxy for aircraft size). As it can be seen, the fuel efficiency varies by a factor of approximately 30 due primarily to vehicle size differences. The normalization of the metric by the measure of what can be transported (or a proxy such as MTOW) can either be performed through the denominator of the metric (i.e. two-parameter metric) or through the correlating parameter (i.e. x-axis as shown in Figure 15).

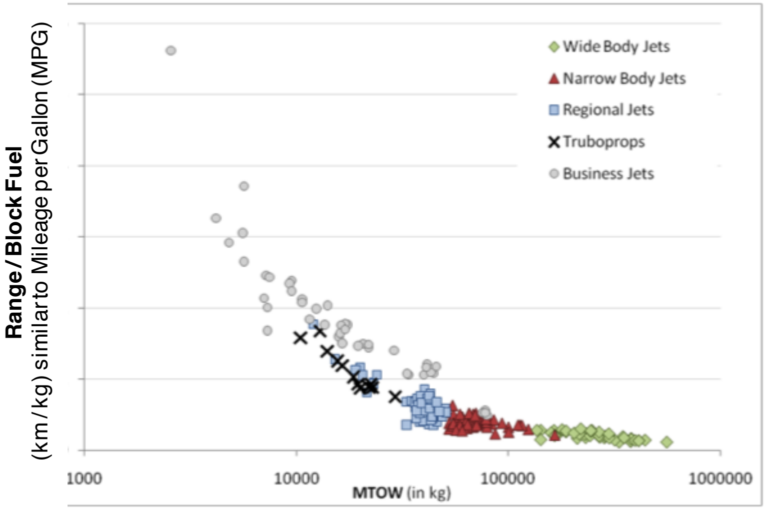


Figure 15: Range / Block Fuel (similar to Mileage per Gallon MPG) as a function of aircraft size (i.e. used MTOW as a proxy for aircraft size) [11]

Instantaneous Performance (Metrics Based on Point Evaluation)

While full mission metrics and evaluation conditions capture the full fuel burn over all phases of a flight, point performance metrics depend only on instantaneous conditions at the measurement point. While point parameters do not explicitly reflect the fuel consumed during an entire flight, their inherent simplicity make them attractive for this research. The instantaneous performance measure most widely used in the aviation industry is Specific Air Range (SAR). SAR describes the distance an aircraft will travel on the next incremental amount of fuel burned. A formulaic description of specific range as defined by:

$$SAR = \frac{dR}{dW_{FUEL}} = \left(\frac{V}{TSFC}\frac{L}{D}\right)\frac{1}{W_{GROSS}}$$

SAR exhibits several advantages. First, it is widely used as a figure of merit for aircraft fuel efficiency. This existing general acceptance implies its use as an aircraft CO_2 emission metric was promising. Another advantage of SAR is its lack of dependence to a specific mission. SAR measurements only require the speed, altitude, weight, and atmospheric conditions unlike full mission metrics that require many more assumptions.

In addition, SAR encapsulates fundamental parameters that directly influence airplane fuel efficiency including: propulsion system efficiency, aerodynamic efficiency, and airplane weight. For a steady state level flight condition, it is assumed that lift (L) equals weight (W) and drag (D) equals thrust (T). The first term (V/TSFC) is equivalent to (T*V)/(Fuel Flow*Heating Value) for a given fuel type, which denotes the ratio of the time rate of work done to the time rate of chemical energy input, also known as the overall efficiency of a propulsion system. The second term (L/D) is the lift-to-drag ratio, a well-known parameter that represents aerodynamic efficiency of an airplane. The last term is airplane weight at the evaluation condition, which includes airframe weight. Therefore, SAR is able to capture the progression of CO_2 reduction technologies encompassing the areas of aerodynamics, propulsion system, and airframe weight reduction.

Because such a point performance metric does not explicitly require any assumptions about a flight profile, mission definition, or even composition of aircraft weight, it may be significantly easier to measure and form the basis for a certification requirement. However, the simplistic nature of a point performance metric does have its disadvantages. Such a metric measured at one condition does not explicitly capture fuel efficiency at any other condition, thus it is necessary to establish a correlation between performance at an instantaneous point and overall mission performance. To address these disadvantages, evaluation conditions and future potential certification procedures could include several instantaneous performance points combined into a proxy for a full mission measure.

Two-parameter Metrics

In order to evaluate the inclusion of a "measure of what can be transported" in the denominator of the metric, a set of two parameter metrics was generated. A total of five metrics based on payload, useful load, maximum take-off weight, floor area and number of available seats were retained. The two-parameter metrics all include a measure of transport capability and productivity. The preliminary assessment how close the productivity measurement is from "true" productivity based on the ICAO Commercial Aircraft System Fuel Efficiency (CASFE) metric which was designed to capture the fuel efficiency and productivity of the air transportation system is listed in Table 4. For the purpose of this analysis and assessment, it was decided that total payload capability (measured by weight) was the closest measurement of "what can be transported". The available seat measure is a proxy for passenger transport. The three remaining measures of productivity are proxies for the payload capability.

Table 4: Summary of Assessment of Productivity Measures

Type of Metric	Metric	Measure of Productivity	
Instantaneous Single Parameter Metric	□ Range ----------------- □ Fuel Weight	**Proxy**	Instantaneous measurement of fuel burn performance (proxy for full mission performance measurement)
Full Mission Two Parameter Metrics	Fuel ----------------- **Payload** * Range	**Closest measure of "True" productivity**	Metric similar to the metric used by CAEP to measure air transportation system operational performance (i.e. Commercial Aviation System Fuel Efficiency Metric CASFE)
	Fuel ----------------- **Useful Load** * Range	**Proxy**	Includes fuel weight (considered as input to the system and not part of "true" productivity)
	Fuel ----------------- **MTOW** * Range	**Proxy**	Includes fuel and aircraft empty weight (considered as input to the system and not part of "true" productivity)
	Fuel ----------------- **Floor Area** * Range	**Proxy**	Floor area may be defined as: Cabin area (=cabin length * avg. cabin width) for passenger aircraft Cargo bay floor area (for cargo aircraft) Alternative measurement: - Cabin length * cabin width at passenger eye's height
	Fuel ----------------- **Av. Seats** * Range	**Measure close to "True" productivity (for passenger aircraft only)**	

Three-parameter Metrics

Two parameter metrics were expanded to three parameter metrics to include a speed (or time) parameter. A total of 10 three-parameter metrics were retained (5 metrics including a measure of speed and 5 metrics including a measure of time).

Discussion on the Inclusion of Speed in the Aircraft Certification Metric

As described in the previous section, a set of 10 parameter metrics, which include a measure of speed or time, was generated for evaluation. There are consequences for including speed in a proposed metric, and there are potential implications for not including any measure of speed. First, Block Fuel and Speed are coupled at the operational level and design level. Operational conditions i.e. cruise speed at which airlines choose to fly, influence fuel burn, as depicted in Figure 16. From a design standpoint, aircraft manufacturers also choose a cruise speed to design a vehicle (influencing fuel burn). Because of this coupling, block fuel energy can be reduced by a significant amount in current aircraft by using a speed less than the design cruise speed. The effect of this reduction in cruise speed has a significant impact on analyzed metrics. Here, reductions in speed outpace fuel burn savings in almost all cases, meaning that even for speeds which offer savings in fuel burn compared to the baseline, there is a penalty in the metric. By including speed in an aircraft CO_2 metric, aircraft designs similar to current vehicles would be driven to higher speeds in order to achieve better metric scores, potentially at the cost of increased actual fuel burn. This suggests that including speed in a CO_2 metric may result in negative unintended consequences.

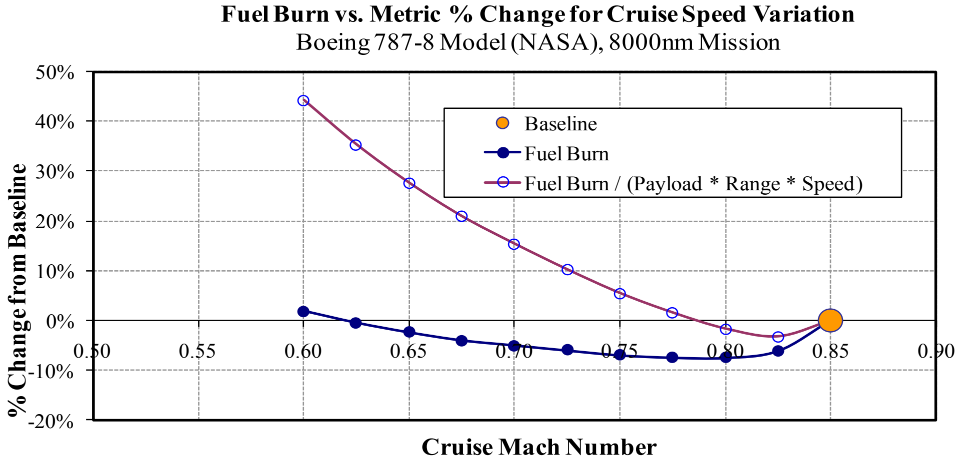


Figure 16: Fuel Burn and Metric Variations for Cruise Speed Variation

The inclusion of the speed in the metric implicitly assumes a relative weight between “time related costs” driven by speed vs. “fuel related costs” driven by fuel burn. This relative weight is similar to the Cost Index used by airlines, on an operational basis, to adjust cruise speed based on the relative cost of fuel and labor. While this works well for operational adjustments (based on “real time” changes on fuel vs. labor costs), the inclusion of a speed parameter in the aircraft certification metric would require forecasting a cost index. However, the ratio of fuel to labor costs (i.e. cost index) has not been constant over time as show in Figure 17. Clearly, speed is a factor, which significantly influences aircraft fuel burn. Because of its significance, speed is a parameter that cannot be ignored in the process of determining a certification requirement regulating aircraft CO_2 emissions. However, it is likely that speed is most appropriately dealt with as a measurement condition in the certification process or in the scope of applicability of the standard.

In summary, all two and three-parameter metrics include measures of transport capability i.e. productivity. Although one parameter metrics do not explicitly include a measure of transport capability in the metric this measure can be included in the correlation parameter or evaluation condition. Speed as a productivity measure may be best included in a certification requirement other than explicitly in a metric.

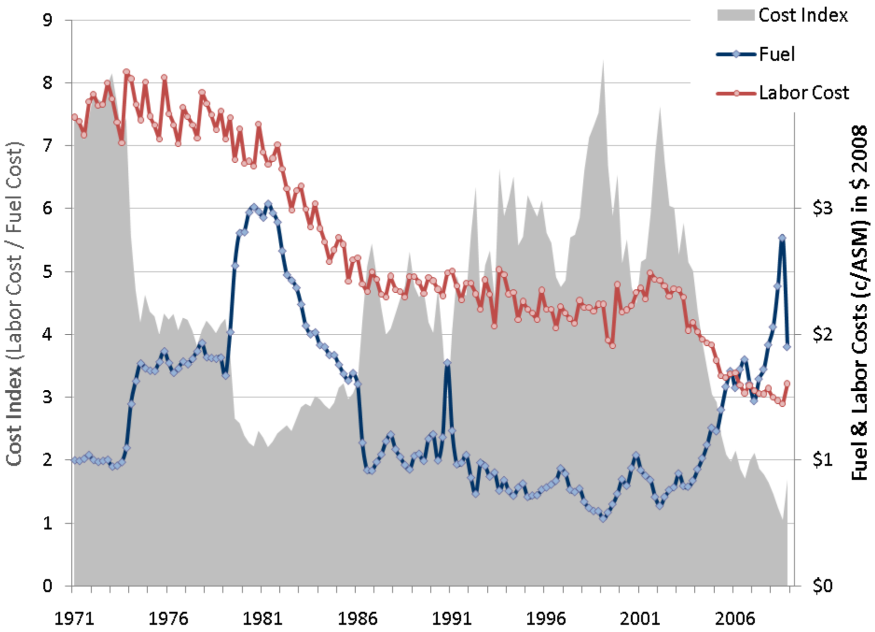


Figure 17: Historical evolution of labor costs, fuel costs and airlines' cost index [15]

All two- and three-parameter metrics include a measure of productivity. One-parameter metrics can include productivity terms in a correlation parameter.

Account for Fundamental Aircraft Design Elements and Capabilities

Aircraft fuel efficiency metric should also account for the fundamental elements of aircraft design and performance, to ensure that a metric appropriately capture all factors that may influence fuel efficiency. Elements of aircraft design that affect fuel consumption and need to be considered as defined in the Breguet-Range equation, include structure, aerodynamics, propulsion, and mission characteristics. All these elements are inherently captured when estimating mission fuel burn, which most of the portfolio of metrics are based on. By its definition, SAR and instantaneous metrics also fundamentally include necessary aircraft design elements and capabilities. Thus, by definition, all presented metrics satisfy this criterion.

All metrics account for fundamental aircraft design elements and capabilities.

Ease of Measuring Metrics: Use of Existing Certified Parameters vs. New Certification Parameters

In order to evaluate how challenging it would be to measure and evaluate aircraft certified performance, each metric was decomposed into the individual measurable parameters. Some of these parameters are already certified whereas others are not. Among the non-certified parameters, some would be easy to certify whereas other may be harder to certify. A preliminary assessment of the measurability and availability of a certified data for the parameters that compose each metric are listed in Table 5. In all cases, there was the need to certify fuel at a given range for full mission metrics or the rate of change of fuel weight and distance for instantaneous performance metrics. This can be achieved by a combination of flight test and/or aircraft performance measures derived from aircraft manufacturers' high fidelity simulation models that are typically performed during current certification procedures. It is the "measure of what is transported" that significantly differentiates the measurability of a metric. As an illustration, it is believed that a metric based on MTOW would be easy to certify since this parameter is already certified. On the other hand, metrics that would be based on payload, floor area or number of seats would be harder to certify. The weight parameters that are currently certified and the ones that are not certified by aviation authorities (but could eventually become certified) are listed in Table 6.

Table 5: Measurability & Availability of Certified Data

Types of Metrics	**Fuel Efficiency Metrics**	**Parameter**		**Measurability & Availability of Certified Data**	
				Availability of Certified Data	Possible Measurement Procedure*
Instantaneous Single Parameter Metric	□ Range ----------------- □ Fuel	(SAR)		SAR: **Not certified but computed for performance commitments to airlines**	FT: Flight Test AN: Analysis
Full Mission Two Parameter Metrics		Fuel		Block Fuel: **Not certified**	FT: Flight Test AN: Analysis
		Range		Range: **Not certified**	FT: Flight Test AN: Analysis
	Fuel ----------------- **Payload** * Range	Payload	Max. Struct. Payload (MSP) = MZFW – OEW	MZFW: **Certified** OEW: **Not Certified** $^{(1)}$	Weight Measurement Procedure (Similar to existing weight certification procedures)
		Max. Payload = Min(MSP,MVP)	Max. Vol. Payload (MVP)	Max. Vol. Payload: **Not Certified**	
	Fuel ----------------- **Useful Load** * Range	Useful Load = MTOW - OEW		MTOW: **Certified** OEW: **Not Certified** (by aircraft manufacturers)**	Weight Measurement Procedure (Similar to existing weight certification procedures)
	Fuel ----------------- **MTOW** * Range	MTOW		MTOW: **Certified**	N/A
	Fuel ----------------- **Floor Area** * Range	Floor Area		Floor Area: **Not certified**	Direct Aircraft Dimension Measurement
	Fuel ----------------- **Av. Seats** * Range	Available Seats		Available Seats: **Not certified***** Alternatively, Max. Number of Seats based on 90 sec. emergency evacuation procedure could be used (but is subject to gaming dynamics)	Seat Count

* Note: Measurement process based on FAA Type Certification
** Note: Manufacturer's Empty Weight (MEW) or other appropriate measure of aircraft empty weight could be used instead of OEW
***Note: Maximum Passenger Seating Capacity –which is a certified metric for passenger evacuation purposes) could be used as a proxy for seat count. However, it is easily foreseeable that this Maximum Passenger Seating Capacity could be gamed.

Table 6: Certified & Non-Certified Aircraft Weight Metrics

Acronym	**Metric**	**Availability of Certified Metrics**	
		Aircraft Manufacturer Certification	Operator Certification
MTW	Maximum taxi weight	**Certified**	N/A
MTOW	Maximum takeoff weight	**Certified**	N/A

MLW	Maximum landing weight	**Certified**	N/A
MZFW	Maximum zero fuel weight	**Certified**	N/A
MFW	Minimum Flying Weight	**Certified**	Certified in TCDS
OEW	Operating empty weight	**Not Certified**	**Certified** (in Airplane Flight Manual)
Max. Payload	Maximum Payload	**Not Certified**	**Certified** (in Airplane Flight Manual)
MEW	Manufacturer's empty weight	**Not Certified**	N/A
SEW	Standard empty weight	**Not Certified**	**Certified** (in Airplane Flight Manual)
BEW	Basic empty weight	**Not Certified**	**Certified** (in Airplane Flight Manual) Used and published mostly in the business aviation industry

Although not required by airworthiness authorities, because it is a fundamental indicator of aircraft performance, manufacturers conduct a considerable amount of flight tests during the certification process to validate SAR cruise performance [16], [17], [18] for the development of flight manuals that are supplied to the operators. It is not uncommon to find flight manuals of military and commercial aircraft which include extensive SAR data developed by a manufacturer using airplane performance models which are calibrated and validated by flight tests. It is expected that SAR would be simpler to measure and report.

SAR is also expected to be relatively easy to specify for certification, especially compared to mission-based fuel measures such as block fuel or air fuel, which require numerous parameters to be defined and agreed upon by a regulatory authority as well as complex methodology to implement within the certification process. As an example, a purchase agreement between the Airbus Industry and US Airways, publicly available from the Security Exchange and Commission's database, specifies SAR values and block fuel values guaranteed by the manufacturer. For the full mission condition, approximately 38 parameters were required to fully define the conditions of the block fuel guarantee. However for SAR, only 4 parameters were required. This inherent simplicity makes instantaneous metrics potentially significantly easier to measure at the certification stage than mission fuel consumption.

As a result, instantaneous point based metrics have equivalent ease of measurement, and all mission fuel based metrics have more complexity in measurement. In general, instantaneous metrics are expected to be easier to measure for certification than mission based metrics.

Metrics or correlating parameters including; Maximum taxi weight, Maximum takeoff weight, Maximum landing weight, Maximum zero fuel weight, Minimum Flying Weight are expected to be easier to use for an aircraft CO_2 emissions standard since these parameters are already certified.

Instantaneous point based metrics have equivalent ease of measurement, and all mission fuel based metrics have more complexity in measurement. In general, instantaneous metrics are expected to be easier to measure for certification than mission based metrics.

Metrics or correlating parameters including; Maximum taxi weight, Maximum takeoff weight, Maximum landing weight, Maximum zero fuel weight, Minimum Flying Weight are expected to be easier to use for an aircraft CO_2 emissions standard since these parameters are already certified.

Independence of Purpose or Utilization

The proper assessment of metrics, correlation parameters and evaluation conditions requires the investigation of the performance of aircraft that were configured to satisfy different purposes for actual use in the fleet, as well as the examination of how different variants score on metric-CP-evaluation condition frameworks. One example of similar aircraft that satisfy different purposes are freighter and passenger variants: in other words a common airframe (and sometimes common engine) can be configured to carry either passengers or cargo. If freighter and passenger variants are based on the same airplane, then a metric-CP pair should not differentiate the two configurations.

First, passenger and freighter variants based on similar aircraft types were identified and listed in Table 7. Of 11 major freighters listed, 10 had comparable passenger variants. External literature validated the assertion that the passenger and freighter variants were based on the same aircraft type.

Table 7: Comparable Passenger/Freighter Airplane Types Available

Passenger Variant Model	**Freighter** Variant Model
Airbus A300 600R	Airbus A300 600F
Airbus A330-200 233t	Airbus A330-200F
B747-200B (833)	B747-200F (833)
B747-400 (875)p	B747-400F (875)
B747-400ER (910)p	B747-400ERF (910)
B757-200 (255)p	B757-200F (255)p
B767-300ER (412)WL	B767-300F freighter
B777-200 LR (766)	B777-200 Freighter
Douglas MD-11 option	Douglas MD-11F (630)
Ilyushin IL-96-400	Ilyushin IL-96-400T

To describe the similarities and differences between these passenger and freighter variants, Figure 18 shows a comparison of a subset of 5 airplanes for several primary aircraft characteristics: MTOW, operating weight empty (OEW), maximum landing weight (MLW), MZFW, fuel volume, and maximum payload. Aircraft type characteristics were compared by a percent difference, normalized to the respective freighter variant. For example, the characteristics of a Boeing 777-200LR passenger aircraft would be compared to the corresponding characteristics of the Boeing 777 Freighter (which is based on the 777-200LR), and the percentage difference between these two types was calculated. By this method, a score of ‘0’ indicates that the passenger variant is identical to the freighter variant for a particular characteristic, and a large variation away from a value of ‘0’ indicates that the passenger and freighter variants differ significantly for that characteristic. Also, specific aircraft names are not included in this figure for data sensitivity reasons, and instead are referred to in general terms as

'Aircraft 1,' 'Aircraft 2,' etc. The deviations of the lines away from a value of '0' show just how significantly the passenger variants differ from the corresponding freighter variants. All passenger/freighter aircraft pairs had very similar MTOWs, a first indication of similarity of the variants. As expected, maximum payload capacity was observed to vary significantly between comparable passenger and freighter aircraft variants; this is due to the added payload capacity of freighters because of the lack of passenger accommodations, freeing that otherwise unproductive weight to be productively carried as cargo. This effect is also observed in the differences in OEW between passenger and freighter variants. While the differences in other aircraft characteristics suggest that there were other differences in the basic nature of these passenger/freighter variant pairs, their overall similarity suggested these 10 aircraft pairs were still suitable for meaningful investigation of the independence of metric-CP pairs to product purpose.

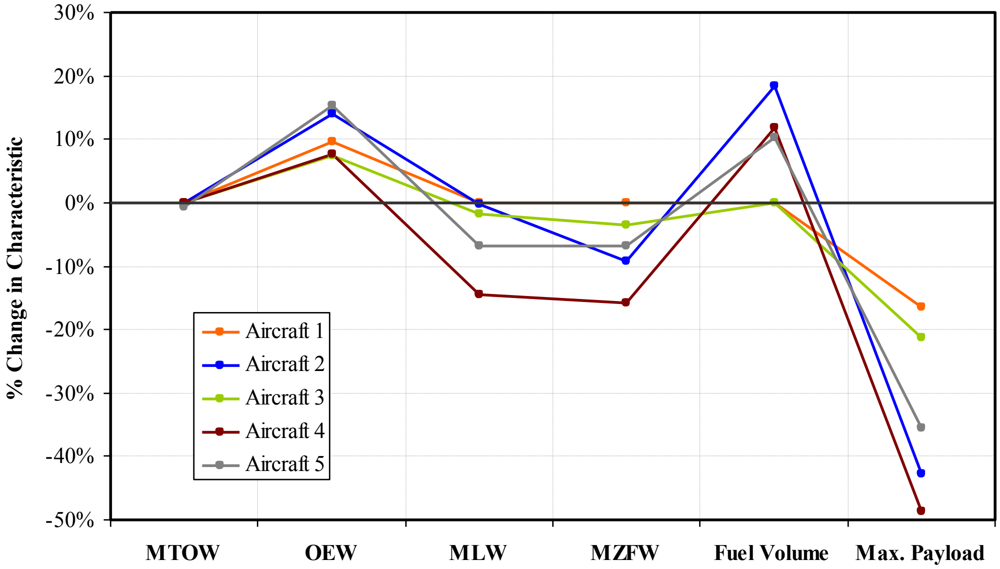


Figure 18: Passenger/Freighter Aircraft Characteristics Comparison (% Difference in Aircraft Characteristics, Normalized to Freighter Variants)

Using available data, aircraft performance for several metric-CP pairs to highlight how the test for this criterion should be interpreted is depicted in Figure 19. The top left shows aircraft performance for the 1/SAR vs. MTOW metric-CP pair. Here, passenger aircraft are designated by open circles, while freighters are designated by filled squares. Passenger and freighter variants of the same aircraft type are shown in the same color. It can be observed that this particular metric-CP pair treats passenger and freighter variants nearly identically, since the two symbols lie nearly on top of each other. This is partly due to the evaluation condition (at fixed percentage of MTOW), but more importantly due to metric's basic nature: 1/SAR is independent of the composition of aircraft weight at a particular condition, and thus treats similar passenger and freighter aircraft the same. As such, 1/SAR does not bias or distinguish freighter or passenger aircraft.

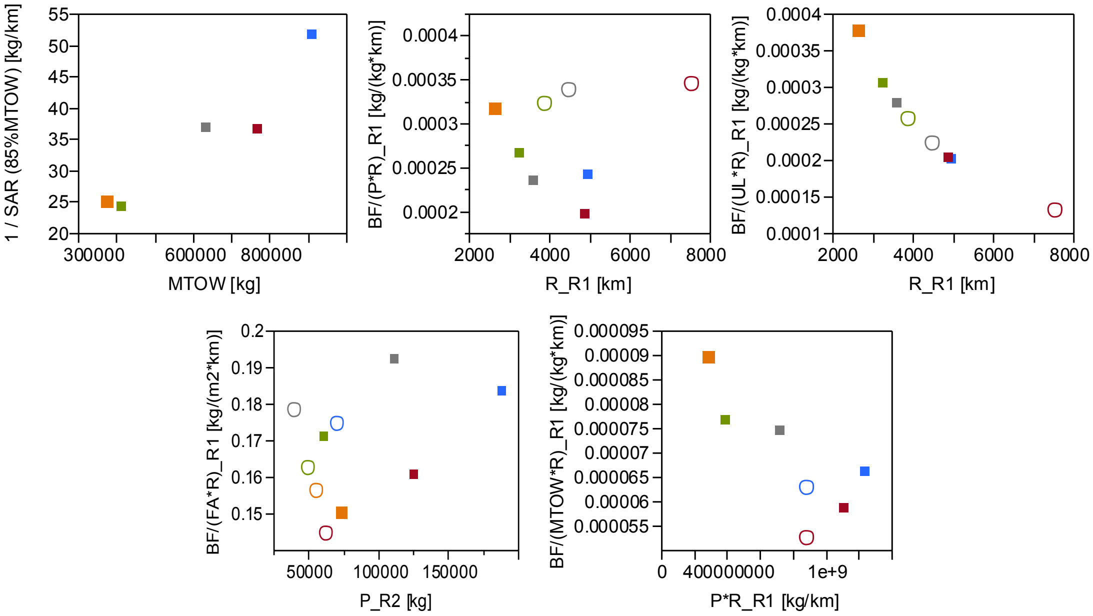


Figure 19: Passenger/Freighter Performance for different metric systems

In contrast, the remaining portions of Figure 19 show several metrics paired with CPs, and each pair. shows significant variation between passenger and freighter variants. This variation is due to the dependencec of some parameters on aircraft configuration, which inherently do not satisfy the criterion of being independent of purpose or utilization. An exhaustive picture of metric-CP performance with respect to this criterion is given in Appendix. From this assessment, there were only one candidate which reasonably satisfied this criterion: 1/SAR vs. MTOW. As a result of this analysis, one metric reasonably satisfy the criterion of "independence of purpose and utilization": 1/SAR vs. MTOW (best performance).

One metric reasonably satisfy the criterion of "independence of purpose and utilization" i.e. 1/SAR vs. MTOW

Assessment of Differentiation of Generations of CO_2 Reduction Technologies

The earlier discussion of lessons learned regarding existing certification requirements provided insight into a feasible approach for the assessment of candidate fuel efficiency metrics for their ability to differentiate technology generation. First, a CP and evaluation condition must be included in analysis in conjunction with a metric. Second, the CP used should reflect aircraft attributes related to size or capability. The use of an attribute-based CP in conjunction with a metric suggests the resulting metric-CP combination should not discriminate against aircraft designed for particular capability, but should allow for a tradeoff between capability and metric performance. Finally, suitable metric-CP combinations are intentionally constructed to reward technology progression. This technology differentiation criterion was the main driver for down selecting appropriate metric-CP pairs that also satisfied the remaining criteria.

Methodology

The primary objective of this study is the development of a methodology that enables a transparent and objective evaluation of the metric-CP candidates for their adherence to the evaluation criterion. The current methodology is focused on identifying a metric system—as a combination of a metric and a CP— that shows suitable ability to differentiate technology generations while not favoring or discriminating airplanes designed for particular mission capabilities, specifically payload and range. A good metric system must present clear separation of technology generation without confounding payload and range capability. A payload-range diagram for two notional technological generations of civil transports is depicted in Figure 20. Each generation includes three vehicles, which have different payload range capabilities to support different market needs. Figure 21 suggests how metric-CP pairs can be tested in a pictorial form. The M1-CP1 pair on the left does not show clear separation of the two technological generations and is considered to be poor in terms of differentiating technology. The M2-CP2 on the right shows good correlation among the aircraft in the same technology generation and clear separation between the two groups.

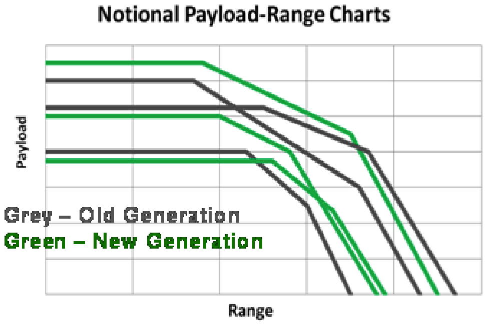


Figure 20: Notional payload- range diagrams of two technology generations

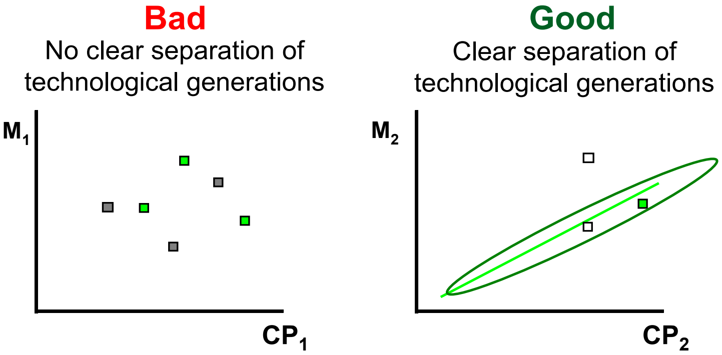
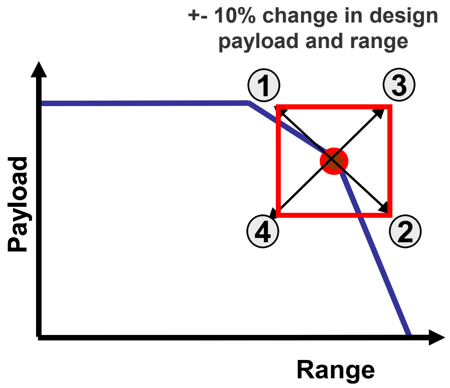


Figure 21: Notional examples of good and bad metric-CP pairs

It was attempted to expand this examination to a larger dataset including more airplanes of diverse sizes from different manufactures. However, it was impractical to use public domain data for metric-CP evaluation due to the inconsistent and often unknown assumptions behind aircraft data available publicly. For example, of the assumptions of the mission profile rules used for developing payload range charts are unknown for most aircraft. In lieu of using public domain data for existing aircraft, experiments were conducted utilizing EDS, which can generate hypothetical airplanes sized for mission requirements and technology assumptions. This approach allowed the application of consistent assumptions for vehicle sizing and performance analysis and the generation of sufficient amount of data required to develop statistically meaningful trends.

A simple test was first conducted with the EDS Large Twin Aisle (LTA) model to assess variations in mission and technology level. From the baseline LTA aircraft with design range of 14,900 km and payload of 28,000 kg, four mission requirements variations were created as shown in Figure 22. Four derivative aircraft were then generated to meet each one of the different mission requirements. Aircraft were resized for a fixed thrust-to-weight ratio and wing loading. Subsequently, another set of five aircraft were generated for the five different missions including the baseline, now with a technology level assumption of 10% TSFC reduction.



Scenario	Payload	Range
①	+10%	- 10%
②	- 10%	+10%
③	+10%	+10%
④	- 10%	- 10%

Figure 22: Payload and range conditions of four variants with respect to the baseline

As is evident, changes in mission capabilities may result in significant changes in both metrics although each metric includes productivity parameters in the denominator. In Figure 23, a comparison of point 1 and point 2 indicates that BF/(P*R) may substantially differ even if aircraft capability (represented by P*R) is maintained. It suggests that the metric can be improved either by trading mission capability parameters at a fixed CP value or adding beneficial technologies. Therefore, the BF/(P*R) vs. P*R system is not able to differentiate technology level from such variation due to mission capability.

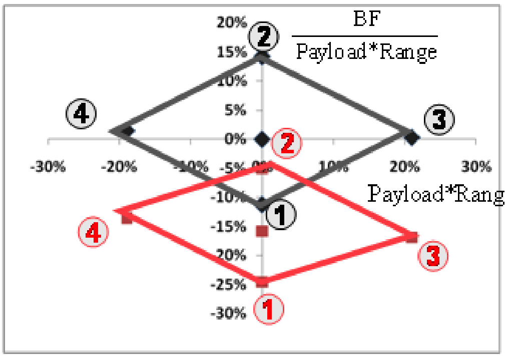


Figure 23: BF/(P*R) vs. P*R (black: no tech infusion, red: 10% TSFC improvement)

In contrast with BF/(P*R) vs. P*R, the aircraft appear to form a trend in BF/(UL*R) vs. UL*R within a technology level, as depicted in Figure 24. The BF/(UL*R) metric is also substantially affected by design mission parameters. However, associating BF/(UL*R) with UL*R is found to enable the metric to differentiate technology level from such variations in mission capability. In addition, it is noteworthy that BF/(UL*R) exhibits very low sensitivity to technology infusion. 10% TSFC reduction technology improves the metric only by 3% while improving block fuel burn by 15%. Although the degree of proportionality of metric sensitivity to block fuel sensitivity is not a focus of this study, the authors would like to note that this area needs a further investigation.

This pilot test suggests that metric ability of differentiating technology levels from mission capabilities can be significantly affected by a CP associated with the metric. The observations from the described experiment concept were deemed effective in testing metrics and parameters ability to separate technology levels.

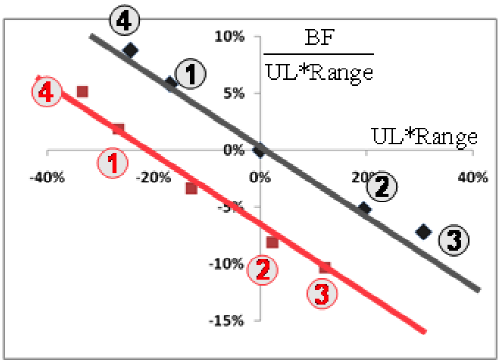


Figure 24: BF/(UL*R) vs. UL*R (black: no tech infusion, red: 10% TSFC improvement)

Results of Analysis of Differentiation of Generations of CO_2 Reduction Technologies

Analysis of Mission Performance Metrics and CPs

The methodology of evaluating metric-CP performance was implemented to all the CO_2 emission metrics and CPs introduced earlier. The evaluation was performed for five EDS aircraft ranging from a Regional Jet (RJ), a Single Aisle (SA), a Small Twin Aisle (STA), a Large Twin Aisle (LTA), and a Large Quad (LQ). For each of the five EDS aircraft, one thousand mission variants were generated within +/- 10% of the baseline design payload and range. The combinations of design payload and design range were generated randomly using a Monte Carlo simulation assuming a uniform distribution for payload and range within the bounds defined. The length of aircraft cabin and number of seats were changed by the same percentage as the design payload changed from the baseline value. For each one of the mission requirements, the baseline EDS aircraft were resized by fixing thrust to weight ratio and wing loading. For the missions generated, three sets of technology levels were applied: baseline technology, a technology that reduces airframe structure weight by 10%, and a technology that improves engine efficiency by 10%. After resizing the aircraft, variations in the CO_2 metrics and CPs were measured around R_2. Analysis results on the STA are presented in this section. The BF/(P*R) metric with P*R as a CP is plotted in Figure 25. Three diamonds in the figure are formed by three thousand aircraft derivatives in different mission capabilities and technology levels. The black group represents aircraft in baseline technology. The green group is aircraft with the 10% aircraft weight reduction technology. The red group is aircraft with 10% TSFC reduction technology. This color scheme is used for the rest of this paper. The circles in the middle of each color group indicate aircraft that fly the same mission as the baseline STA aircraft.

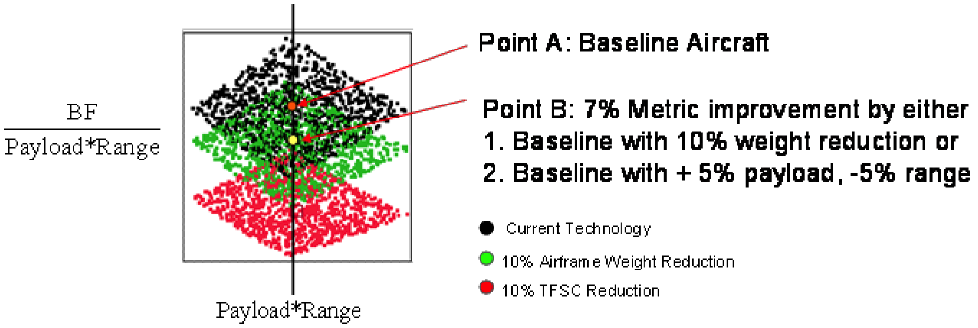


Figure 25: BF/(P*R) against P*R

For this metric–CP pair, the relative size of the diamonds to the degree of separation between the diamonds is comparable. Overlap between the technology groups indicates that the manufacturer has options to improve the metric value either by improving the technology or changing the design mission. For example, if the manufacturer is mandated to improve the metric by 7% from the baseline (Point A), it could achieve that by adopting a technology that saves aircraft structural weight by 10% or increasing design payload by 5%. A standard based on this metric system may motivate the manufacturers to change the design mission rather than to implement fuel burn reduction technology. This effect could have implications to the manufacturer in terms of driving capability to particular levels, rather than promoting technology adoptions.

Two metric-CP pairs that include MTOW term either in the metric or in the CP are presented in Figure 26. The metric on the left, BF/(MTOW*R) against Range, is showing good aggregation of aircraft in same technology level. However, the green group is above the black group, which means the metric penalizes aircraft with the structural weight reduction technology, although the absolute fuel burn is reduced. This metric-CP system fails to differentiate technology. The BF vs. (MTOW*R) pair, depicted on the right side of Figure 26, shows very tight collapse of aircraft in different missions but the same technology level. However, as the overlap between the black and green lines indicates, assuming that a notional stringency line is parallel to the trend lines, this metric-CP pair does not reward aircraft with better structural efficiency.

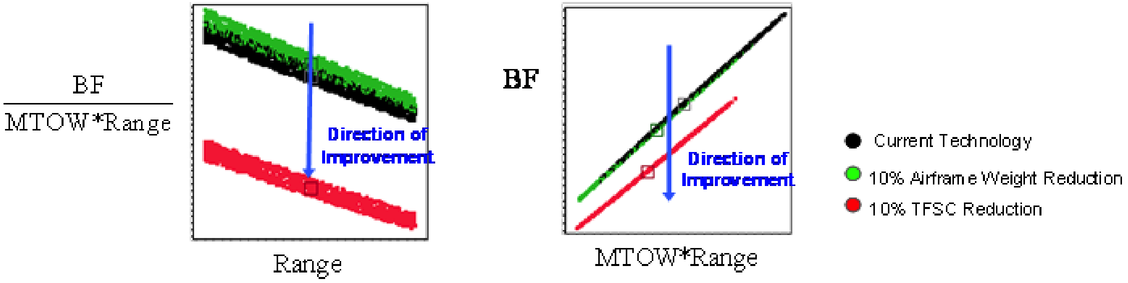


Figure 26: Examples of Metric-CPs with MTOW Term

The two metric-CP pairs plotted in Figure 27 show better characteristics of discriminating aircraft in different technology level without being compounded by mission effect. The BF/(UL*R) metric with (UL*R) on the left shows very tight collapse of aircraft in the same technology levels and distinctive separation of aircraft in different technology levels. Also, the BF/R with P*R exhibits clear separation between technology groups. However, the useful load metric includes fuel term both in numerator and denominator; it tends to cancel out the fuel burn reduction impact, whereas the BF/R metric accurately reflects fuel burn reduction. For the baseline mission of the EDS STA, 15% metric improvement implies 15% fuel burn reduction for the BF/R metric, and about 3% for the BF/(UL*R) metric.

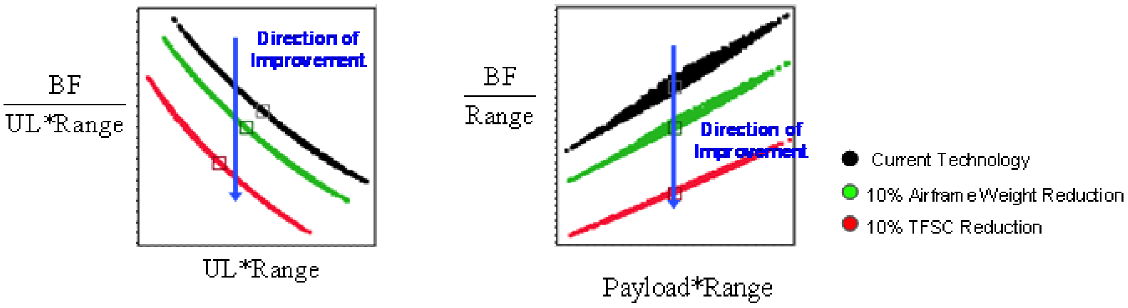


Figure 27: BF/(UL*R) vs. UL*R (Left) and BF/(P*R) vs. P*R (Right)

Finally, all mission based metrics and CPs are plotted simultaneously in Figure 28. Here, metrics are shown on the ordinate axis and CPs are shown on the abscissa. Each box in this figure shows exactly the same data, but organized by the corresponding metric (each row corresponds to one metric) and CP (each column corresponds to one CP). This figure simply uses a condensed, simplified way to observe many plots simultaneously. By comparing the plots within each row, it is observed that a metric's ability of differentiating technology generation is substantially affected by the choice of CP. Therefore, an assessment of metric and CP must be performed together. The key observations from Figure 28 are summarized as follows:

- Metrics that include "load" terms [BF/P, BF/(P*R), and BF/(FL*R)] show large dispersion within a technology group scoring worse on being able to differentiate technologies
- Metrics that include weight in denominator [BF/(MTOW*R)] do not reward airframe weight reduction technology
- Use of MTOW as a CP may not fully reward fuel burn reduction through airframe weight reduction depending on the functional form of the regulatory level, i.e. the use of MTOW as a CP may not result in improvements in the margin to the regulatory level and hence may not incentivize aircraft manufacturers to invest in airframe weight reductions (for the sole purpose of meeting a CO_2 certification requirement).
- BF/(UL*R) and BF/(TOGW*R) exhibit substantially low sensitivity to technology improvement for fuel burn
- BF/R vs. P*R and BF/R vs. Floor*R among the metrics and CPs considered were identified to best support technology differentiation ability for the STA aircraft.

The analyses presented in the previous sections were repeated for the four other EDS Aircraft. The results are provided in Appendix. Since each aircraft has different sensitivities to design payload and design range variations, some of the observations made for the STA aircraft were different for other vehicles. An aircraft with low payload fraction is less sensitive to payload change. An aircraft with high fuel fraction, e.g. long range aircraft, is more sensitive to range change. For example, the RJ and SA have relatively shorter design ranges than other three aircraft and therefore are relatively less sensitive to the relative change in design range. Due to their relative low sensitivity to design range change, some of the metrics for the RJ and SA aircraft performed quite differently. In the case of BF/R, its sensitivity to payload and range was quite similar for the STA, LTA, and the LQ aircraft. Therefore, BF/R vs. P*R showed very good ability to differentiate technology. However, BF/R was much more sensitive to payload variation than range variation for the RJ and SA aircraft, making the degree of dispersion of the metric associated with some two parameter CPs such as P*R, MTOW*R, and FL*R much larger.

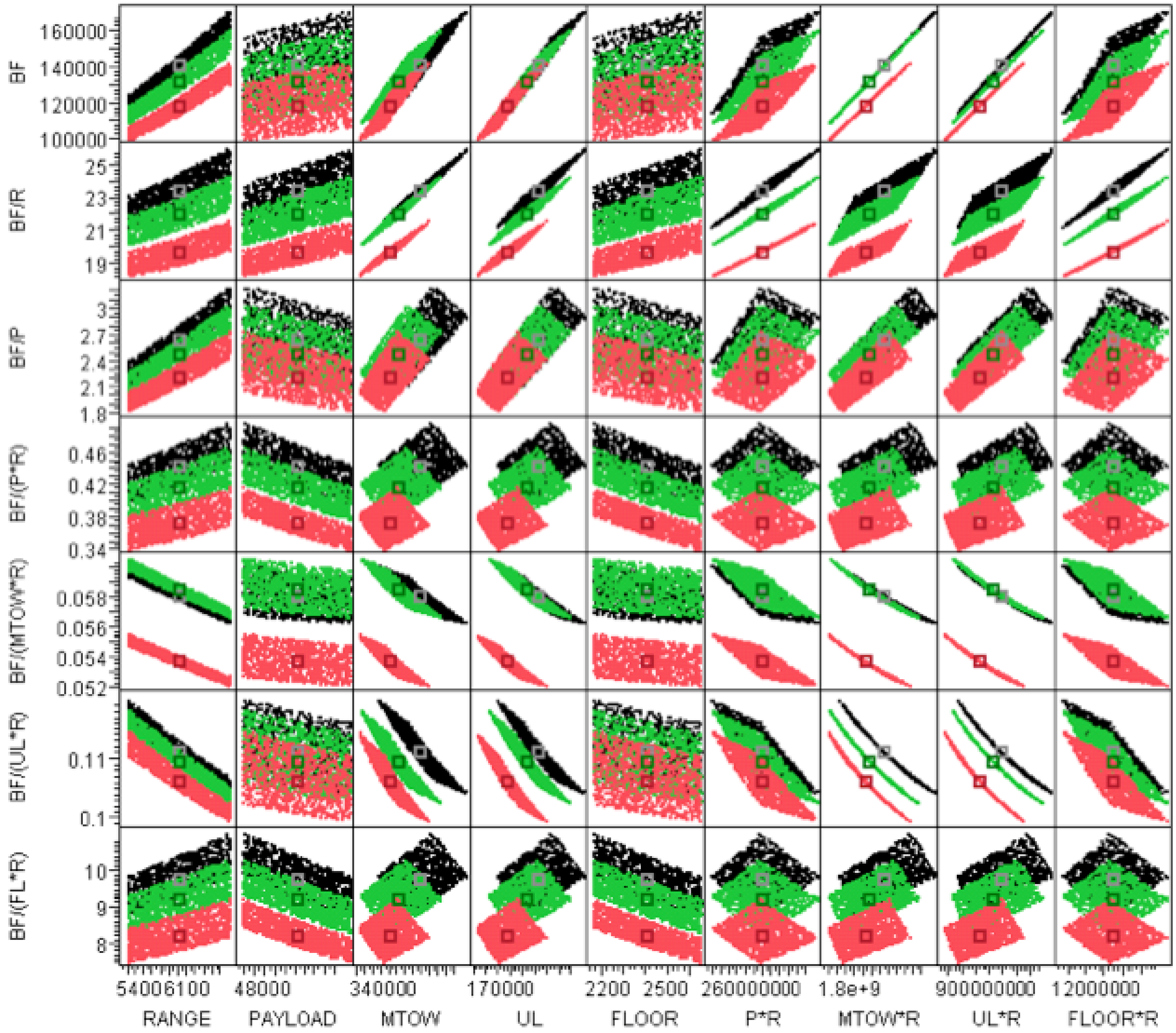


Figure 28: Mission Performance Based Metrics and CPs – EDS Small Twin Aisle Analyses

Key observations (consistent on all five vehicles):

- **Metrics that include "load" terms [BF/P, BF/(P*R), and BF/(FL*R)] show large dispersion within a technology group, especially on the STA, LTA, and LQ aircraft, which substantially reward aircraft with more capacity, i.e. payload or floor area.**

- **BF/R vs. P*R and BF/R vs. FL*R among the metrics and CPs considered were identified to best support the evaluation criterion for the STA, LTA, and LQ aircraft. However, BF/R vs. P*R and BF/R vs. FL*R can potentially reward an aircraft with lower payload or floor area for the RJ and SA aircraft. BF/R vs. UL also shows medium level of dispersion within a technology group and should be considered as a metric-CP candidate.**

- **Finally, while BF/R vs. MTOW may not differentiate airframe weight reductions, it consistently show tight collapse of aircraft in the same technology group while reducing the block fuel and should be considered as a metric-CP candidate.**

Analysis of Point Performance Metrics and CPs

The (SAR) based CO_2 metrics are evaluated with respect to the evaluation criterion. In order to evaluate SAR metric performance with respect to the technology differentiation criterion, the process formulated previously was implemented. SAR was evaluated at a certain fraction of MTOW at the International Standard Atmosphere (ISA) temperature. For a given weight condition, the best altitude and speed that maximized SAR was calculated. In order to see whether the specific weight condition selected would affect metric performance, three different weight conditions were tested. The same set of CPs used in the previous sections was evaluated.

The metrics are 1/SAR85, 1/SAR80, and 1/SAR75 are depicted in Figure 29. These three metrics are the inverse of SAR measured at 85, 80, and 75% of MTOW, respectively. Two other metrics in the bottom rows are 1/(SAR*P), and 1/(SAR*MTOW). The key observations from the STA aircraft performance are as follows:

- 1/SAR metrics were found to exhibit very good quality that supports the evaluation criterion when associated with either UL, P*R, or FL*R
- 1/(SAR*P) show large dispersion within a technology group scoring worst on the evaluation criterion, especially
- 1/(SAR*MTOW) does not reward aircraft structural weight improvements

General observations that are consistent for all 5 EDS aircraft are that 1/SAR exhibit very similar characteristics to the BF/R metric. In addition, 1/(SAR*P) showed very similar trend to BF/(P*R), and 1/(SAR*MTOW) was very close to BF/(MTOW*R). Among the three different metrics, 1/SAR seems to be most desirable. Good CP candidates for this metric are P*R and FL*R for the STA, LTA, and LQ. Again, for the RJ and SA aircraft, 1/SAR vs. P*R and FL*R had a tendency to favor aircraft with low capacity. Considering the fact that the key advantage of SAR based metric is its independence to mission and utilization, choosing a CP that is dependent on mission performance would not be desirable.

When 1/SAR is associated with MTOW, it shows best collapse of aircraft in the same technology group for all five aircraft. Moreover, 1/SAR vs. MTOW has the great advantage of being much simpler than any other metric systems considered in this study. SAR is potentially simpler to measure than mission parameters, and MTOW is already certified and mission and utilization independent. However, as discussed previously, this pair may not explicitly reward aircraft improvements via better structural efficiency with respect to a margin but the absolute value is reduced, but a similar trend is observed with EPNdB versus MTOW of noise certification.

1/SAR vs. UL shows very good characteristics with respect to the evaluation criterion. Since UL is MTOW less OEW, it does not have issue of not incentivizing aircraft structural weight reduction as MTOW does. A disadvantage of using UL as a CP over MTOW is that UL relies on currently non-certified parameters, which is less desirable as discussed in other evaluation criteria. In addition, a standardized OEW would need to be defined, which presents definition difficulties when the entire fleet is considered. As 1/SAR85, 1/SAR80, and 1/SAR75 show very similar results, the ratio of airplane weight to MTOW at a measurement point makes no significant impact on SAR metrics' behavior, only changing the scale. While further investigation is warranted, this study suggests that measuring SAR at a certain fraction of MTOW seems to be fair. Analysis results from four other EDS aircraft provided in Appendix. A more detailed discussion on the analysis presented in this section can be found in Kirby 2010 [19].

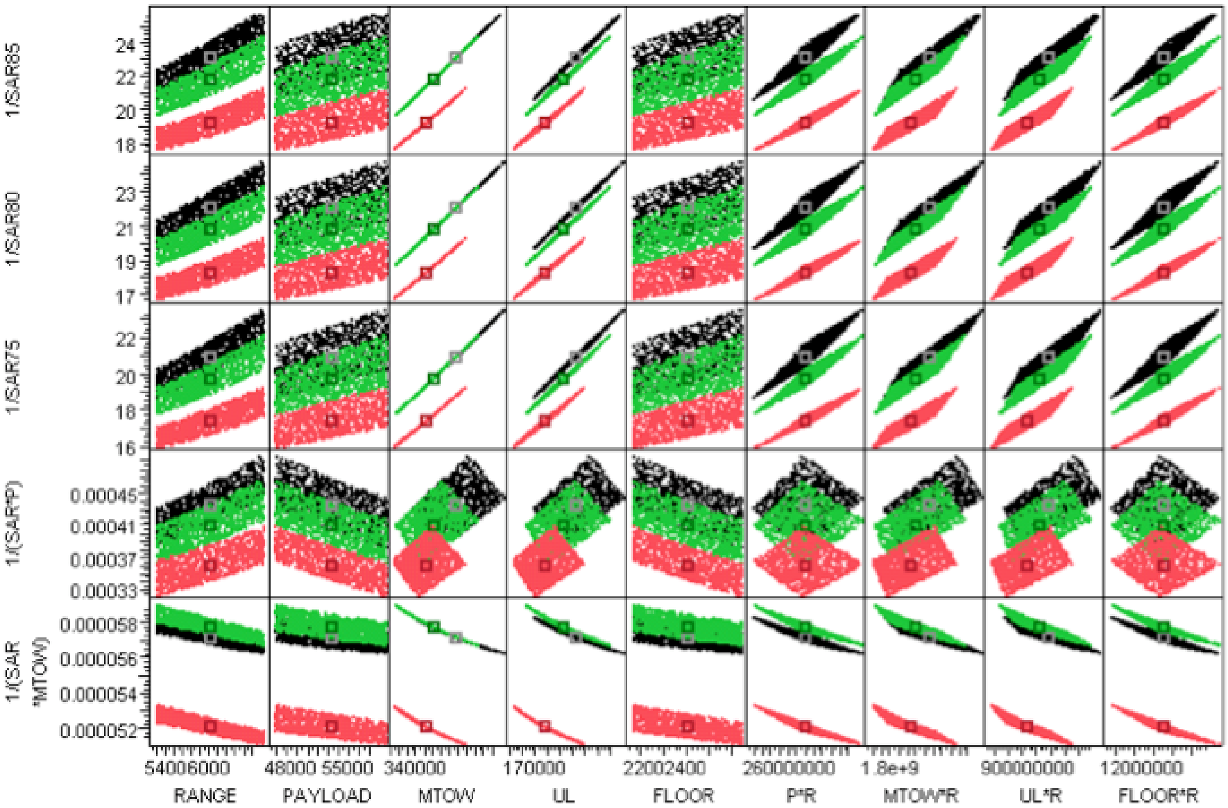


Figure 29: 1/SAR: EDS STA Analyses

Assessment of Robustness of Metric-CP pairs

Further testing of the different metric-CP pairs was investigated against known aircraft family technology progression. It is a general practice of industry to produce a family of aircraft in order to capture diverse market demands. The product family approach is often planned from the beginning of the development process in order to maximize commonality within a family and thereby to minimize development and production cost. During development, aircraft manufacturers continue revising their plan in order to react to the changes in market conditions and take advantage of technology advances over time. Examining a metric-CP pair for a particular aircraft family can provide excellent insight as to how the metric-CP pair treats progressions in design specification and technology levels.

One particular aircraft family in the SA class was investigated with respect to two different metrics: 1/SAR shown in Figure 30 and BF/(P*R) metric measured at P60 in Figure 31. This aircraft family was developed in three distinctive generations. The first generation, shown in red in both figures, was introduced in the mid 1960's. Variants in the second generation, shown in blue, were certified during the 1980's. The most modern generation of aircraft, represented in green, were certified between late 1990's and early 2000's. Within each generation, various product types were developed with diverse payload and range capabilities, including several BJ models, depicted as triangles in both figures. The 1/SAR vs. MTOW pair shows very clear separation of the three distinct generations of aircraft variants. At the same time, the metric-CP pair exhibits very strong correlation among the aircraft in the same generation. This striking example illustrates all qualities desired for satisfying the technology differentiation criterion.

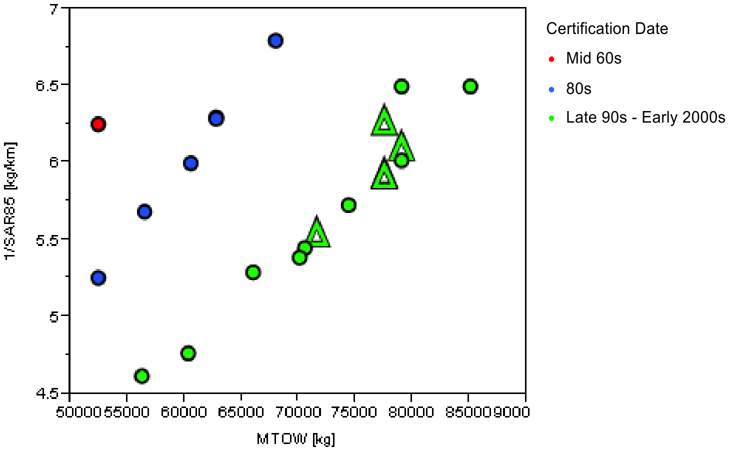


Figure 30: /SAR vs. MTOW for a SA Class Aircraft Family (triangle: business jets)

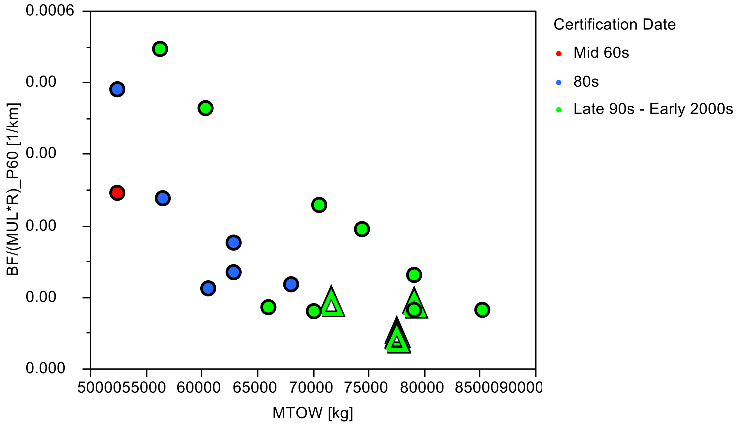


Figure 31: BF/(MUL*R) at P60 vs. MTOW for a SA Aircraft Family (triangle: business jets)

In contrast, the BF/(MUL*R) metric, does not show clear distinction of aircraft generations when associated with the MTOW CP. The first generation aircraft in red performed much better than a second generation aircraft of similar MTOW. Second generation variants marked in blue score better than most of the modern generation marked in green. As such, BF/(MUL*R) vs. MTOW would fail this criterion. In contrast, these illustrations further support the strong ability of the 1/SAR vs. MTOW metric-CP pair to meet this criterion.

Further analysis was then conducted for the 1/SAR metric for four different CPs, using in and out-of-production categories for aircraft in the SA class, shown in Figure 32. Here, all out-of-production aircraft are shown in red and all in-production aircraft are shown in blue. In addition, to distinguish certain aircraft types from passenger jets, BJs are shown in triangles, TPs are shown in open circles. All passenger aircraft including RJ, SA, STA, LTA, and LQ are shown in closed circles. While all four CP options show a degree of distinction between the in and out-of-production aircraft categories, the 1/SAR vs. MTOW pair separates the two groups best, followed by the 1/SAR vs. Maximum Zero Fuel Weight (MZFW) pair. Maximum useful load (MUL) and payload*range at R_1 (P*R_R1) show poorer ability to differentiate the two groups. In addition, MUL and P*R show slight preference towards BJs, since they are somewhat separated from and show better performance than their passenger counterparts. As such, MTOW appears the most promising CP for this class of aircraft.

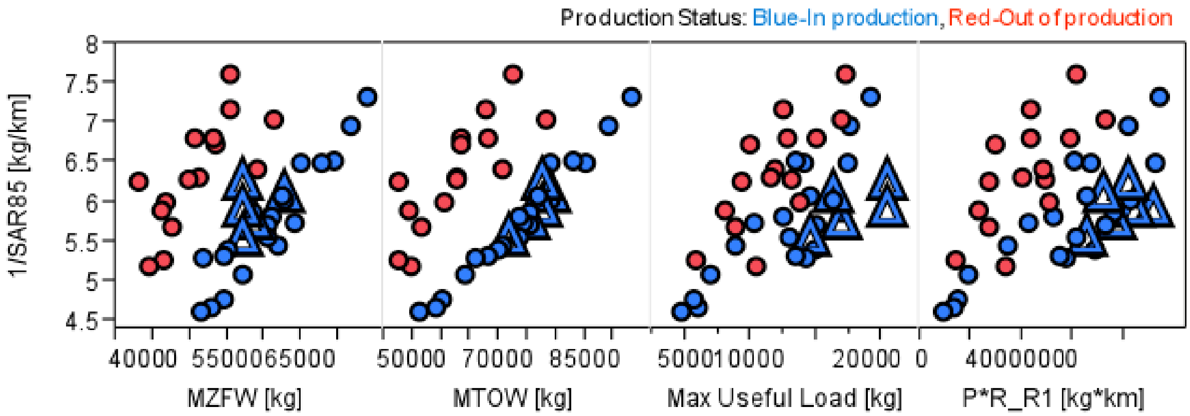


Figure 32: 1/SAR vs. MZFW, MTOW, MUL, P*R (triangle: business jets)

Identification of Promising Candidates from Results

Based on the extensive vehicle and fleet level analyses of mission fuel and instantaneous point metrics and CPs, several conclusions were made regarding the ability to meet this challenging criterion. While no single metric-CP fully satisfied evaluation criterion across the fleet, and a judgment was necessary to select the best pair, several promising candidates were identified:

- 1/SAR metric associated with MTOW as a CP appeared to be the most promising, despite its weakness of not explicitly rewarding aircraft weight reduction technologies
- BF/R metric associated with MTOW as a CP appeared to be the most promising, despite its weakness of not explicitly rewarding aircraft weight reduction technologies

Additionally, a few other metric-CP combinations were identified for further investigation and include 1/SAR with UL and BF/R with UL.

While no single metric-CP fully satisfied evaluation criterion across the fleet, and a judgment was necessary to select the best pair, several promising candidates were identified:

- 1/SAR metric associated with MTOW as a CP appeared to be the most promising, despite its weakness of not rewarding aircraft weight reduction technology.
- 1/SAR with UL as CPs was recommended for further study.
- BF/R with MTOW, UL, FL*R, or P*R as CPs were recommended for further study.

Fairness across Sets of Stakeholders

To the extent possible, a combination of metric, correlation parameter and evaluation condition should be fair to all stakeholders. However, the evaluation of fairness is highly dependent stakeholder viewpoints and generally requires a value judgment. The same metric may be fair for one stakeholder but unfair for another. Within the context of this study, the team assumed that fairness implied that no particular manufacturer or aircraft type was unduly segregated from the rest. As an example, on the left hand side of Figure 33, the plot depicts the fuel efficiency performance (based on the BF/P*R; and BF is depicted as fuel energy) across the aircraft spectrum from business jets to wide body aircraft. Based on this metric, the performance of business jets stand out compared to the rest of the fleet (because of lower payload than other aircraft categories). As a result, this metric may be perceived to be unfair to the business jet aviation industry, but fair for the turboprops or regional jet industry. Another metric (e.g. BF / MTOW*R) as shown on the right hand side could appear to be fair for the business jet industry.

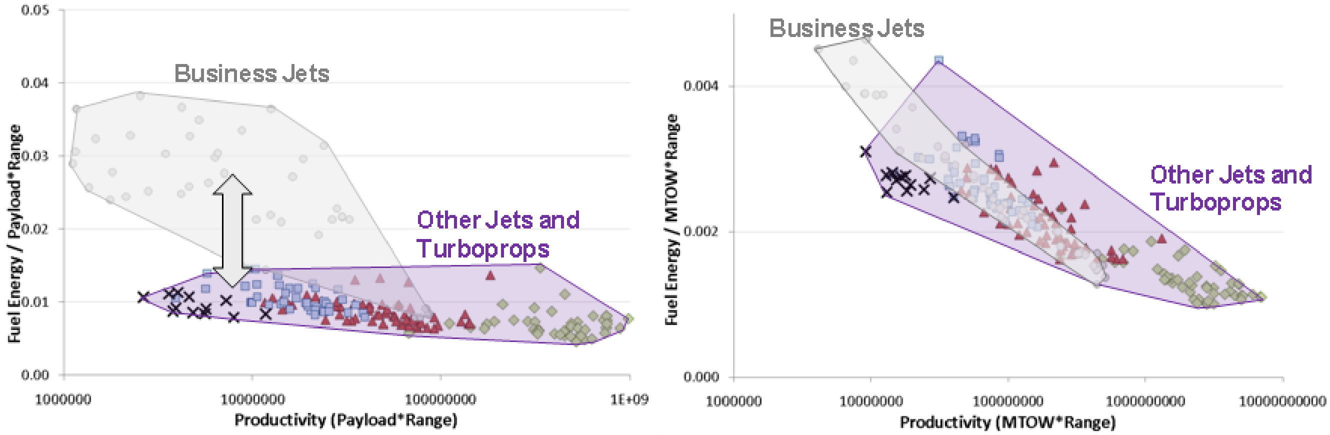


Figure 33: Variation of performance spread between business jets and other aircraft types [11]

To a first order, "fairness" is defined based upon the relative performance between groups of stakeholders. For the purpose of this project and analyses, potential for fairness issues is evaluated through "performance spread" across sets of stakeholders and whether or not the metric-CP pair can capture all possible aircraft within the fleet. The "performance spread" in this context is defined as whether or not all manufacturers or aircraft types fall in line with a trend line of the metric-CP and are not segregated from the rest of the fleet. The "fairness" was evaluated and compared across aircraft categories and categorized into 5 groups (i.e. business jets, turboprops, regional jets, narrow body jets, wide body jets). It was found that the MTOW and useful load metric limit the "unfairness" between aircraft categories, and thus, manufacturers, as depicted in Figure 34.

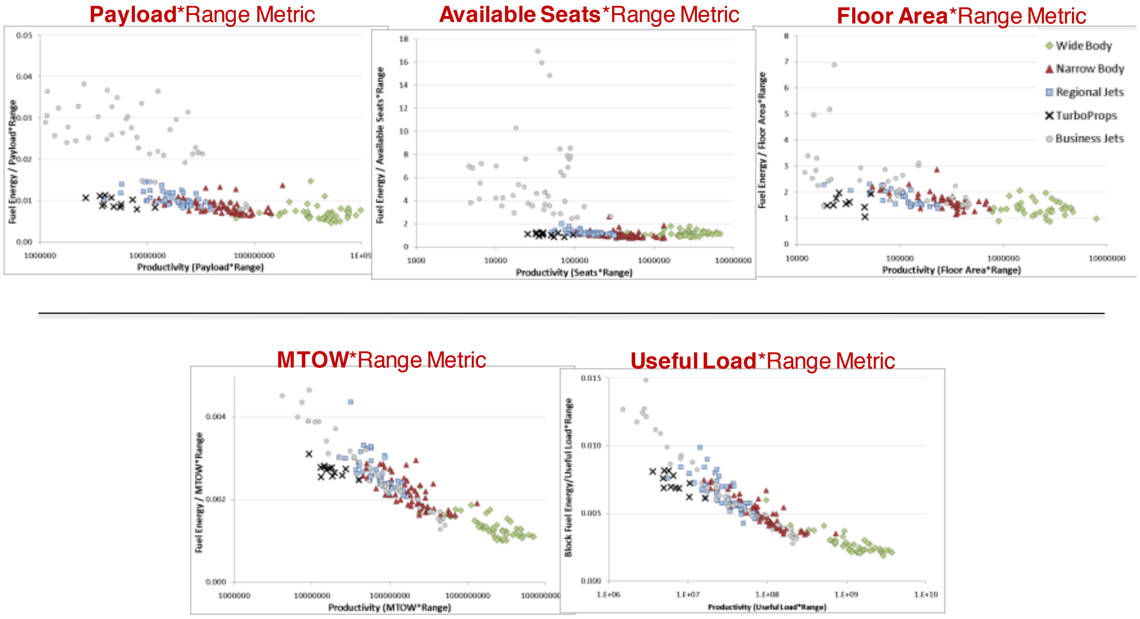


Figure 34: Comparison of "fairness" for aircraft types for several metrics (as a function of productivity) [11]

The reduced ”fairness” between business jets and the rest of the fleet (as opposed to other metrics such as payload) is explained by the differences in weight fraction distribution across aircraft categories based on the chosen metrics and CPs. As shown on Figure 35, business jets have a low maximum payload fraction (i.e. 12% of MTOW) where as its useful load fraction comparable to other aircraft categories (i.e. Business Jets Useful Load = Average Useful Load across all aircraft categories = 44%).

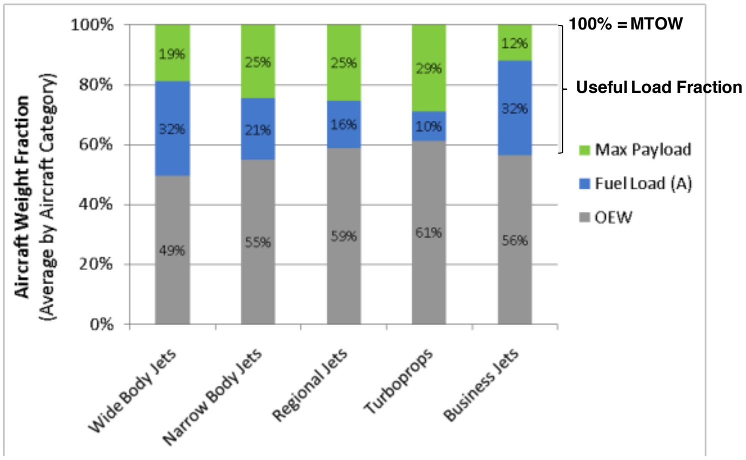


Figure 35: Aircraft weight fractions across categories of aircraft

Metrics containing 'MTOW' and 'Useful Load' were observed to be most fair across stakeholders.

Limit Potential Unintended Consequences

The use of poorly defined metrics to establish policies used to set certification requirements can result in negative or perverse effects [20] and the emergence of unintended consequences on aircraft designs and configurations. These unintended consequences or outcomes have the potential to reduce the effectiveness of the originally intended policies and as a result, need to be assessed during the development process of a certification requirement to insure its effectiveness. Illustrations of unintended consequences of standards include -in the automobile industry-, the emergence of the SUV class of vehicle that was not covered by the CAFE standards. In the airline industry, the use of operational data reporting procedures using the Aircraft Communications Addressing and Reporting System (ACARS) system have resulted in unintended safety problems for ground crews due to pilots releasing parking brakes while staying at the gate to “trick” the ACARS system.

Using both aircraft performance modeling and interviewing stakeholders, potential responses to a standard and their effects are identified and discussed below. Unintended consequences can emerge as a response to three characteristics of the standard; (1) the metric, CP and evaluation conditions definition, (2) the certified level and (3) the scope of applicability of the standard. The following section addresses potential unintended consequences that have the potential to emerge due to metric, CP and evaluation conditions. The definition of the metric (i.e. parameters used to define the metric) has the potential to alter design optimization gradients that guide the design of current and future generations of aircraft and result in unintended fuel burn performance effects.

Instantaneous performance metrics

A CO_2 certification requirement could be based on a single parameter -instantaneous performance metric- such as SAR. Given that this metric measures the performance at one point of the cruise portion, it does not explicitly cover fuel burn performance during other phases of flights (e.g. climb and approach). As a result, there may be a perception that designing aircraft that meet the certified level at cruise but would exhibit lower performance during other phases of flight compared to full mission metrics. However, from a physical perspective, SAR is fundamentally related to total mission fuel burn. Thus, this issue may not be of a major concern.

Full mission based metrics

Among the set of two parameter metrics, several potential unintended consequences can be envisioned. First, the inclusion of two parameters in the productivity metric implies a relative trade-off between the two parameters (e.g. payload vs. range). However, while constructing a metric for a future certification requirement. It should be acknowledged that aircraft types are designed according to specific design philosophies and objectives that reflect market requirements. The maximum structural payload as a function of range R_1 for wide body jets down to small business jets is shown in Figure 36. While turboprops, regional jets, narrow body and wide body jets follow the same trend lines (scaled due to aircraft size differences), business jets tend to be designed with greater emphasis on range rather than payload.

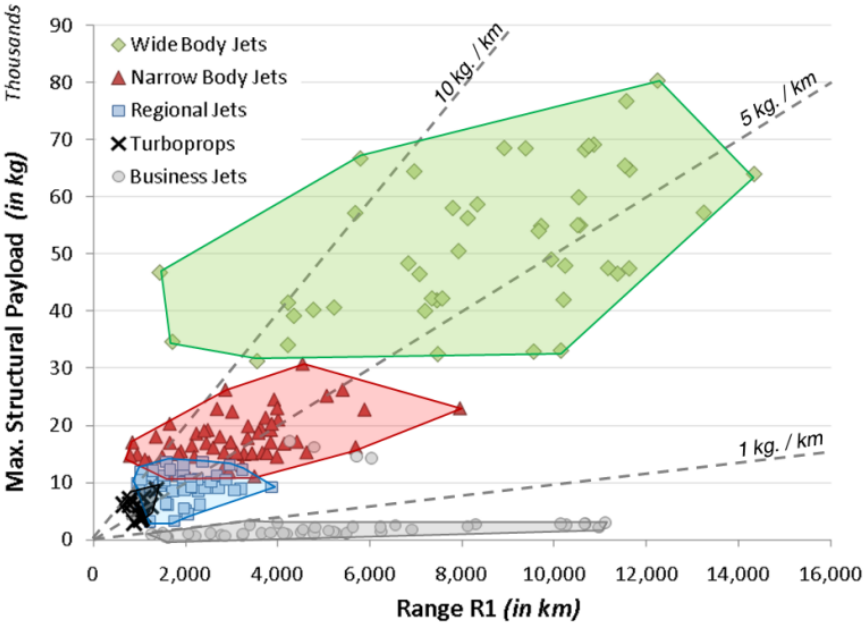


Figure 36: Payload vs. Range combinations capturing different aircraft design philosophies with regard to payload vs. range [11]

This observation was confirmed by interviews with stakeholders (i.e. aircraft manufacturers) representing various aircraft categories. There is therefore the need to take into account these design philosophies in the analyses of effects of metrics on future aircraft designs and performance. Second, the inclusion of specific aircraft characteristics (i.e. measure of what is transported) in the productivity factor provides specific design incentives that have the potential for unintended consequences, such as:

- The metric based on Payload*Range, -due to its preference for high payload, low range designs-, could incentivize the development of this type of designs if a measurement scheme is not chosen carefully
- The metric based on Useful Load*Range could incentivize the development of aircraft with lower payload fraction and longer stage lengths (fuel fraction)
- The metric based on MTOW*Range, limits the incentives to reduce OEW, compared to other metrics such as payload-based metric
- The implementation of the Floor Area*Range based metric could incentive the development of aircraft with “unproductive” floor area (e.g. raising floors of existing tube concept aircraft to gain cabin width, or lengthening of fuselage that could offset improvements in OEW reductions)
- Finally, the metric based on Available Seats*Range, has the potential to result in the certification of aircraft with a maximum number of seats that would later be reduced to a fraction of this number for operations.

Additionally, the inclusion of speed in the metric provides different incentives to aircraft manufacturers compared to other metrics. With speed included in the denominator of the metric (i.e. distance*measure of what is transported*speed), manufacturers have incentives to evaluate and certify fuel efficiency performance at higher cruise speeds as shown in Figure 37. It was determined that metrics of this nature (and associated higher speed assumptions) would result in an approximately a 1% inefficiency penalty compared to other metrics for a given aircraft design.

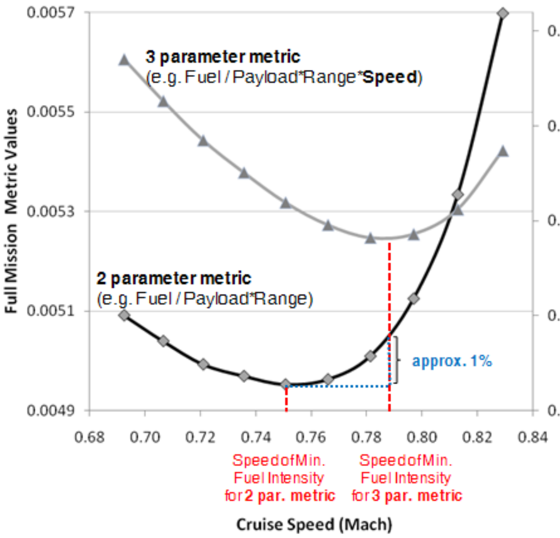


Figure 37: Sensitivity of Aircraft Fuel Intensity to Speed (effects of two parameter vs. three parameter metric based optimization)

It should also be noted that from a design stand point, the inclusion of speed in the metric could significantly disincentive aircraft manufacturers to design aircraft with lower cruise speed (and that have the potential for providing significant environmental performance improvements [21]. These findings suggest that including speed in a CO_2 metric may result in negative unintended consequences on environmental performance.

All metrics may have opportunity for unintended consequences if all aspects of certification not handled appropriately. 1/SAR may be least prone to unintended consequences due to its insensitivity to aircraft types and choice of evaluation option.

Accurately Reflect CO_2 Emissions and Fuel Burn at the Aircraft Level

Due to market demands, ATC constraints, and operator inefficiencies, aircraft are not always flown where they exhibit the best fuel performance. Aggregate 2006 BTS data [22] scatter plots (Figure 38) show that the aircraft is operated very frequently at payload and range combinations much lower than R_1-Maximum Structural Payload (MSP), resulting in reduced fuel efficiency during operations. As a result of this insight, the ICAO 2006 Common Operations Database (COD) [23] was utilized to evaluate the observed frequency of operations for each aircraft type. Figure 39 is an operational pattern indicative of most short haul aircraft. Aggregate analysis was conducted across each aircraft category to gather information about trends based on aircraft size and configuration. Figure 40 shows that smaller aircraft tend to operate a higher percentage of their missions at lower, more inefficient range fractions. Because many aircraft are flying well below their optimal range point, there may be efficiency losses due to the way the aircraft are operated by various operators.

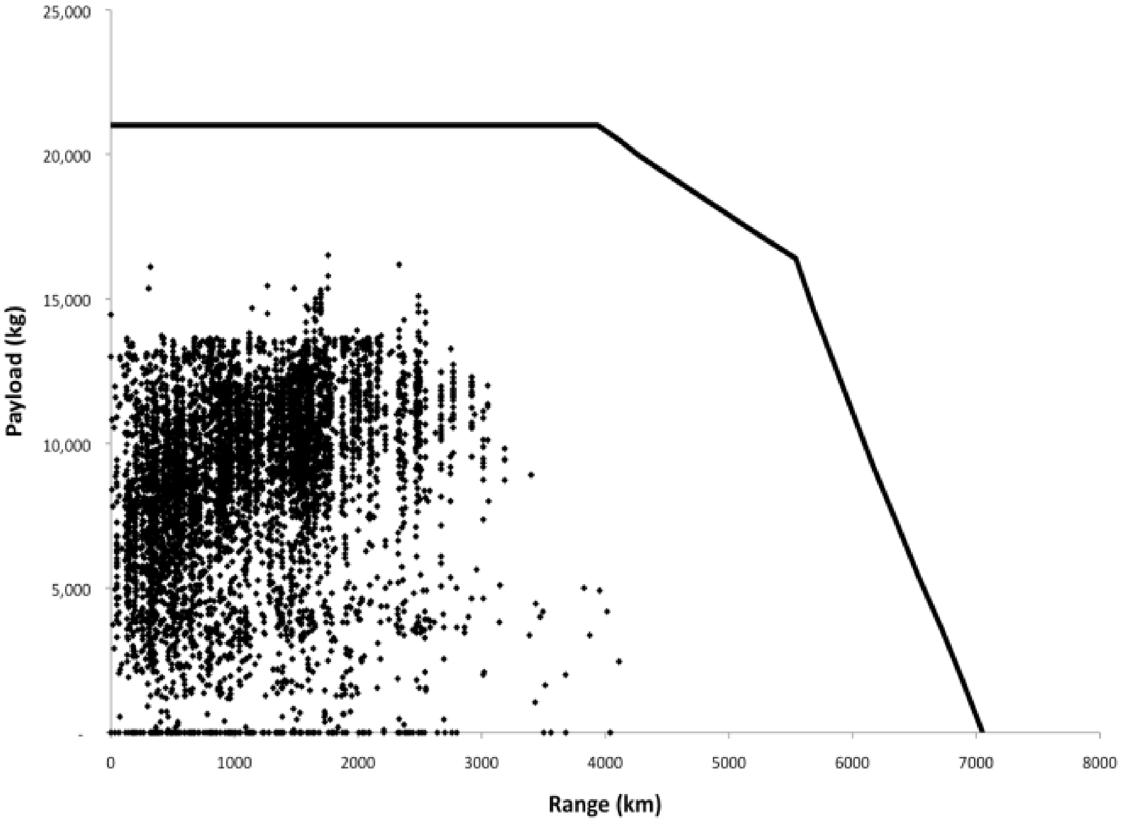


Figure 38: BTS 2006 Form 41 T-100 Actual Operations for 737-800 [22]

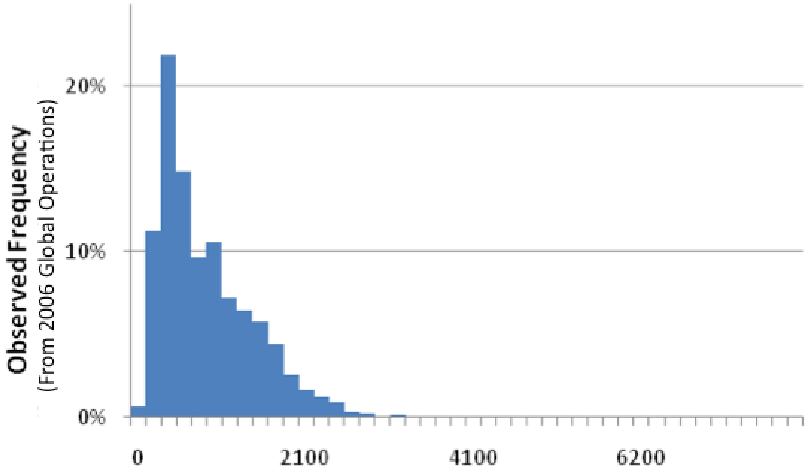


Figure 39: Frequency of ranges for 737-800 model for 2006 global operations [23]

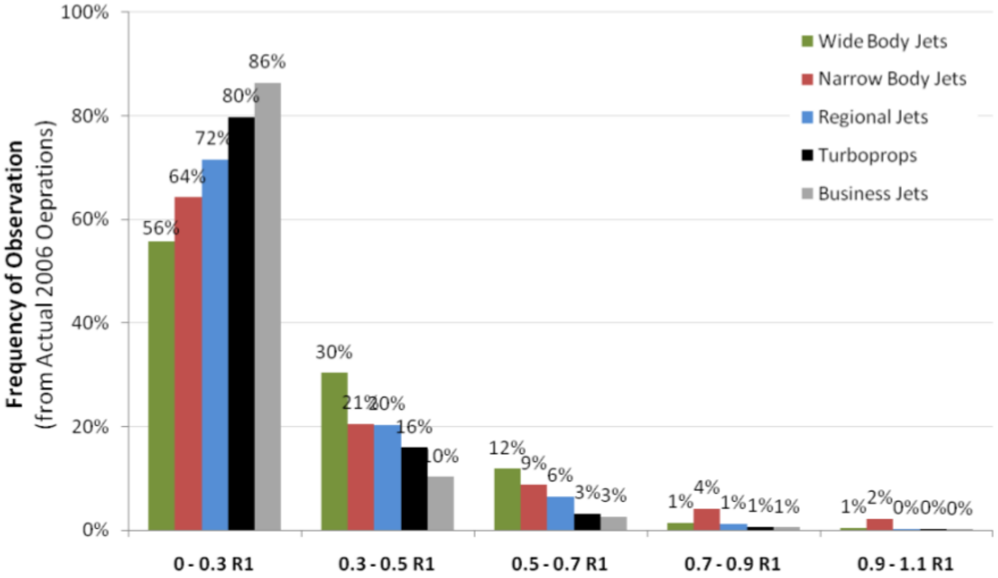


Figure 40: Observed frequency of fractions of R_1 from global 2006 operations [23]

A similar analysis was conducted for all passenger and passenger-freight mixed flights (cargo filtered out) in the BTS form 41 T-100 database for 2006. Passengers were allotted 200 pounds (90.7 kg) each and all belly freight and mail were accounted for in the payload fraction. The different aircraft categories in Figure 41 exhibit widely varying operational frequencies with most of the operations occurring well below the optimum MSP point. Again, there may be efficiency losses due to the way the aircraft are operated by different operators.

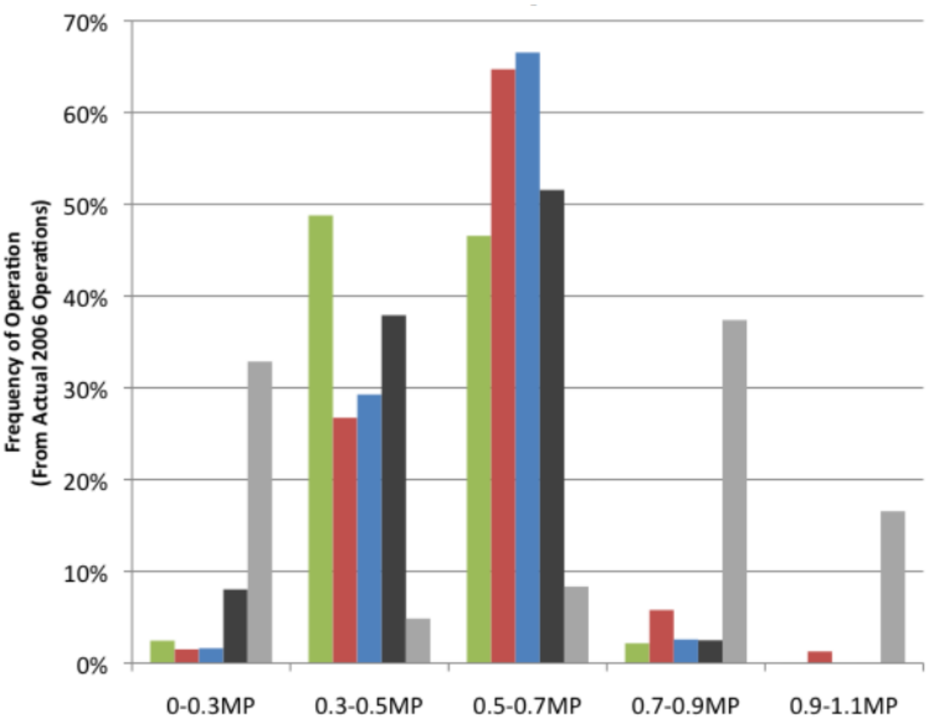


Figure 41: Frequency of observed operational payloads [23]

BTS form 41 T-100 data does not report the amount of fuel consumed for each entry. T-2 data, which is much more highly aggregated (7,000 entries as opposed to 430,000+), reports fuel consumption for a few aircraft types. This data proved to be too sparse to provide adequate coverage of the operational fleet. Thus, in order to obtain takeoff weight distributions it was necessary to combine both the performance data from Piano-X with the operational data from BTS form 41 T-100. Payload and range combinations from BTS were fed into a bi-cubic interpolator which used the 30 fuel performance mission simulations for each aircraft type to calculate the amount of fuel required to complete that mission (given the standard diversion, holding, and contingency assumptions). The relative uniform distribution of useful load factors in Figure 42 leads to a potential assumption of 50% load factor as a starting point for metric evaluations.

This data was also used to support the evaluation of SAR as a potential metric. Because SAR only requires the assumption of an instantaneous gross weight and associative atmospheric conditions, it is helpful to understand typical aircraft take off weights. Selecting a takeoff weight has mission implications, as each takeoff weight is associated with multiple combinations of payload and range. Thus, there exists a mission dependence on takeoff weight. If a defendable takeoff weight assumption were known, further assumptions as to the value of mission payload and range could be made. Because of the relative uniform distribution amongst aircraft categories and the fact that the weighted average takeoff weights are so closely related (see Figure 43), a first-level approximation of 85% MTOW could be made in order to more closely evaluate use of SAR as a CO_2 emissions metric for certification.

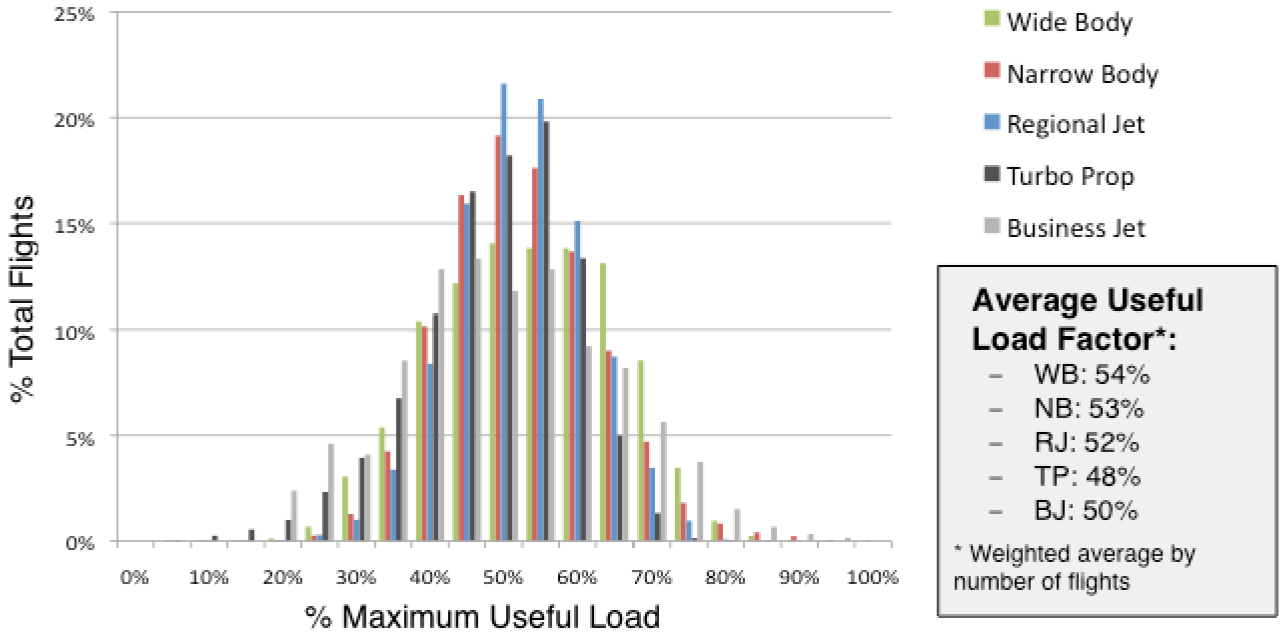


Figure 42: Frequency of observed BTS database operational useful loads.

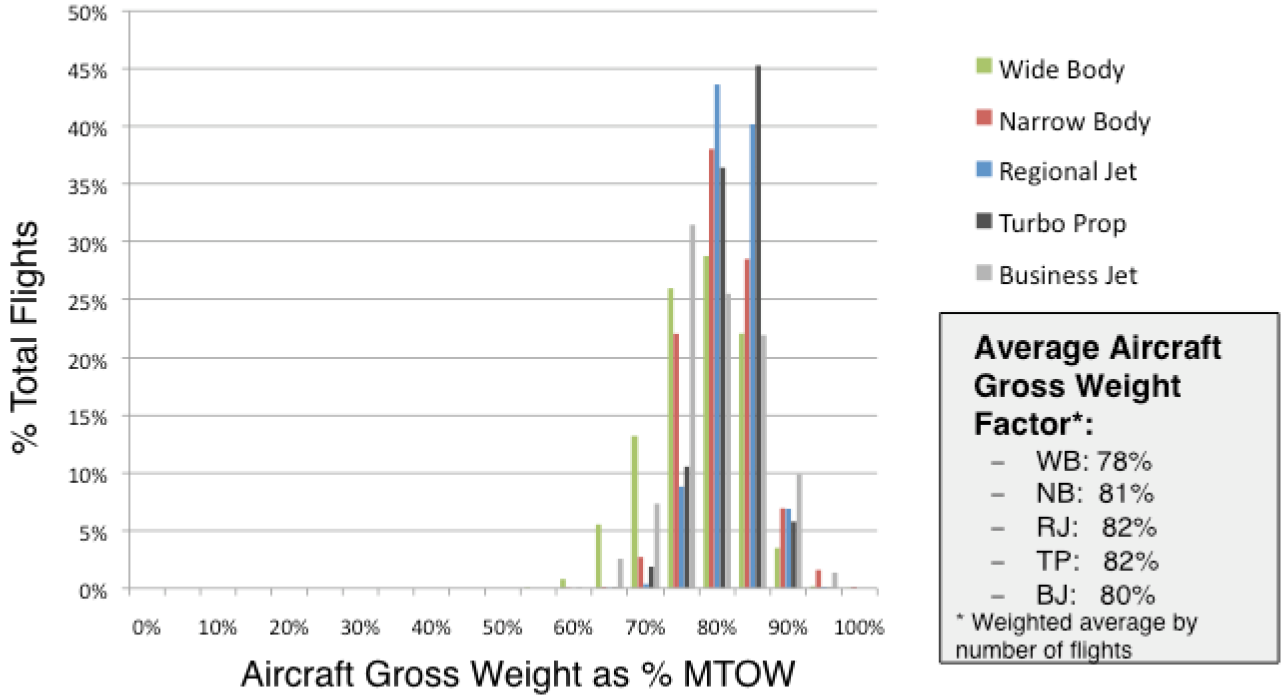


Figure 43: Frequency of observed BTS database operational takeoff weights.

As such, Piano-X simulations at varying ranges and maximum payload were completed for all 217 aircraft using the above assumptions and criteria. For each mission, the fuel burn was noted and used to calculate values of metrics at those specific payload and range combinations. Thirty missions were flown for each aircraft in the smaller subset of 147 aircraft types appearing in both the BTS and Piano-X database. Each mission corresponds to a fraction of maximum structural payload (MSP) and R_1 range. Fuel burn at each of the thirty grid points was noted as a result of the aircraft simulations.

Fuel grid data is used to calculate the value of metrics at each evaluation point, and also to serve as interpolation inputs for missions that occur off of grid points. Figure 44 is an illustrative use of this data to show sensitivity to mission (payload and range) for two different aircraft types (one short haul and one long haul). Fuel efficiency performance is measured in terms of BF/P*R, which does not necessarily reflect trends for other metrics. The Boeing 737-800 exhibits its best fuel performance on this metric at the Max Payload-R_1 operating point. However, a Boeing 777-300ER exhibits it best fuel performance at a Max Payload but a fraction of R_1 (i.e. approximately $0.4R_1$). Additionally, both aircraft exhibit declining fuel efficiency as the fraction of MP is decreased. Both of these phenomena are explored in greater detail.

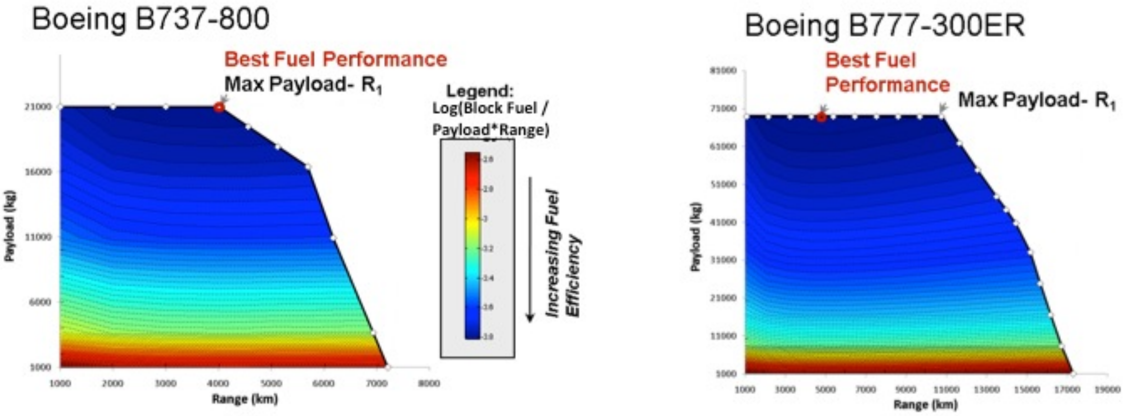


Figure 44: Illustration of fuel efficiency sensitivity to payload and range for short and long haul aircraft.

Sensitivity to range was evaluated by observing the fuel burn data at 100% MSP and varying ranges. This analysis was conducted at 20%, 40%, 60%, 80%, and 100% fractions of R_1. In Figure 45, a Boeing 737-800 is shown on the left hand side to illustrate aircraft that perform best at Max Payload-R_1 and a Boeing 777-300ER is shown on the right to illustrate aircraft that perform best at Max Payload - Fraction of R_1. Figure 46 shows that the aircraft within these two sets are largely dependent on the R_1 range of the aircraft. Aircraft that tend to operate best at Max. Payload-R_1 are generally aircraft with R_1 below 4000km and aircraft that exhibit the pattern of best fuel efficiency performance at Max. Payload - Fraction of R_1 have design ranges above 4000km.

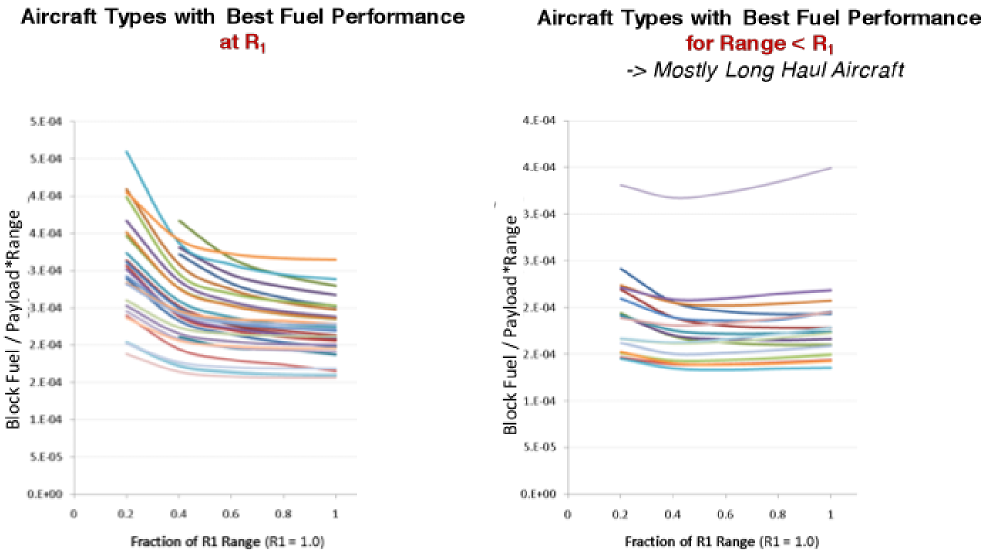


Figure 45: Sensitivity of aircraft certified fuel performance as function of deviation from R_1 range.

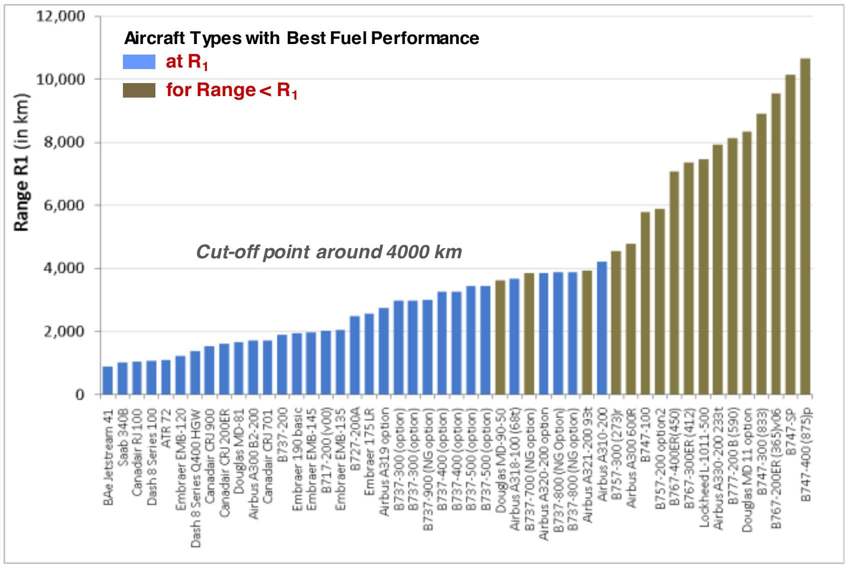


Figure 46: Range R_1 across aircraft types with best fuel performance at R_1 or below R_1

It is clear that any deviation from the operating point of best fuel efficiency performance will yield to a “loss of efficiency”. The impact of this efficiency loss can be evaluated using operational data that appear in a later section. A similar analysis was conducted using a constant R_1 range and varying payload fraction. As shown in Figure 47, any deviation from 100% MP will yield to a “loss of efficiency”. It is again clear that aircraft operational performance is highly dependent on the characteristics that define each mission.

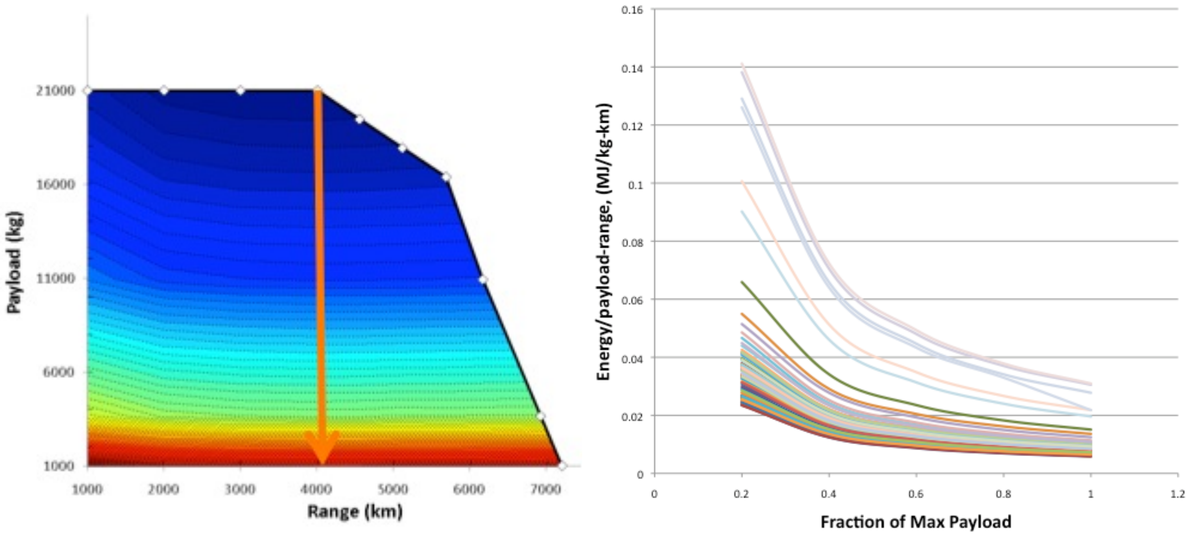


Figure 47: Sensitivity of aircraft performance as function of deviation from maximum payload.

Due to changing aerodynamic forces with speed and the relation between speed and distance, there exists some optimal aircraft speed at which range is maximized. Figure 48 is an illustration of how metric values change as a function of the cruise speed for a Boeing 737-800. The dashed redline indicates the 737-800's Maximum Range Cruise (MRC), and the approximate point at which each of the metrics is minimized. This MRC speed varies for widely amongst aircraft category and amongst aircraft types within each category. For this reason, it may not be appropriate to define a speed at which a multitude of aircraft should fly a certification mission. A more equitable approach would be to allow manufacturers to certify their aircraft at a speed that they determine minimizes the value of the metric or meets the market needs.

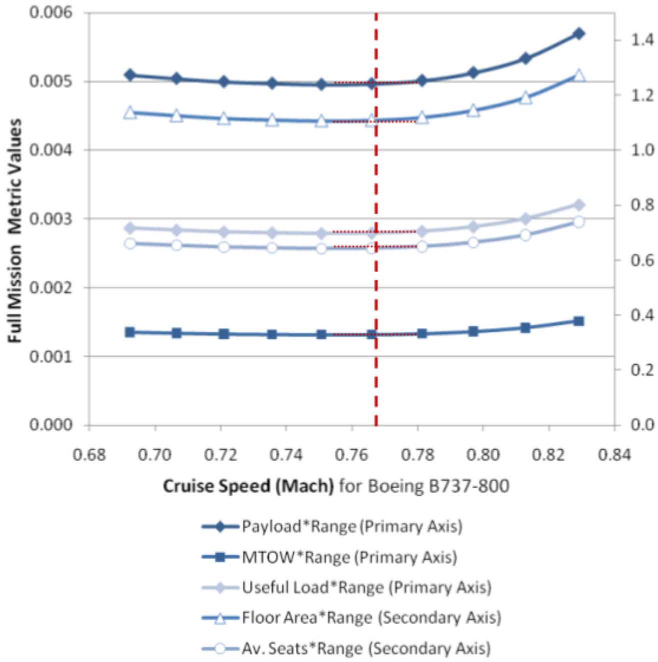


Figure 48: Sensitivity of aircraft fuel performance as function of Mach number.

The effect of including speed within the metric has been well established as a decision with potential negative consequences due to the inability to forecast cost index and the penalty imposed to slower and potentially more fuel efficient aircraft, yet, penalizing the utilization of the aircraft on a daily schedule basis. A speed sensitivity analysis was also conducted. Figure 37 is an illustrative example of the incentive manufacturers would have to fly at higher cruise speeds due to a new metric-optimal flight speed. The resulting loss in efficiency from flying at the higher speed is on the order of 1%.

Due to dynamic aircraft weight throughout the mission resulting from fuel burn, and decreasing air density at higher altitudes, aircraft performance at any point in the mission is dependent on flight altitude. For every aircraft type, configuration, and flight condition (i.e. speed, weight, etc) there exists an optimal altitude. As the mission progresses and the aircraft becomes lighter, this optimal altitude increases. Optimal flight performance is attained by a gradual, continuous climb pattern (Figure 49); however Air Traffic Control (ATC) restrictions limit flight profiles to discrete levels. The compromise between ATC restrictions and optimal fuel performance has led to the adoption of staged-climb profiles in which aircraft cruise short segments of the mission at an increasingly higher altitude. Stage-climb profiles result in decreased efficiency, increased fuel burn, and thus an exacerbated environmental impact. All three altitude schemes were investigated to develop defendable rationale for certification mission assumptions.

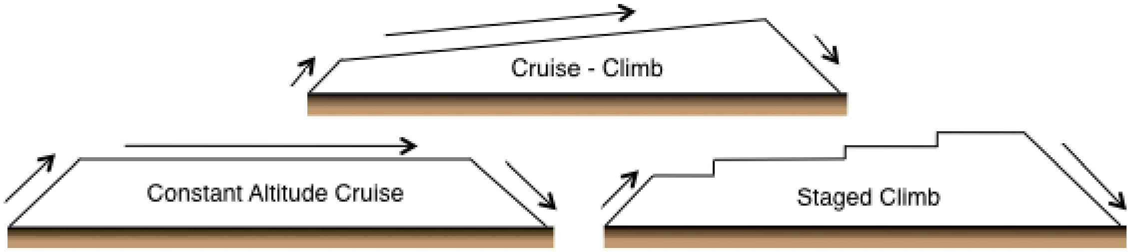


Figure 49: Illustration of three generic flight profiles.

One representative aircraft was chosen from each category as an illustration of fuel intensity sensitivity to altitude across varying aircraft types. Each aircraft flew at MSP and $0.2*R_1$. It's apparent from Figure 50, in which aircraft were flown on varying constant-altitude missions, that there exists a clear coupling between optimal flight level during constant-altitude cruise and aircraft type. Thus, setting a common altitude across all aircraft types may introduce significant discrepancies between certified and operational performance. However, the benefit of staged versus constant altitude cruise was evaluated by flying each representative aircraft at MP and $0.75*R_1$. Most aircraft in Figure 51 exhibit a benefit from flying a staged pattern, with the magnitude of that benefit seeming to increase with R_1 range within each category.

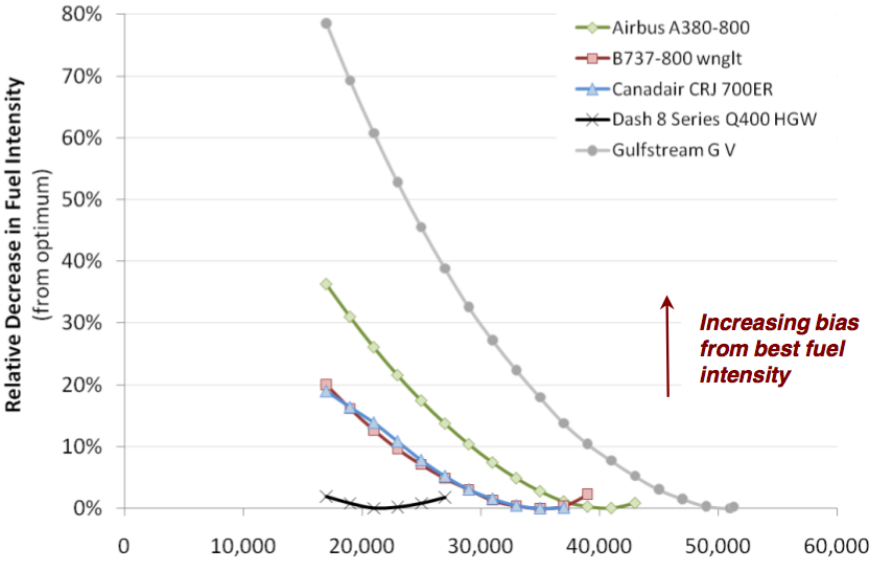


Figure 50: Sensitivity of aircraft fuel performance as function of flight level.

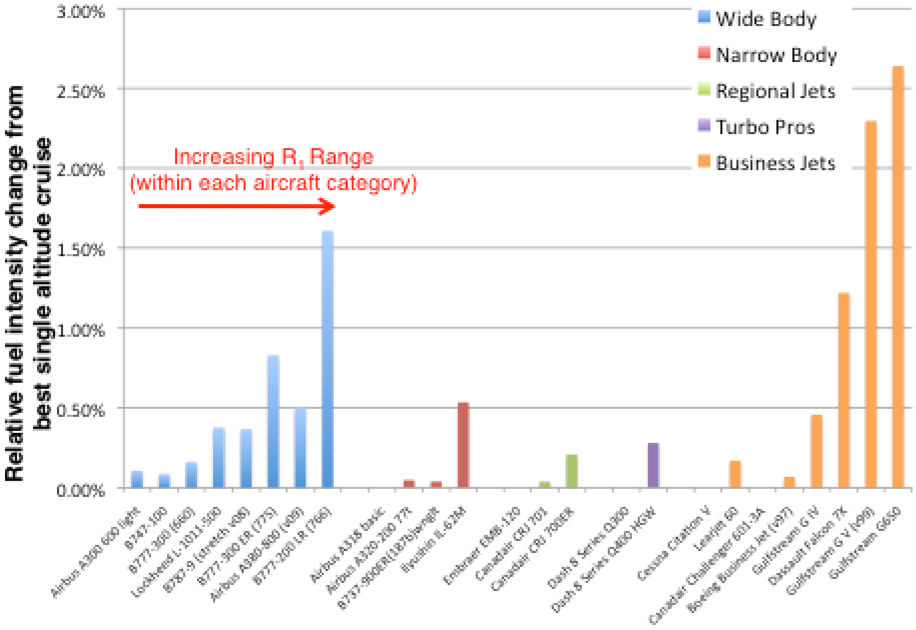


Figure 51: Benefit of staged cruise over constant altitude cruise for varying aircraft types.

This is likely due to the fact that longer haul aircraft spend a larger fraction of mission time in cruise and can take advantage of more staged flight levels throughout the cruise, thus more closely replicating an optimal cruise-climb mission. Because of the varying difference across aircraft types, it's unlikely that identifying a staged altitude scheme for all aircraft types is feasible. It therefore might be more equitable to allow flights at manufacturer-determined optimum staged or constant vertical profiles while still meeting ATC constraints.

Next, 1/SAR was investigated for similar aspects. The 1/SAR variation with speed and altitude is a complex relationship driven by aircraft design philosophy, technology, and performance characteristics, and is unique to each aircraft. Figure 52 shows how 1/SAR varies as function of both speed and altitude for a representative narrow body aircraft.

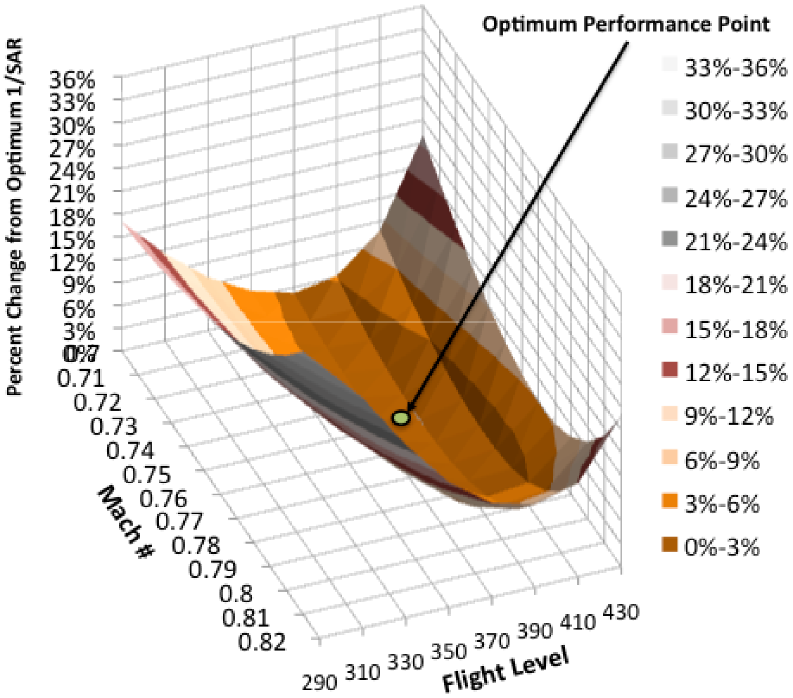


Figure 52: 1/SAR percentage changes from optimum as a function of speed and altitude for a representative narrow body aircraft

Because aerodynamic characteristics and engine performance change with speed, there exists some optimal aircraft speed at which aircraft fuel intensity is optimum. As a result, the 1/SAR value (as well as CO_2 emissions per mile travelled) is minimized. This speed is defined as Maximum Range Cruise (MRC) and is also known in the industry as 100% SAR speed. 100% SAR varies widely amongst aircraft categories (from approximately Mach 0.4 for turboprops to over Mach 0.8 for wide body jets). Due to this variation, identifying and setting a unique speed at which all aircraft should fly during a certification test would introduce a significant bias in 1/SAR measurements and would favor certain aircraft types. Recognizing the fact that airlines will attempt to operate aircraft at speeds not too distant from optimum (i.e. generally between 100%SAR and 99%SAR), a more reasonable and equitable approach would be to allow manufacturers to certify aircraft at a speed that minimizes the value of 1/SAR. This approach requires the definition of an evaluation weight, while allowing freedom to optimize speed, altitude, center of gravity, and trim.

Another aspect of testing metric performance against this evaluation criterion was to determine whether or not an improvement in a single point evaluation would translate to improvements in actual operations. This would provide insight not only to the metric and CP under consideration, but also provide evidence for the environmental effectiveness of single point evaluation conditions when the actual aircraft is fielded and operated day to day by different airlines. In order to assess the existence of relationship between the instantaneous metric 1/SAR and a reduction of CO_2 emissions of day to day operations, the FAA's EDS tool was employed with the EDS SA and LTA aircraft. For this study, the impact of a 10% fuel flow reduction technology was investigated in order to determine if an improvement in the 1/SAR metric value would correspond to improvements in the CO_2 performance of the vehicle at reduced ranges, thus representing potential day-to-day operations.

There is a caveat to this analysis: it should be understood that implementing advanced technologies inherently changes the capability of an aircraft. More specifically, there is a limited possibility that a manufacturer could maintain all boundaries of a baseline payload and range envelope exactly based on the infusion of an engine or aerodynamic efficiency improvement technology. For instance, the slope of the MTOW limit that connects R_1 and R_2 is governed by thrust-specific fuel consumption (TSFC) and lift to drag (L/D) via fundamental physics of flight. This suggests that technology infusion must be accompanied by an inevitable change in the MTOW limit. In order to alleviate potentially biasing of the results, efforts were made to keep the advanced vehicle payload and range capabilities as close to those of the baseline vehicle as possible by designing the vehicle to the same design payload and design range, in addition to the maximum payload, fuselage geometry, cruise speed, and fuselage fuel capacity. However, this approach only ensures that two conditions on the payload-range diagram remain constant, specifically, the design point (design payload and range) and the maximum structural payload (MSP) limit. The envelope conditions will change from R_1 to the maximum range as shown by: the change in slope between R_1 and R_2; the change in position of R_1 and R_2; and the change in maximum ferry range capability. The EDS SA and LTA were subjected to a 10% TSFC reduction and resized for minimum MTOW while meeting the payload and range of the original design point and all other design constraints, including field lengths, second segment climb gradient and top of climb excess thrust as examples.

The payload-range diagram for the technology-infused vehicles, shown in red, compared to their respective baselines which are shown in blue as depicted in Figure 53. The vehicle design mission was fixed for each vehicle and is shown for reference in green. The design payload is defined as a full cabin loading of a representative two class seating arrangement, more specifically 95.2 kg per each passenger multiplied by 174 passengers for SA and 301 passengers for LTA. The design range for both the baseline and the advanced technology vehicle was fixed 5,463 km for SA and 13,778 km for LTA.

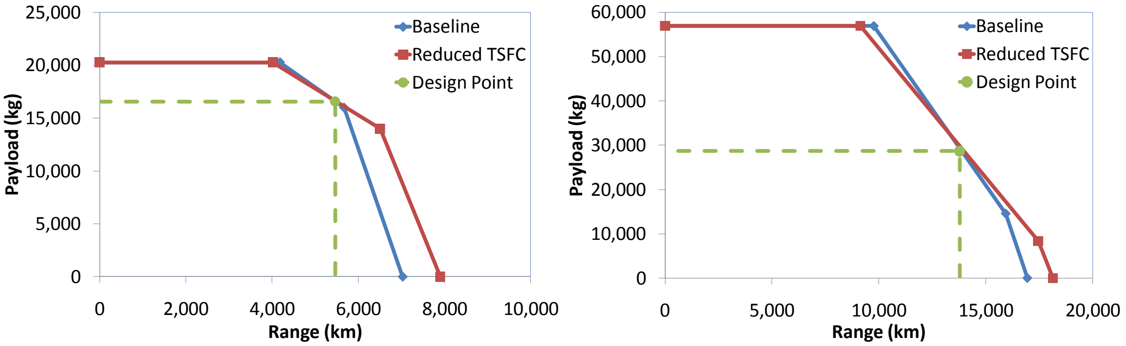


Figure 53: Payload-Range Diagram Shift for 10% Fuel Flow Reduction for SA (left) and LTA (right)

To understand the improvements on potential day-to-day operations, the baseline and advanced vehicles were designed to the payload-range capability specified earlier and flown at a sweep of five operational mission distances (at 20%, 40%, 60%, 80%, and 100% of the design range). Using the EDS tool, the block fuel for each mission distance was evaluated. Additionally, 1/SAR was evaluated at three different vehicle weights (75%, 85%, and 95% MTOW). As a point performance parameter, 1/SAR was assessed at best altitude and Mach number at standard atmospheric conditions. The resulting metric improvements after technology implementation were compared to baseline metric values, and the corresponding percent changes are depicted in Figure 54 for the SA (SA at left, LTA at right). For the EDS SA aircraft, the percent improvements in these metrics vary from approximately 11% to 13% over the mission distances, with the greatest benefit occurring at the design range (denoted in both plots as BF at 100% Design Range). 1/SAR improvements over baseline values do mimic the percent improvements in block fuel; however, the resulting improvements in these 1/SAR metrics are slightly higher than the block fuel improvements. The EDS SA aircraft at the design range revealed a percent improvement in block fuel of approximately 12% while the percent improvement in 1/SAR at this range was 15%. While the block fuel and 1/SAR impacts are not identical, the results do illustrate the strong ability of 1/SAR to capture beneficial technology improvements that can reduce fuel burn over the different operational stage lengths, even when the mission lengths are short and fuel burn is significantly influenced by climb performance. For the EDS LTA, the percent improvements in block fuel are in the range of 14% to 16%. At the design point, the block fuel improvements are slightly under 16% while the 1/SAR improvement is closer to 17% at 85% MTOW. As with the SA, the 1/SAR improvements are slightly higher than the block fuel improvements, but they do show a similar behavior.

These similarities suggest that although 1/SAR is a point performance metric, improvements at this single point appear to translate to improvements in block fuel on potential operating conditions. Furthermore, the percentage improvements in 1/SAR metric and block fuel are proportional. These results provide further support that an improvement in 1/SAR at 75%, 85%, or 95% MTOW (in the context of a certification requirement) would translate into improvements (i.e. reductions in fuel burn) in day-to-day operations.

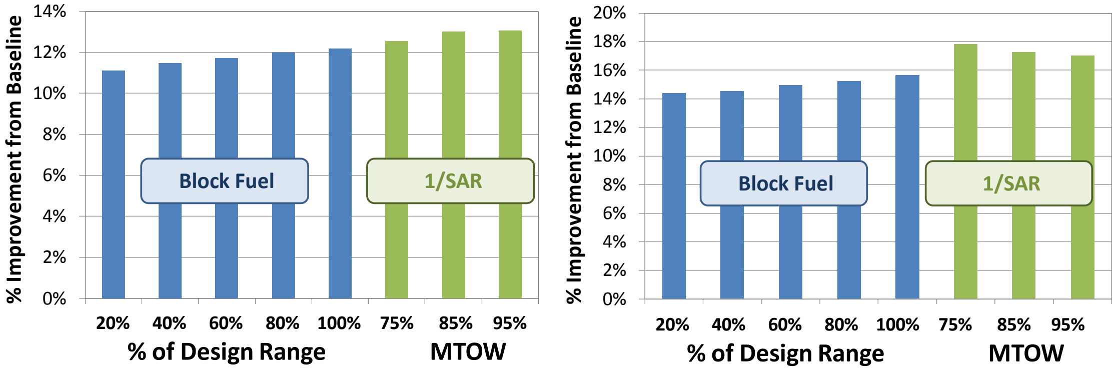


Figure 54: 10% Fuel Flow Reduction for EDS SA (left) and LTA (right)

Performance for mission fuel metrics varies widely across different missions. Improvements in 1/SAR translate to improvements in mission fuel for a variety of missions.

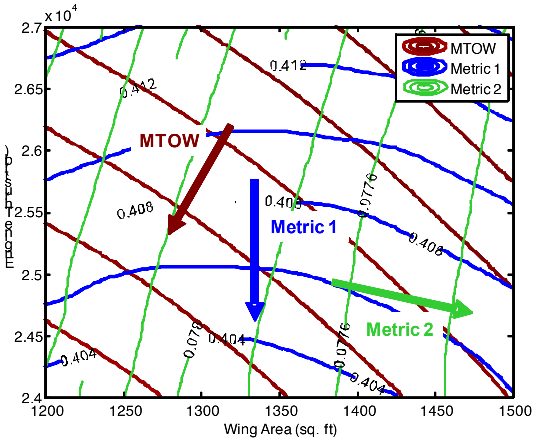
Mission fuel evaluation conditions should be based on manufacturer-optimized cruise speed and flight profile, while evaluation conditions for 1/SAR should based on a defined vehicle weight and manufacturer-optimized altitude and speed. With appropriate evaluation conditions, both mission fuel and 1/SAR metrics can accurately represent CO_2 emissions and fuel burn at the aircraft level.

Contribute Positively to Environmental Benefits

In order to limit potential adverse incentives and to maximize fuel burn and CO_2 reductions, it was necessary to analyze the potential effects of the adoption of candidate metrics on future vehicle designs. One way to ensure benefits at a vehicle level was to evaluate the alignment of candidate metrics with traditional design objectives of minimized takeoff weight and fuel burn. Metric gradients highly aligned with objectives like fuel burn would be likely to produce actual fuel burn improvements if simultaneously considered in the design process. Metrics not aligned with objectives like fuel burn may not produce any fuel burn improvements in future designs. As described previously, this alignment was analyzed in three ways which provided a comprehensive view of the impacts of candidate metrics.

Local Sensitivity Analysis

The local sensitivity assessment (LSA) test measured the degree of alignment between sensitivity of a CO_2 metric and Block Fuel at a reference point. In this case, the reference was the calibrated EDS representation of a specific in-production aircraft and engine combination. Higher alignment between the two responses indicates a metric would drive block fuel burn more directly. This alignment was calculated as an inner-product gradient, where a maximum value of "1" implied perfect alignment, and "-1" implied completely opposite trends. Greater alignment between metric and block fuel sensitivity was desired, as that metric was more likely to be effective at reducing fuel consumption at the vehicle level. An example of this type of sensitivity analysis is shown in Figure 55 This analysis represents a 150-passenger vehicle at the 'design point' near R_2 and shows the improvement directions of all these objectives in one slice of the design space. The point in the middle of the chart represents the baseline configuration of this vehicle, and the contours correspond to vehicle responses provided in the legend; the values of the contours represent a percent change away from the baseline configuration.



Metric 1

$$\boxed{\frac{\text{Block Fuel}}{\text{Range} \cdot \text{Payload}}}$$

Metric 2

$$\boxed{\frac{\text{Block Fuel}}{\text{Range} \cdot \text{MTOW}}}$$

Figure 55: Example of alignment of metrics with design objectives

By overlaying contours of desired responses on a vehicle design space, a direction of improvement for each response can easily be observed. In this example, it is noticeable that the direction of improvement of Metric 2 is nearly orthogonal to the direction of decreasing TOGW, a common objective in aircraft design. The same metric is similarly nearly orthogonal to fuel burn. This lack of alignment of this particular metric with traditional objectives implies that a design objective based on this metric might incentivize design trends that garner little or no fuel burn improvements.

It should be noted the while the direction of improvement of Metric 2 in Figure 55 is not aligned with the traditional objective of minimizing TOGW, the gradient of improvement of the metric is at a significantly smaller scale than the traditional objective. As such, this slice of the vehicle design space, shown in only a few dimensions, does not tell the whole story necessary to draw summary conclusions. A more thorough analysis was completed which investigated a larger number of dimensions in a design space, and investigated the alignment of metrics to traditional objectives in relation to all dimensions considered. This Local Sensitivity Analysis was conducted with the EDS SA vehicle model. Five CO_2 metrics listed in Table 8 were considered. Block fuel responses were obtained from four different range missions: 500 nm range, 1000 nm range, 1500 nm range, and R_2. All mission analyses were performed with R2 payload. The design variables include nine variables under three categories:

- Design parameters: engine thrust (sea level static), wing area, and fuselage length
- Mission parameters: design payload (R_2 payload), number of passengers, design range (R_2)
- Technology factors: Airframe Weight Improvement, Engine Fuel Efficiency Improvement, Aerodynamic Efficiency Improvement

Normalized inner product values calculated with all combinations of the CO_2 metrics and the block fuel responses considered. All metrics, except for Block Fuel/ (MTOW*Range), exhibit very high values.

Table 8: Preliminary results of analysis of Local Sensitivity Analysis

Vehicle Metric **CO2 Metric**	$W_{Fuel\,(500nm)}$	$W_{Fuel\,(1000nm)}$	$W_{Fuel\,(1500nm)}$	$W_{Fuel\,(R2)}$
$\frac{Block\ Fuel}{Payload * Range}$	0.95	0.99	0.95	1.00
$\frac{Block\ Fuel}{Useful\ Load * Range}$	0.94	0.98	0.94	1.00
$\frac{Block\ Fuel}{MTOW * Range}$	0.73	0.82	0.73	0.89
$\frac{Block\ Fuel}{Floor\ Area * Range}$	0.95	0.99	0.95	1.00
$\frac{Block\ Fuel}{Seats * Range}$	0.95	0.99	0.95	1.00

0.6 **0.7**	**0.7** **0.8**	**0.8~** **0.85**	**0.85** **~0.9**	**0.9** **0.95**	**0.95** **1.0**

→ **Desired**

Parametric Analysis

The parametric analysis (PA) compared percent changes in CO_2 metrics and fuel burn observed from varying a single design variable, mission parameter, or technology impact variable at a time within a range. Aircraft was resized for the baseline wing loading and thrust-to-weight ratio values except for the cases that used those variables to develop trend curves. The sensitivity of all the metrics to an improvement in airframe technology for a 150 passenger vehicle, measured at R_2, is depicted in Figure 56. Plotting the sensitivities of the metrics along with the sensitivity of aircraft takeoff weight and fuel burn facilitates the observation of metric trends that might be counter to that of traditional objectives. In this case, it is evident that most metrics have sensitivities in line with fuel burn and takeoff weight trends, meaning that for a reduction in airframe weight due to advanced technologies, which leads to a reduction in fuel burn, an improvement of the metric response also results. There is one major exception evident here, corresponding to BF/(MTOW*Range), which has the opposite trend; a reduction in airframe weight will lead to a degradation in BF/(MTOW*Range) metric, but an improvement of block fuel. This counter-productive incentive implies that in at least this dimension, this metric is not as effective as others in garnering fuel burn improvements. In contrast, BF/(P*R), BF/(Floor Area*R), and BF/(Seat*R) exhibit the exactly same trend as BF for this dimension.

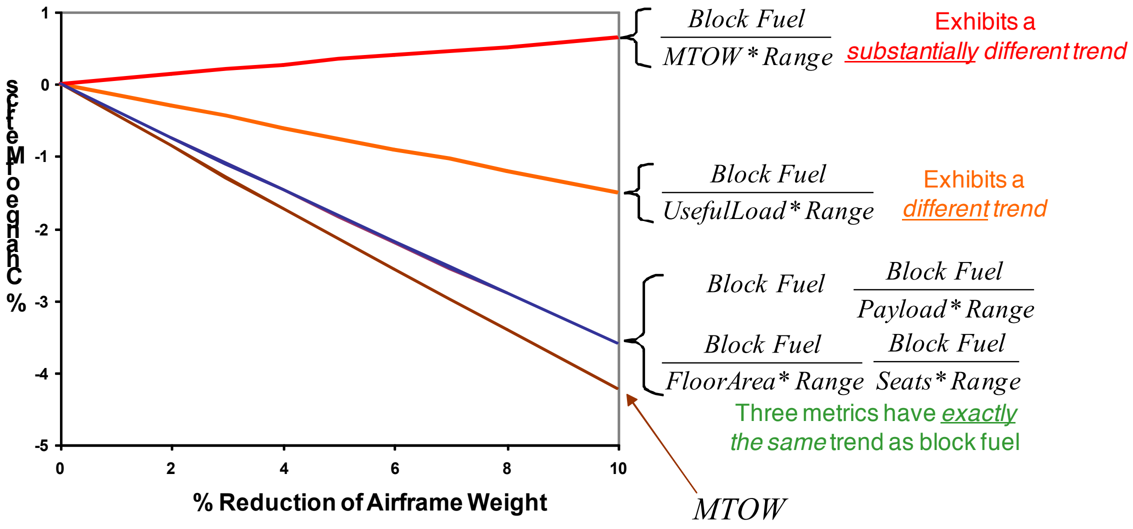


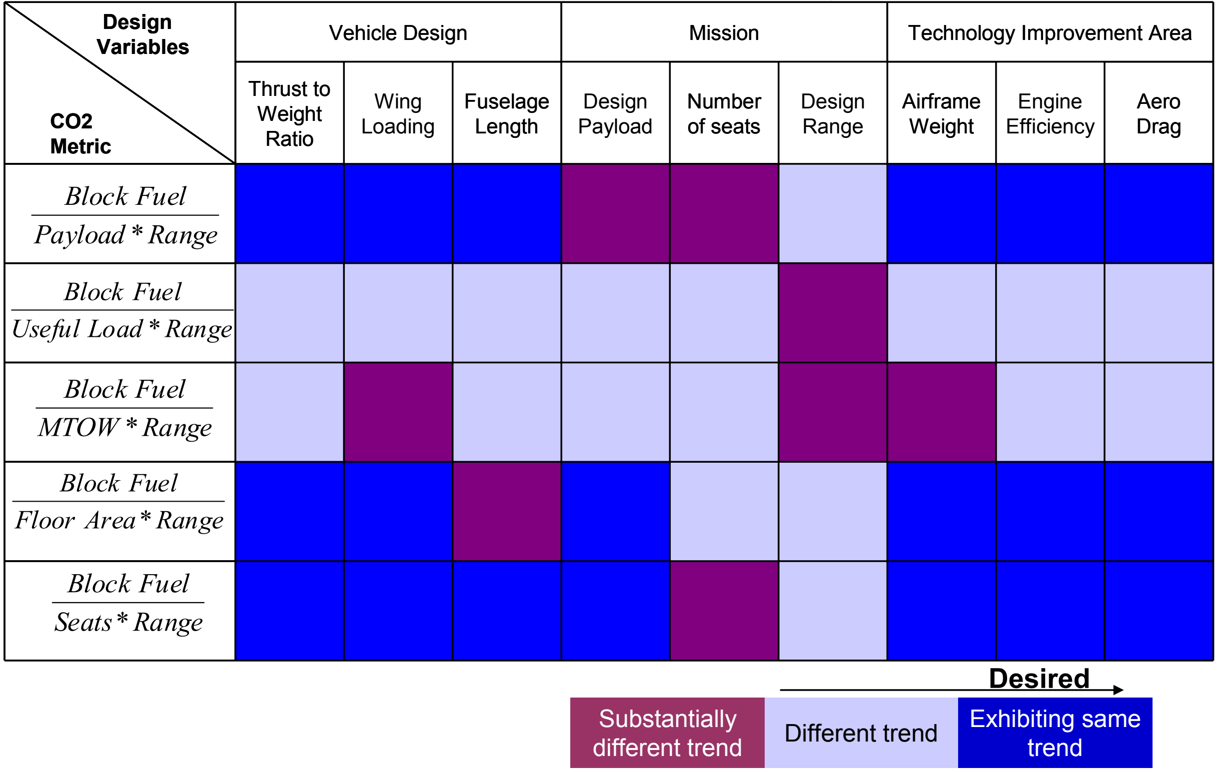
Figure 56: Example of vehicle model sensitivity

The alignment of the candidate metrics was evaluated using EDS SA vehicle, and the summary is listed in Table 9. The alignment was evaluated qualitatively by observing the sensitivity of the metrics to perturbations in design, mission, and technology variables and using three categories:

- Same Trend: Like BF/(P*R) of the example in the previous chart, a metric exhibits the same trend as Block Fuel shows.
- Different Trend: Like BF/ (UL*R) of the example in the previous chart, a metric exhibits a different level of slope but same direction.
- Substantially Different Trend: Like BF/(MTOW*R) of the example in the previous chart, a metric exhibits an opposite or a substantially different trend compared with the Block Fuel response.

The test conducted with the EDS SA model indicates no metric shows the same trend with block fuel for all parameters. All metrics show a substantially different trend for at least one parameter. Nevertheless, BF/ (UL*R) and BF/(MTOW*R) metrics appeared to be less attractive than others overall.

Table 9: Summary of Parametric Analysis



Design Variables / CO2 Metric	Vehicle Design			Mission			Technology Improvement Area		
	Thrust to Weight Ratio	Wing Loading	Fuselage Length	Design Payload	Number of seats	Design Range	Airframe Weight	Engine Efficiency	Aero Drag
$\frac{Block\ Fuel}{Payload * Range}$	🟦	🟦	🟦	🟪	🟪	⬜	🟦	🟦	🟦
$\frac{Block\ Fuel}{Useful\ Load * Range}$	⬜	⬜	⬜	⬜	⬜	🟪	⬜	⬜	⬜
$\frac{Block\ Fuel}{MTOW * Range}$	⬜	🟪	⬜	⬜	⬜	🟪	🟪	⬜	⬜
$\frac{Block\ Fuel}{Floor\ Area * Range}$	🟦	🟦	🟪	🟦	⬜	⬜	🟦	🟦	🟦
$\frac{Block\ Fuel}{Seats * Range}$	🟦	🟦	🟦	🟦	🟪	⬜	🟦	🟦	🟦

Desired →

🟪 Substantially different trend

⬜ Different trend

🟦 Exhibiting same trend

Multivariate Analysis

A Multivariate Analysis (MA) added depth to the LSA and PA by considering CO_2 metrics and block fuel behaviors over a design space rather than at a single point. In this analysis, a number of hypothetical aircraft designs were developed by randomly varying multiple design variables simultaneously, in a method depicted in Figure 57. CO_2 metrics and block fuel responses of resulting aircraft models were calculated. Processing the collected data with a statistic tool, the correlation (rho) between a CO_2 metric and a block fuel response were calculated. A higher correlation between CO_2 metric and block fuel is desired.

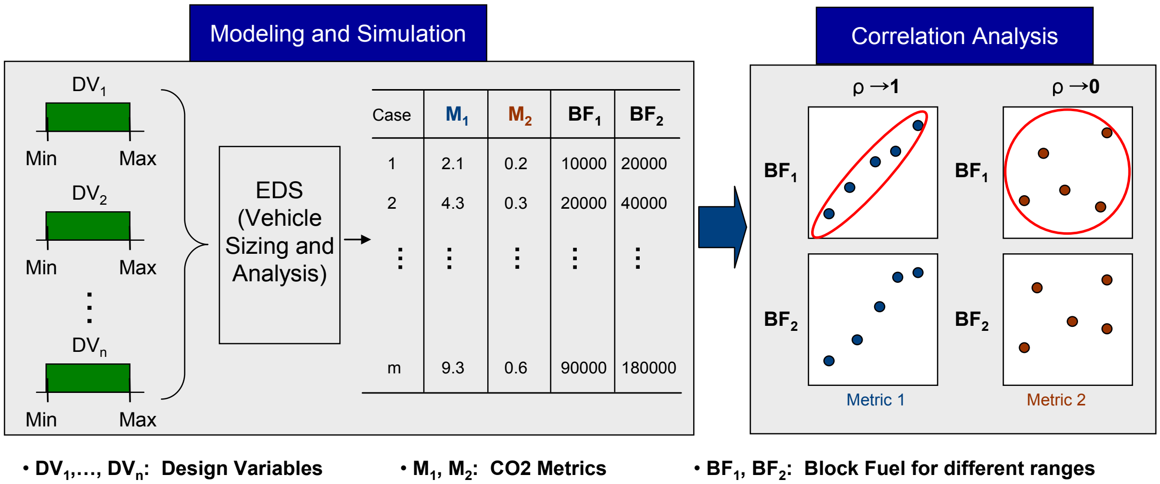


Figure 57: Multivariate Analysis Methodology

A multivariate analysis (MA) was conducted using an EDS SA model results. Hypothetical aircraft were developed by randomly varying 1) design parameters such as wing area, engine thrust, and fuselage length from -5% to 5% around the EDS SA baseline; and 2) technology factors such as airframe weight, engine TSFC, and Drag from 0 % to -10% reduction to the EDS SA baseline. Mission parameters were fixed at the EDS SA baseline values. The cases randomly generated from uniform distributions were evaluated using the EDS tool and infeasible designs were filtered out. Three thousand survivals were depicted in a scattered matrix plot in Figure 58. Each cell of the matrix portrays where the three thousand random cases are in terms of a CO_2 metric and a Block Fuel response. For example, the cell on the top left shows Block Fuel for 500 nm mission and BF/(P*R) values of the random cases. Note that all metrics were evaluated at R_2 point. The green box indicates an example of CO_2 metric exhibiting a good correlation with a Block Fuel response, while the red box presents an example of “poor” correlation.

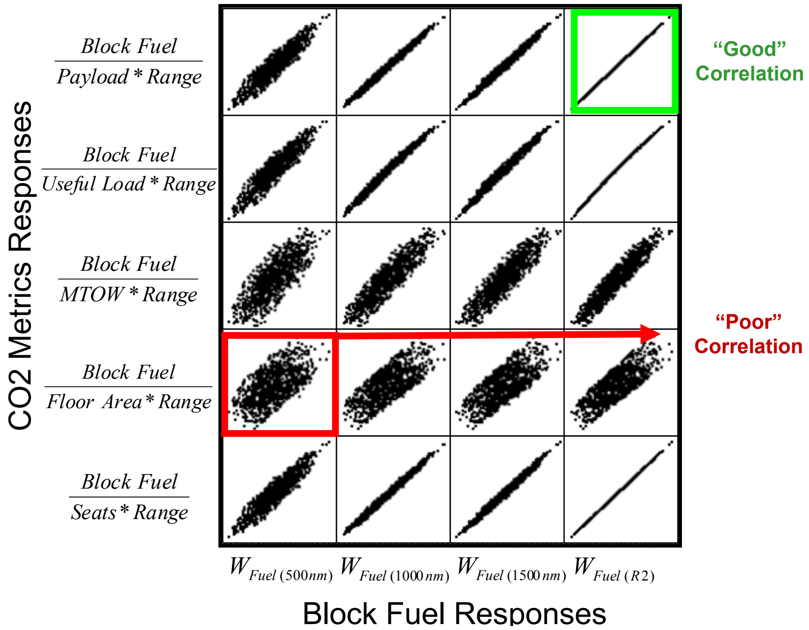


Figure 58: Multivariate Analysis Results – EDS SA Model

Since mission parameters were fixed, BF/(P*R), BF/(UL*R), and BF/(Seats*R) responses are all essentially Block Fuel (R_2) responses multiplied with a different constant. Therefore, those three CO_2 metrics presents the same shape of distributions and present a perfect correlation with Block Fuel (R_2) responses. Correlation analyses were conducted to measure the strength of the linear relationships between each pair of CO_2 metrics and vehicle metric using a JMP, a statistics software product developed by SAS. These resulting correlations are depicted in Table 10.

BF/(P*R), BF/(UL*R), and BF/(Seats*R) metrics exhibit high degree of correlation with different Block Fuel responses. BF/(MTOW*R) is ranked next to this group, and BF / (Floor Area*R) was found to be the worst. A column-wise comparison indicates that correlation diminishes as mission range reduces. Especially Block Fuel with 500 nm range results in considerably lower correlation. This is mainly because all CO_2 metrics were evaluated at R_2 while the Block Fuel was measured at a substantially shorter range mission where climb and descent fuel burn contribution become significant. Due to basic physics with a metric that contains BF/R, the metric will always go to infinity as flown range goes to zero. Hence, the lack of correlation a shorter ranges. These three different vehicle sensitivity tests led to the observation that metrics that involve “MTOW” and “Floor Area” exhibits a weaker correlation with block fuel responses than other metrics. To the extent it was considered in this research, these observations suggest metrics involving "MTOW" and "Floor Area" would be less effective at garnering environmental benefit.

Table 10: Summary of Multivariate Analysis

Vehicle Metric / **CO2 Metric**	$W_{Fuel\,(500nm)}$	$W_{Fuel\,(1000nm)}$	$W_{Fuel\,(1500nm)}$	$W_{Fuel\,(R2)}$
$\frac{Block\ Fuel}{Payload * Range}$	0.93	0.99	0.99	1.00
$\frac{Block\ Fuel}{Useful\ Load * Range}$	0.93	0.99	0.99	1.00
$\frac{Block\ Fuel}{MTOW * Range}$	0.78	0.90	0.90	0.94
$\frac{Block\ Fuel}{Floor\ Area * Range}$	0.58	0.70	0.71	0.76
$\frac{Block\ Fuel}{Seats * Range}$	0.93	0.99	0.99	1.00

0.1 **0.2**	**0.2** **0.3**	**0.3** **0.4**	**0.4** **0.5**	**0.5** **0.6**	**0.6~** **0.7**	**0.7~** **0.8**	**0.8** **0.9**	**0.90** **1.0**

Metrics which explicitly include "MTOW" and "Floor Area" do not reasonably satisfy this criterion. All other metrics correlate well with fuel consumption, and reasonably satisfy contributing positively to environmental benefit at the vehicle level.

Not Require Inappropriate Level of Resources to Implement

Cruise performance data is routinely collected when flight testing new aircraft designs [16], [17], [18]. Since SAR is one of the explicit data collected during this testing process, it is expected that implementing SAR as a fuel efficiency metric as a basis for an aircraft CO_2 certification requirement would have very little additional burden on the appropriate authorities. Thus, all instantaneous metrics can be categorized as having very little burden required for implementation. Mission fuel based metrics, however, are more challenging since, while data is likely collected, having confidence in accurate block fuel estimates is significantly more difficult, and more effort is likely required to determine an acceptable level of accuracy for implementation. Additionally, block fuel estimates would require a mission profile definition across the entire fleet, which may have difficulty in terms of fairness across all aircraft. Thus, all mission fuel metrics can be categorized as requiring more effort than SAR, although the actual amount of required resources is unknown. The main takeaway here is that all instantaneous metrics are relatively easier to implement, while all mission fuel metrics are relatively more difficult to implement.

All instantaneous metrics are relatively easier to implement, while all mission fuel metrics are relatively more difficult to implement.

Explainable to Public

A fuel efficiency metric applied to commercial aircraft should be explainable to the general public. While technical engineering terms may be best to describe intricacies of aircraft performance, it is highly desirable that the general public also be able to understand general concepts. This enables a degree of traceability and transparency, so the public can also recognize how aircraft fuel efficiency metric may relate to broader impacts and efforts to mitigate environmental impacts. To this end, a metric should not include many complex terms or "tools of the trade" understood only by those intimately familiar with aircraft performance. Or, if so, the intent and purpose of these parameters should be explainable so as to be generally relatable to other, simpler concepts.

Most of the metrics in the current research portfolio and their parameters are relatively easily to understand, with a few shining examples of metrics that are extremely simple to understand. For instance, BF/R is directly relatable to miles per gallon (MPG) for other transportation sectors, a metric widely used today. SAR similarly relates to MPG at an instantaneous condition. The only potentially confusing parameter included is "useful load," the definition of which may not be immediately apparent in non-aviation circles. Even this parameter, however, should be relatively simple to explain if given the opportunity, by relating to a rough estimation of the sum of payload and fuel.

All metrics considered reasonably satisfy this criterion.

Future Work

An extensive assessment of candidate aircraft fuel efficiency metrics was successfully accomplished in this project, and an understanding of the behavior of metrics, CPs, and evaluation conditions was gained. Many other considerations relating to metric assessment require additional research to refine the evaluation of the portfolio of candidate CO_2 emission metrics. The majority of current research accomplishments have investigated how current and future aircraft behave with respect to different metrics and correlation parameters, and how metrics inherently treat different classes of vehicles across a variety of assumptions. However, current efforts have not adequately addressed questions related to the broader air transportation system level implications of the adoption of a particular aircraft CO_2 emission metric. Also, further research may be desired to more fully investigate the potential of using multi-point or weighted evaluation conditions for measuring aircraft metric performance.

There are two major areas of future research regarding broader implications of the adoption of particular CO_2 emission metrics and CPs. The first research area aims at understanding the potential interdependencies of CO_2 emissions with other environmental objectives (such as NO_X and noise) at the aircraft level. Identification of the degree of dependence between environmental objectives at the vehicle level reaps immediate benefits in understanding the potential benefits and penalties of single objective and balanced approaches to mitigating impacts at the vehicle level. The second research area deals with the potential implications that implementing a particular standard based on a metric-cp-evaluation condition framework will have on system-wide environmental impacts. Quantifying the potential environmental benefit resulting from the adoption of a particular certification requirement framework is important to determining the most appropriate metric-CP-evaluation condition framework. Addressing these two areas in parallel could also provide insight into the potential system-wide interdependent impacts of the adoption of particular metrics on emissions and noise exposure. Since these implications are potentially significant, and could even affect the selection of leading fuel efficiency metrics and CPs, a possible approach to addressing these issues is presented here, developed by leveraging the insight gained and lessons learned from current and past research.

Vehicle-Level Interdependencies

Recognizing that CO_2 emissions are the main focus of this research, it is also necessary to investigate the effect that the choice of proposed CO_2 metrics may have on other environmental objectives. Indeed, the degree of interdependence between a candidate metric and other environmental objectives may be used to evaluate the effectiveness of a metric at mitigating environmental impacts. Ideally the implications of the selected CO_2 metric would complement existing environmental regulations and not be detrimental to overall environmental benefits. However, it is not always easy to obtain simultaneous improvements in areas of aircraft fuel burn, NO_X emissions, and noise. For example, if it is desired to improve aircraft fuel consumption by increasing engine overall pressure ratio (OPR), the resulting change to the engine cycle may actually result in an increase in NO_X production. If there are such counterproductive interdependencies related to CO_2 emission metrics, they should be recognized, understood, and quantified.

One potential approach for quantifying the interdependencies of CO_2 emission metrics with other environmental objectives is to estimate required improvements to aircraft and engines to keep pace with anticipated future environmental standards. By using appropriate tools to model advances necessary to meet more stringent CO_2, NO_X, and noise requirements (likely through the addition of new technologies), the resulting interdependent impacts can be quantified. However, it is essential to utilize an appropriate physics-based analysis tool capable of capturing the fundamental interdependencies of aircraft design and performance.

The successful quantification of a variety of cases using the considerations above will quickly shed insight into what impacts improvements intended for particular CO_2 metrics also have on NO_X and noise, or the reverse. Depending on what methods are used to reduce CO_2, for example, it may be difficult to reduce CO_2 very much without observing a penalty in NO_X or noise. The precise identification of these trends will reflect critical insight into the actual interdependencies between CO_2, NO_X, and noise, related to potential aircraft improvements to meet performance targets. Furthermore, assessment of a large enough number of cases will yield insight into how much CO_2 could be improved if it were the only driver, compared to potentially more realistic improvements if CO_2, NO_X, and noise impacts were all considered equally in a balanced approach. Quantification of these comparisons can add realism to the analysis, and provide support to the expected magnitude of improvements in the assessment of effectiveness of CO_2 emission metrics.

Scenario Analysis

Perhaps the most important issue for assessing candidate CO_2 emission metrics is to understand how effective metric-cp-evaluation condition frameworks may be at reducing fleet-wide CO_2 emissions over time. Given the desire to mitigate CO_2 emissions in the future, understanding how the choice of metrics may influence aggregate aviation CO_2 emissions over time would be extremely beneficial. A high level approach to fleet-level scenario analysis is presented below.

One way to assess the approximate magnitude of CO_2 emission savings stemming from the choice of CO_2 emission metric is to examine a number of scenarios that take advantage of differing assumptions to assess their implications on system-level impacts. Here, system-level impacts mean aggregate total of CO_2, NO_X, and other emissions from aviation across all aircraft and all operations across the globe during a given time period. Given the factorial number of scenarios (i.e. combinations of metric, CP, evaluation conditions, stringency level, scope of applicability, technology response, etc.), scoping the subset of scenarios for further evaluation can be challenging.

First, it is important to clarify what is meant by a 'scenario,' and to identify all the critical pieces. A scenario for assessing effectiveness of CO_2 emission metrics is a unique combination of a set of analysis assumptions, including study scope, non-CO_2 standard consideration, metric and correlation parameter, stringency levels, time-frames, applicability, technology response, a forecast of aircraft operations over time, and aggregation of results.

The scope of a study must be set to determine whether impacts will be studies on a global, national, or local level, and whether non-CO_2 impacts will also be addressed. Future stringencies for appropriate environmental objectives can be estimated for several future timeframes. For a CO_2 requirement, a different CO_2 emission metric, CP, and evaluation condition set can be used as a basis for each scenario. The definition of future stringencies will drive the required technological improvement for aircraft and engines, and the appropriate technology response should be estimated for aircraft which will be introduced in the future. Using a forecasted set of operations, future technology-response aircraft can be inserted into the fleet according to a schedule, to see their influence on aggregate CO_2 emission production. Comparing each scenario to a business-as-usual baseline will provide a quantitative estimate of how effective a metric-CP-Evaluation-Option set may be at reducing CO_2 emissions in the future. Finally, appropriate tools can be used to quantify the physical and monetary changes in climate, air quality, and noise due to aviation policies, to provide more comprehensive information about the overall impacts of each scenario.

Synthesis and Conclusions

In order to inform the development of an aircraft CO_2 emissions certification requirement, there is the need to first identify metrics that objectively and accurately reflect CO_2 emissions at the aircraft level. This report serves (1) to provide a summary of the ongoing study being funded by the U.S. Federal Aviation Administration (FAA) to generate and evaluate CO_2 emissions metrics, and (2) to recommend, based on quantitative and qualitative analyses completed under the study thus far, the most promising metrics, correlating parameters (CP) and evaluation conditions for a potential aircraft CO_2 emissions certification requirement. It also frames the problem and approach of the assessment of the potential effects of notional aircraft CO_2 emissions certification requirements on current and future aircraft fleets and system wide performance, as well as interdependencies with other environmental certification requirements.

First, this report describes the problem of aircraft CO_2 emissions from commercial aviation and the rationale for generating metrics that could be used to establish an aircraft CO_2 emissions certification requirement. It then presents a portfolio of candidate metrics that were evaluated for their suitability. This portfolio of metrics was generated through systematic brainstorming sessions, literature review, interactions with industry, and interactions with the CO_2 Task Group members from the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) Working Group 3. This report then presents qualitative and quantitative criteria by which each metric was evaluated using a multitude of tests. These included qualitative and quantitative analyses utilizing a variety of secondary data sources available to the project team, such as public-domain information, PIANO-X, PIANO-5, FAA's Environmental Design Space (EDS), the ICAO 2006 Common Operations Database, Bureau of Transportation Statistics (BTS) database, and extensive technical literature. Tests included the assessment of parameters that compose each metric, metric performance comparison across aircraft types and categories, sensitivity analyses of mission and flight conditions, estimation of technology influences on metric values, effects of metrics on notional future aircraft designs, and others. The insight gained from these tests directly supported the comprehensive assessment of the portfolio of metrics and the identification of a subset of most promising metrics.

From the set of over 30 metrics that were considered in this study (and many more combinations of metric-correlation parameter), a subset of 2 metrics (corresponding to 5 metric-correlation parameter combinations) are believed to exhibit attributes of promising metric-CP candidates. These two metrics fall under two distinct categories: full mission and instantaneous performance;

- The full mission metric (i.e. **Block Fuel / Range**) requires the complete definition of a representative flight(s), including payload, range, taxi time, climb schedule, cruise altitude(s), diversion distances and a host of other parameters.
- The instantaneous performance metric **1/Specific Air Range** (SAR),analogous to 'miles-per-gallon' for automobile and represents the incremental air distance an aircraft can travel for a unit amount of fuel at a particular flight condition (i.e. cruise). SAR can be calculated by dividing true air speed (measured in km/s) by fuel flow (measured in kg/s). When measured in steady-level conditions, 1/SAR primarily depends only on aircraft weight, altitude, air speed, and ambient temperature. As a result, 1/SAR limits the regulatory certification burden by greatly reducing the number of assumptions required to define the measurement point(s). In addition, SAR is common use in aerospace/airline industry which may simplify the certification process. 1/SAR encapsulates fundamental parameters that directly influence airplane fuel efficiency including: propulsion system efficiency, aerodynamic efficiency, and airplane weight. Since 1/SAR does not measure performance across all phase of flight and may not be as robust against unintended consequences as a Block Fuel / Range full mission metric; however, research to-date suggests that 1/SAR could sufficiently capture technology improvements during relevant phases of flight.

The two metrics described above were assessed to be the most promising metrics to date when paired with Maximum Takeoff Weight (MTOW). Advantages and disadvantages of candidate metrics and correlation parameters are summarized in Table 11.

Table 11: Summary of Advantages and Disadvantages of Most Promising Candidate Metrics and Correlation Parameters **Summary of Advantages and Disadvantages of Most Promising Candidate Metrics and Correlation Parameters**

Metric Evaluation Criteria / Metric & CP		Include a measure of transport capability	Metric and CP based on Certified Parameter	Accurately reflect CO_2 emissions and fuel burn at aircraft level	Fairness across sets of stakeholders across aircraft categories	Independence of Purpose or Utilization	Possible Impacts of Metrics on Future Vehicle Development	Limit unintended consequences	Differentiation of Generations of CO_2 Reduction Technologies
1 ---------- SAR	MTOW	Proxy	SAR: Not Certified (Relatively easy to certify) MTOW: Certified	Reasonably well	Yes	Yes	(1) May not fully reward airframe weight reductions (2) Does not explicitly reward fuel efficiency improvement in non-cruise	Least prone to unintended consequences due to its insensitivity to aircraft types and the choice of evaluation condition	Very good for all evaluation conditions
Block Fuel ---------- Range	MTOW	Proxy	Block Fuel: Not Certified (Relatively difficult to certify) Range: Not Certified (Relatively difficult to certify) MTOW: Certified	Yes	Yes	Yes	May not fully reward airframe weight reductions	Depending on the evaluation condition, may severely penalize aircraft with long range	Good / Bad (varies significantly depending on the evaluation condition)

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Appendix

Appendix A

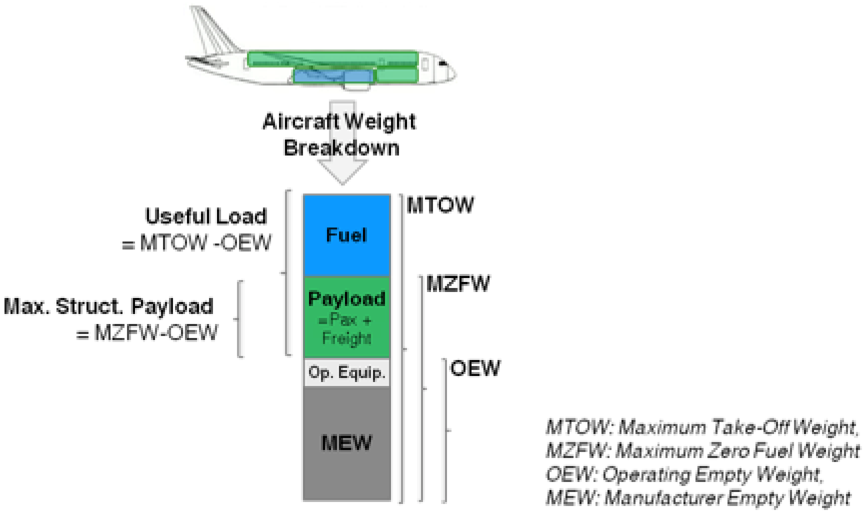

Figure 59: Definition of Weight Based Parameters

Appendix B

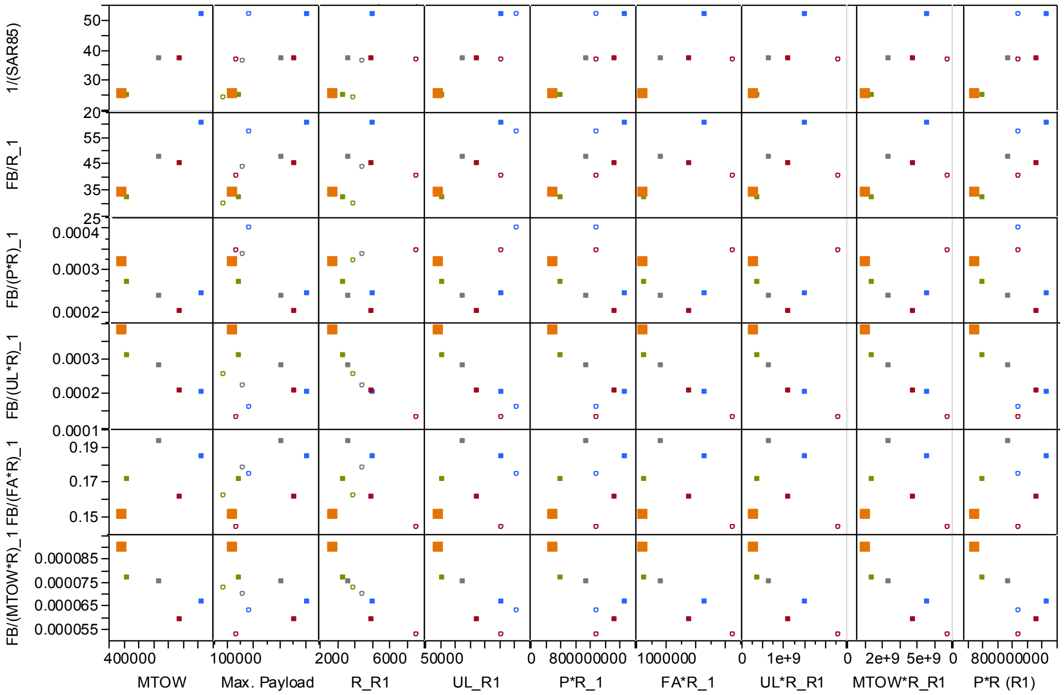

Figure 60: Freighter and passenger aircraft variants for many metric-CP pairs for purpose and utilization independence test

Appendix C

Metric and Correlating Parameter Analyses with Five EDS Aircraft

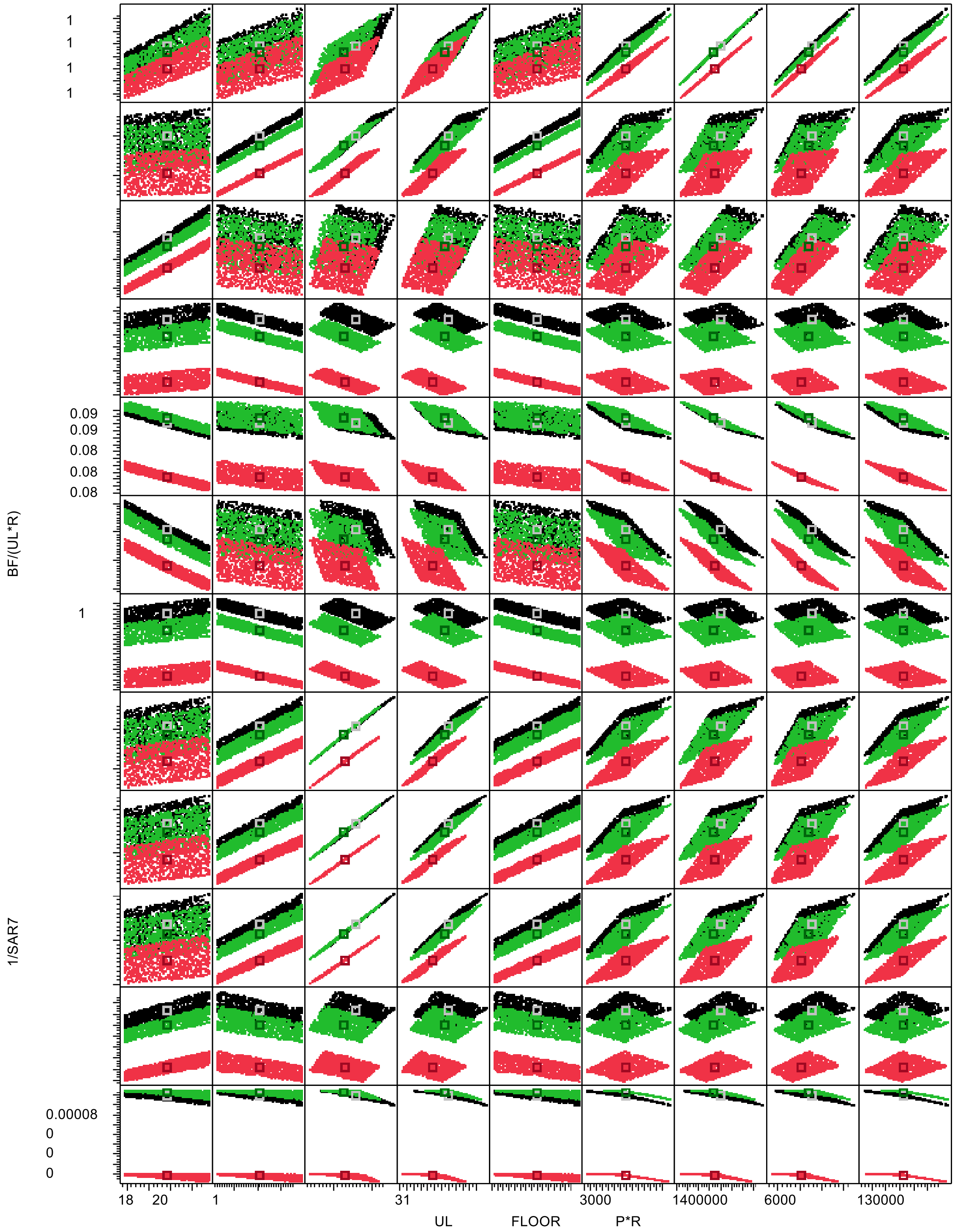

Figure 61: Mission and SAR-Based Metrics and CPs – EDS Regional Jet Analyses

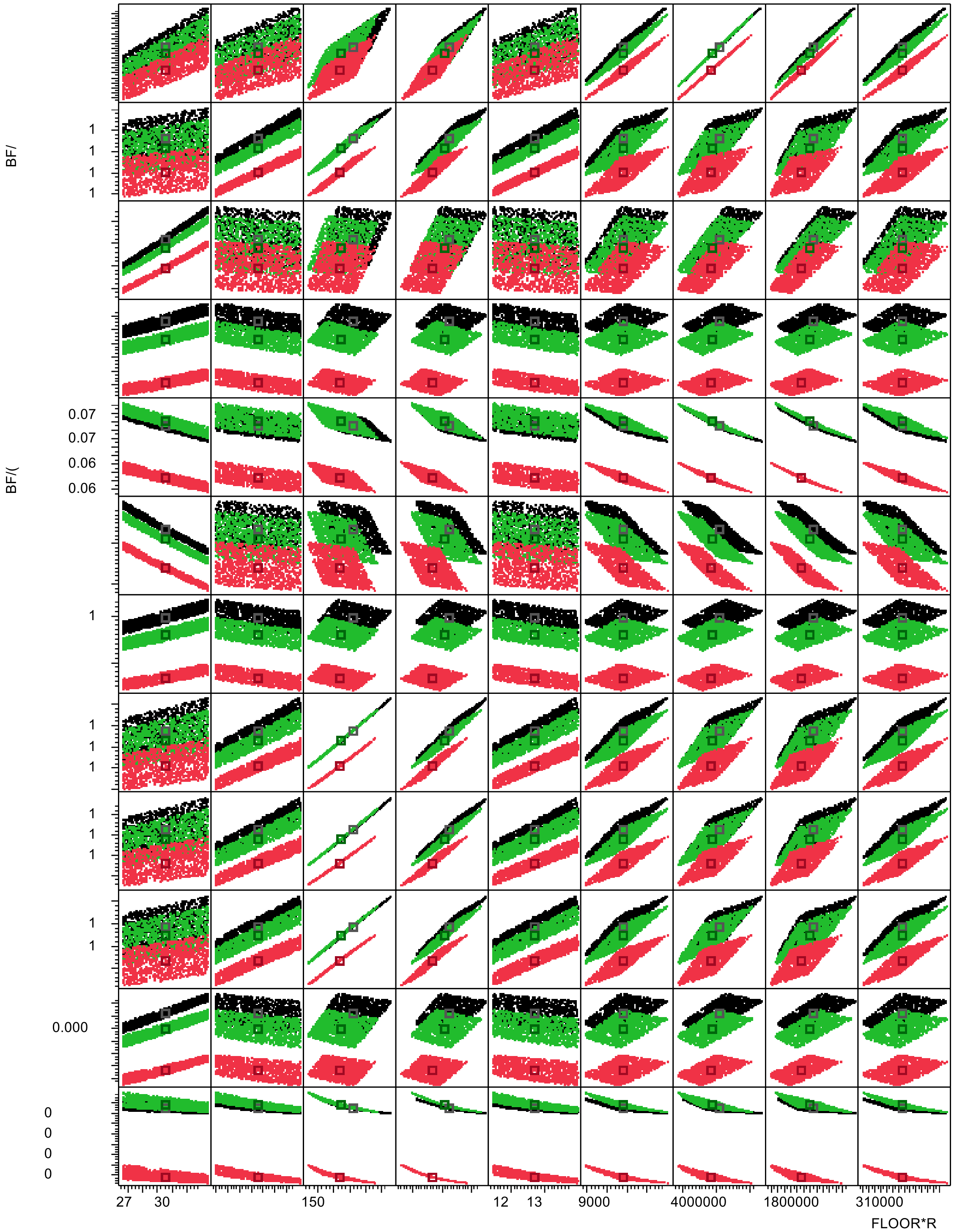

Figure 62: Mission and SAR-Based Metrics and CPs – EDS Single Aisle Analyses

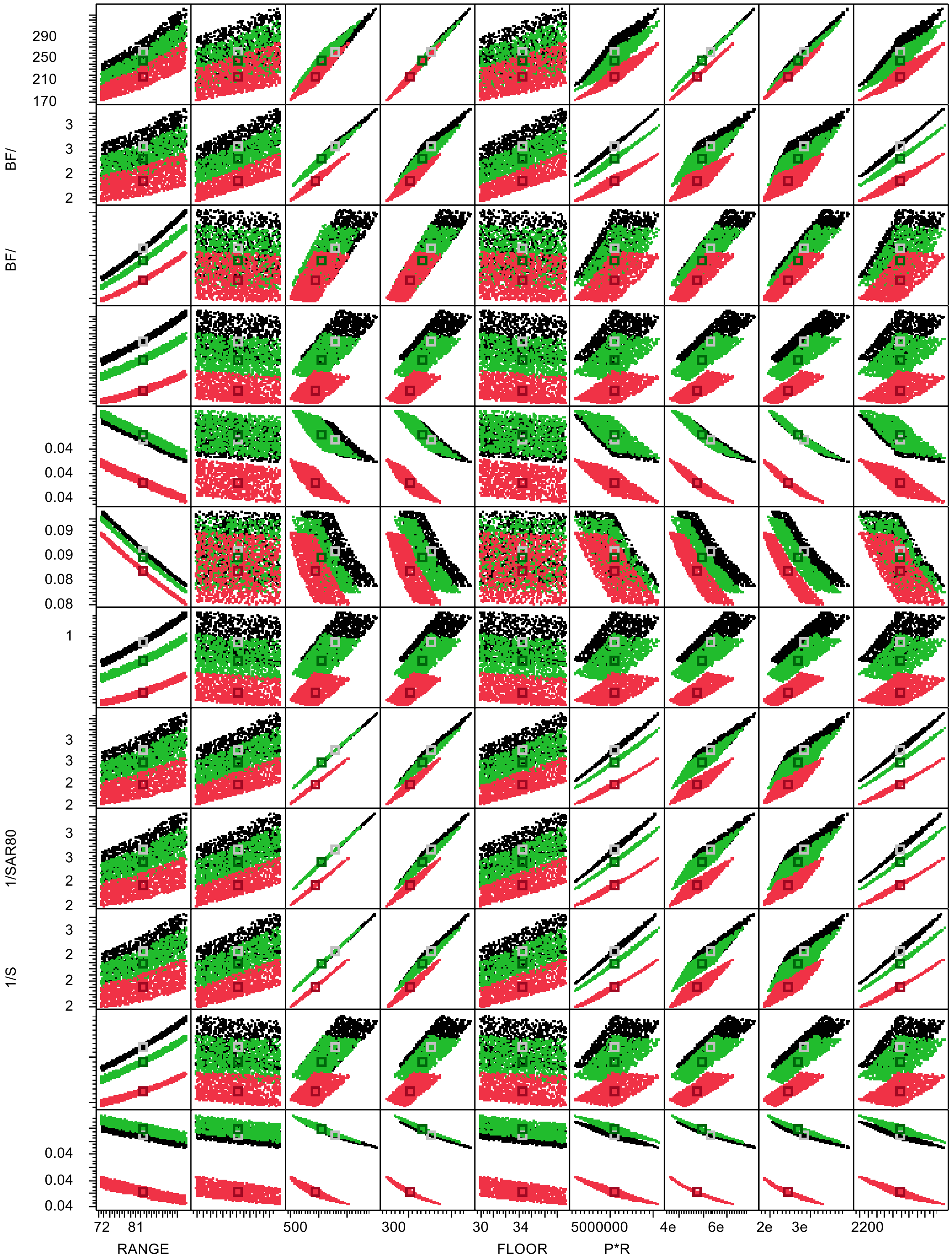

Figure 63: Mission and SAR-Based Metrics and CPs – EDS Large Twin Aisle Analyses

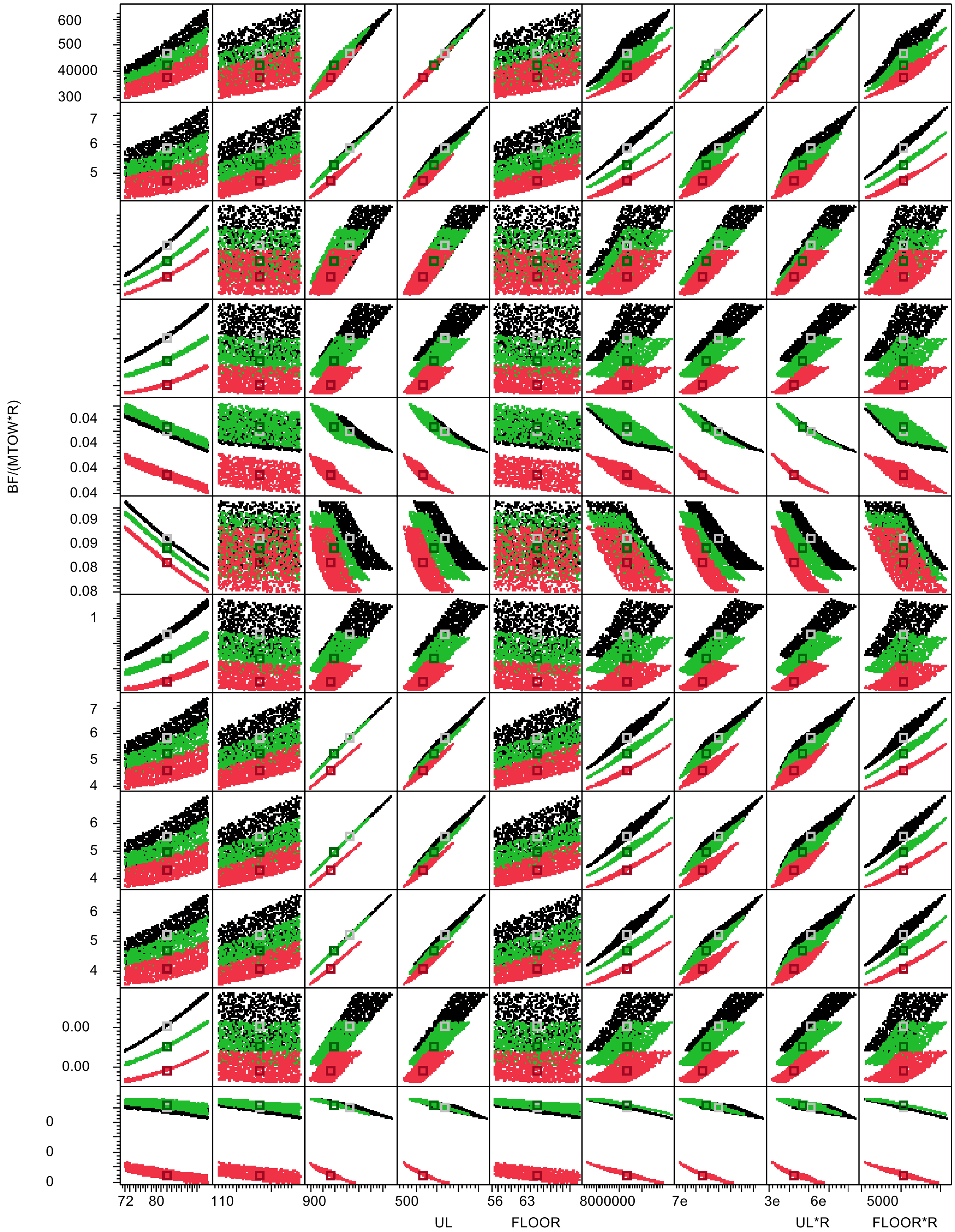

Figure 64: Mission and SAR-Based Metrics and CPs – EDS Large Quad Analyses