AN INVESTIGATION OF THE POTENTIAL IMPLICATIONS OF A CO_2 EMISSION METRIC ON FUTURE AIRCRAFT DESIGNS

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Abstract

Increasing concern over anthropogenic greenhouse gas emissions and climate change motivates mitigating CO_2 emissions in all sectors, including commercial aviation. Adopting a certification standard is one way to mitigate aviation emissions. The identification of metrics and any other parameters that form the basis for certification is a critical first step towards developing such a standard. The purpose of this research is to identify a method for simultaneously assessing a metric and correlation parameter for the purposes of an aircraft CO_2 standard based on a set of evaluation criteria. The framework described herein takes into account historical approaches to develop a method to identify metrics and correlation parameters that emphasizes aircraft design and technology development while preserving disparity of aircraft capability or manufacturer's design choice of payload-range delivered. The use of this methodology highlights promising metrics and correlation parameters that could be used as part of the basis for an aircraft CO_2 standard. Lastly, potential unintended consequences associated with the choice of metric and correlation parameter are discussed.

1 Introduction

Increasing concern over the potential for global climate change has placed considerable emphasis on anthropogenic greenhouse gas emissions. One of the most concerning emissions species is carbon dioxide (CO_2), due to its direct greenhouse effect through absorption and reemission of infrared radiation, its prevalence throughout various sources, and its long-lasting effects [1, 2]. A December 2009 finding that identifies carbon dioxide as one of several pollutants that endangers public health and welfare [3] mandates the US Environmental Protection Agency under the Clean Air Act [4] to regulate the emission of this pollutant. Given the expected rise in aviation demand [5], which may only exacerbate aviation's contribution to the harmful production of CO_2 and the mandate to regulate this pollutant, it is anticipated that an aircraft certification standard will be used in the near future to regulate civil aviation carbon dioxide emissions.

The first step in developing an aircraft certification standard is establishing what the methodology for construction should constitute. In particular, the metric used to measure aircraft CO_2 emissions is a critical piece that must be addressed as a first step. Historically, an environmental standard typically includes a metric (on the y-axis) and one or more correlating parameters (CPs on the x-axis) that are related to the capability of the system, which must also be investigated from the outset. Ultimately, a metric and CP must be evaluated together for their use and potential effectiveness. The objective of the research described herein is to identify a method to assess a portfolio of candidate metrics and CPs for an aircraft CO_2 certification standard, focusing on civil transport airplanes with turbofan engines.

2 Background

A historical investigation was conducted to identify any analogies that would be applicable for the current investigation. Two well known examples were chosen to determine if any lessons could be learned from existing aircraft environmental standards; aircraft noise and aircraft engine emissions, specifically regarding nitrous oxides (NO_X).

Engine emissions standards controlling NO_X have been in effect since the 1970's, when they were adopted to limit aviation impact on local air quality. The metric, D_P/F_{oo}, was chosen to directly reflect engine pollutant emissions (D_P), while normalizing by thrust (F_{oo}), which allows an engine to emit pollutants in proportion to its services rendered [6]. The certification limits are constructed to relate the metric to engine overall pressure ratio (OPR) as a correlation parameter, to reflect intrinsic engine design tradeoffs between emissions, fuel flow, and engine size. This metric and CP pair enables simple comparisons between engines [7], and highlights an intrinsic tradeoff between engine emissions and combustor inlet temperature (of which OPR is a proxy) for a given level of technology.

Aircraft noise standards were also introduced decades ago, and were aimed at limiting the exposure of people to aircraft noise. Because of its ability to account for tones and other factors related to the human perception of noise, the effective perceived noise level (EPNdB) metric "was chosen as a technically superior way to measure the impact of noise exposure to people" [8]. The certification limits for aircraft noise are set as a function of maximum takeoff weight (MTOW), relating noise production to aircraft capability. The inclusion of MTOW in the standard also highlights technological capability: since "weight is directly related to the propulsion requirements of an aircraft, and those requirements significantly affect the amount of quieting that can be accomplished, the purpose of the weight parameter in Part 36 is to ensure that all reasonable noise abatement technology is applied for each weight" [8].

Consideration of advances in technology across families shows a clear improvement in NO_x with technology adoption as shown in Fig. 1. For an engine family, de-rating the engine to a lower thrust (i.e. OPR) allows for a diversity of capability and freedom of the product of the manufacturer and the standard inherently reflects that by similarity of the slope of the standard with the slope of the products/families. This trend implies that introducing a more stringent standard is fair across stakeholders. This should also be the case with a CO_2 standard consisting of a metric and a CP (such as D_P/F_{oo} vs. OPR for the NO_x standard), highlighting a trend which responds to technology levels. Additionally, the CP here is also a measure of capability, just as in the case of noise with TOGW. Thus, the use of CPs related to size or capability for CO_2 should be investigated, especially if those are the primary drivers of fuel burn and would lead to reductions in CO_2 emissions across the fleet.

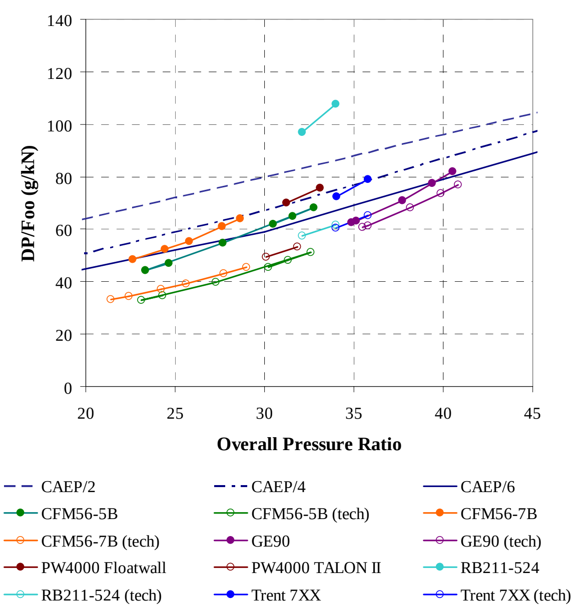


Fig. 1 Influence of Technology on NO_x Standard

2.1 Evaluation Criteria

This historical perspective highlights several lessons that may be useful for assessing metrics and CPs as the basis for an aircraft CO_2 standard. First, the metrics used are simple and directly reflects the physical properties of interest for the given standard. Furthermore, a CP representing size or capability is used in both NO_X and noise standards to reflect a tradeoff between performance and useful capability. Finally, the metric and CP combination is intentionally constructed to equitably measure performance across aircraft or engine architectures, and explicitly highlight and reward technological progression. These historical lessons yield several evaluation criteria (EC) that can be used to assess metrics and CPs for aircraft CO_2 emissions:

- (EC1) Differentiate technology generation
- (EC2) Be independent of purpose
- (EC3) Reflect fundamental design elements and capabilities
- (EC4) Fair and equitable across stakeholders

These criteria will be the fundamental aspects by which metrics and CPs are evaluated for their suitability for an aircraft CO_2 standard.

2.2 Candidate Metrics

Since CO_2 emissions are directly proportional to the amount of fuel burned in an engine for a given fuel type, candidate CO_2 metrics are all based on fuel consumption performance and are related to fuel efficiency concepts. Normalizing fuel consumption with respect to usefulness or capability relates CO_2 emissions to total amount of fuel consumed in flight. Thus, most metrics considered relate block fuel consumption to a measure or proxy of useful capability. Since definitions for 'useful capability' can vary widely, multiple candidate metrics were generated that address this concept in different ways; all block fuel based metrics include a measure of distance traveled, and most include some measure of the load transported. These metrics are shown in Fig. 2. Here, fuel burn (FB) is defined as fuel consumed during an entire mission, from the start of aircraft taxi out to the end of taxi in, which does not include reserve fuel. This is typically defined as block fuel and will be denoted further as BB in this paper. Useful load (UL) is defined here to be MTOW less operating empty weight (OEW). Cabin floor area (FL) was considered as measure of aircraft capacity. Payload (P) and range (R) are measured for a specified mission.

$$\frac{FB}{R} \qquad \frac{FB}{P*R} \qquad \frac{FB}{UL*R}$$
$$\frac{FB}{MTOW*R} \qquad \frac{FB}{FL*R} \qquad \frac{FB}{Seats*Range}$$

Fig. 2 Block performance based metrics

Since the metrics measure fuel consumption for an entire mission, the immediate question raised is which missions should be used? For consistency and simplicity, two missions were used in this research, unique to each aircraft considered but which represent typical aircraft capability trends. These are detailed in a representative payload range curve in Fig. 3. The first is the maximum range at maximum payload (R_1), and the second is the intersection of maximum takeoff weight and maximum fuel capacity (R_2).

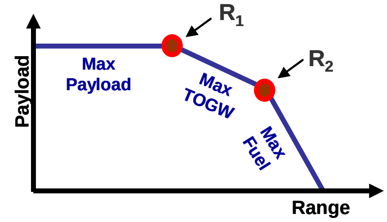


Fig. 3 Representative missions for comparison

An alternative metric is specific air range (SAR), an instantaneous measurement typically used in industry today to gauge fuel efficiency. Specific air range, also known as Nautical Air Mileages (NAMS), is the still air distance flown per unit of fuel in a steady-state flight. Historically, it has been used by the industries, operators, and government agencies to define aircraft fuel efficiency. By definition,

$$NAMS = \frac{Speed}{FuelFlow} = \frac{Speed}{TSFC \cdot Thrust} \qquad (1)$$

where TSFC denotes thrust-specific fuel consumption. Assuming steady-state flight means that *Thrust* = *Drag* and *Lift* = *Weight*, thus it can also be written as:

$$NAMS = \left(\frac{Speed}{TSFC} \cdot \frac{Lift}{Drag}\right) \cdot \frac{1}{Weight} \qquad (2)$$

Because of NAMS' simplicity, three metrics are included as candidates: 1/NAMS (at different weights), 1/NAMS*payload, and 1/NAMS*MTOW.

2.3 Correlation Parameters

In the spirit of constructing a simple, transparent, and generally understandable standard, it is desired to use the fewest parameters and assumptions possible while maintaining equity across products and stakeholders. This is challenging due to the extreme disparity in size and capability of aircraft in the current fleet. Ideally, any of these metrics could be adopted by itself for a CO_2 certification standard and a single limiting level set: a normalized capability measure embedded in the metric should wash out differences in size or capability, allowing uniform application. However, for all of the metrics that are considered in this paper, trends due to disparity in aircraft size still exist even after normalization, implying other important factors are not addressed. These persistent trends imply an equitable standard will be very difficult to apply based on a metric alone. Using the precedent of OPR in NO_X standards and MTOW in noise standards, it is anticipated that a CP can be found in addition to a metric to construct the basis for an equitable and effective aircraft CO_2 certification standard.

3 Initial Investigations

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 criteria. Amongst the four ECs developed in Section 2.1, the current methodology is focused on identifying a metric system—as a combination of a metric and a CP— that shows good performance on EC1 and EC4: a good metric system must be able to differentiate technology generations while not favoring or discriminating airplanes designed for particular mission capabilities, specifically payload and range.

3.1 Evaluation of EC1 and EC4

A good metric system must present clear separation of technology generation without confounding payload and range capability. Fig. 4 shows payload-range diagrams for two notional technological generations of civil transports. Each generation includes three vehicles, which have different payload range capabilities to support different market needs. Fig. 5 suggests how metric-CP pairs can be tested in a pictorial form. The M_1-CP_1 pair on the left does not show clear separation of the two technological generations and considered to be bad in terms of EC1 and EC4. The M_2-CP_2 on the right shows good correlation among the aircraft in the same technology generation and clear separation between the two groups.

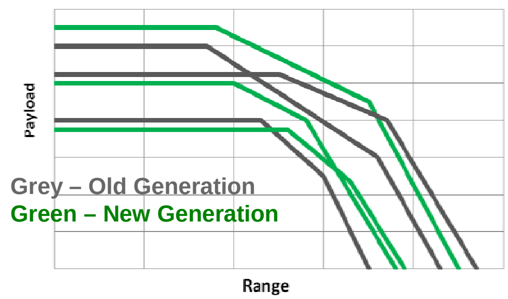


Fig. 4 Notional payload- range diagrams of two technology generations

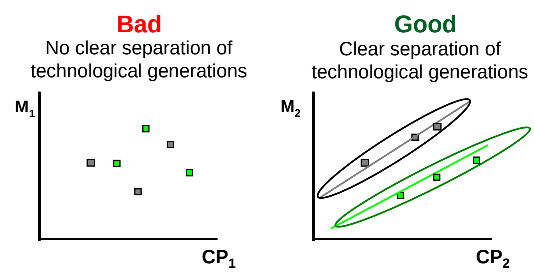


Fig. 5 Notional examples of good and bad metric-CP pairs

This test concept was applied to two pairs of metrics and CPs with public domain data for the Boeing 737 aircraft family. This family aircraft served as a great example because it has two distinct technology generations with a variety of payload and range capabilities as depicted in Fig. 6. For each aircraft, the total fuel (TF), the sum of block fuel and reserve fuel, was estimated with payload-range charts included in Boeing 737 airport planning documents [9]. TF was measured at the R1 mission defined in Fig. 3.

The 737 family fuel efficiency is compared in a metric-CP pair of TF/(P*R) vs payload*range (P*R) in Fig. 7. The fuel efficiency of 737-400 appears to be very similar to that of 737-600 when it is measured with this particular metric-CP pair in spite of the significant technology gap between the two models. In contrast, Fig. 8 plots fuel efficiency in TF/R vs P*R and exhibits a clear distinction between two technological generations. The comparison of Fig. 7 and Fig. 8 understandably indicates that the two metric systems have dissimilar ability to differentiate technology generations from the effect of mission capabilities. This test indicates that particular metric-CP pairs can be identified that meet the stated criteria for their potential use for an aviation CO_2 standard.

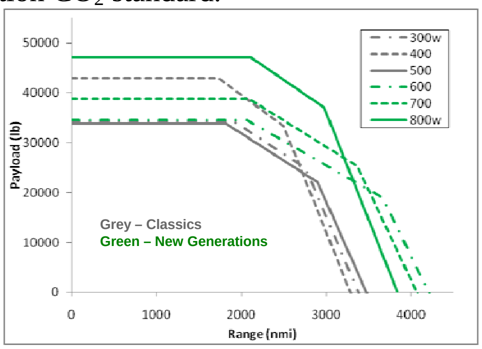


Fig. 6 Boeing 737 Classic and New Generation aircraft payload-range diagrams

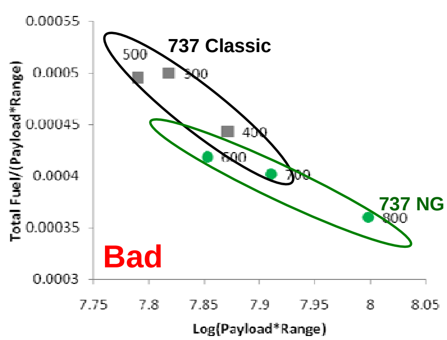


Fig. 7 Boeing 737 Classic and New Generation aircraft fuel efficiency comparison in TF/(P*R) vs P*R

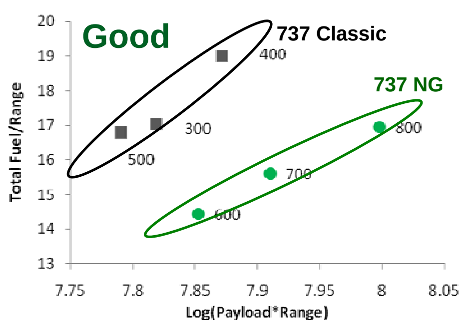


Fig. 8 Boeing 737 Classic and New Generation aircraft fuel efficiency comparison in TF/R vs P*R

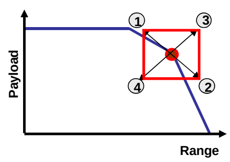
The authors attempted to expand this examination to a larger dataset including more airplanes of diverse sizes from different manufactures. However, it was impractical to use public domain data for metric-CP evaluation due to the inconsistent and often unknown assumptions behind aircraft data available publicly. More importantly, the actual aircraft data cannot provide sufficient decoupling of mission, technology, or design efficiencies. Capturing technology level with introduction date would show some improvement over time but could be misleading. It is a general industry practice to develop a family of products that share common subsystems. Due to this commonality, each aircraft is not generally optimized for its own design requirement, but rather embeds some degree of growth potential. All these compounding factors prevented the authors from drawing further meaningful observations from public domain data.

3.2 Experiments in Environmental Design Space (EDS) Tool

In lieu of correlating public domain data for existing aircraft, experiments were conducted utilizing an aircraft sizing and synthesis tool, which can generate hypothetical airplanes sized for mission requirements and technology assumptions specified by users. 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.

The Environmental Design Space (EDS) [10] was used for this analysis, and is a building block of a comprehensive suite of software tools that are under development by the U.S. Federal Aviation Administration Office of Environment and Energy (FAA/AEE) to allow for thorough integrated assessment of the fuel burn and environmental effects of aviation. EDS is a high-fidelity vehicle design and performance analysis tool capable of estimating performance, source noise, and exhaust emissions of future vehicles under various technological and policy scenarios.

A simple test was first conducted with the EDS Large Twin Aisle (LTA) model to examine the effect of variations in mission and technology level. The EDS LTA is representative of a Boeing 777-200ER. From the baseline LTA aircraft with design range of 8,048 nm and payload of 63,210 lbs, four mission requirements variations were created as shown in Fig. 9. Four derivative aircraft were then generated to meet each one of the four different mission requirements. Aircraft were resized for a fixed thrust-to-weight ratio and wing loading. Subsequently, another analysis was conducted for the same 5 design points for the LTA but with a technology level assumption of 10% TSFC reduction.



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

Fig. 9 Design payload and range conditions of four variants with respect to the baseline

The performances of the ten aircraft sized for five different missions at two technology levels (current and 10% TSFC reduction) were evaluated for two different metrics in Fig. 10 and Fig. 11. Fig. 10 shows FB/(P*R) against P*R. Note that the ordinate and the abscissa represent percent changes of the metric and CP relative to the baseline values. Similarly, FB/(UL*R) values are compared against UL*R in Fig. 11. As is evident, changes in mission capabilities may result in significant changes in both metrics although each metric includes productivity parameters in the denominator. Comparison of point 1 and point 2 of Fig. 10 suggests that FB/(P*R) may substantially differ even if aircraft capability represented by P*R is maintained. This is essentially due to the fact that fuel burn is much more sensitive to design range than payload. 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 FB/(P*R) vs. P*R is not able to differentiate technology level from such variation due to mission capability.

In contrast, the 10 aircraft appear to form a trend in FB/(UL*R) vs UL*R within a current technology level. The FB/(UL*R) metric is also substantially affected by design mission parameters. However, associating FB/(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 this metric exhibits very low sensitivity to technology infusion. A 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.

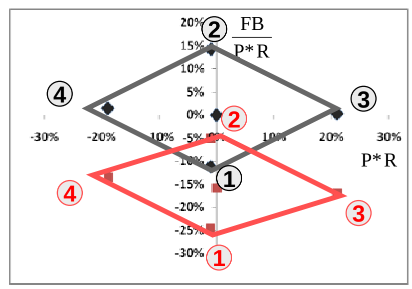


Fig. 10 FB/(P*R) vs P*R. (◆ : no tech infusion, ■ : 10% TSFC improvement)

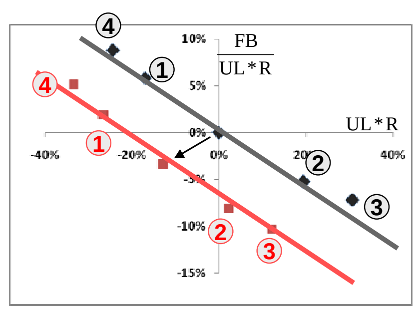


Fig. 11 FB/(UL*R) vs UL*R (◆ : no tech infusion, ■ : 10% TSFC improvement)

This pilot test suggests that a chosen metric's ability to different technology levels from mission capabilities can be significantly affected by a correlation parameter associated with the metric. The observations from this experimental concept were deemed effective by the authors in testing metrics and parameters for EC1 and EC4.

4 Analyses of the Mission Performance Metrics and Correlation Parameters

The methodology of evaluating metric-CP performance developed in Section 3 was implemented to all the CO_2 emission metrics and CPs introduced earlier. The evaluation was performed for five EDS aircraft, including 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 aircraft, a thousand mission variants were generated within +/-10% of the baseline design payload and range. The combinations of design payload and range were generated randomly using a Monte Carlo simulation. 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 reduced airframe structure weight by 10%, and a technology that improved engine efficiency (i.e., TSFC) by 10%. After resizing the aircraft, variations in the CO_2 metrics and CPs were measured at R_2. This section presents the results on those CO_2 metrics that were based on block fuel consumption.

4.1 Evaluation of the Mission Based Metric-CPs on the Small Twin Aisle Aircraft

The FB/(P*R) metric with P*R as a CP is plotted in Fig. 12. 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.

For this metric system, 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 infuse technology. Depending on the time to achieve a new standard, either approach may be feasible.

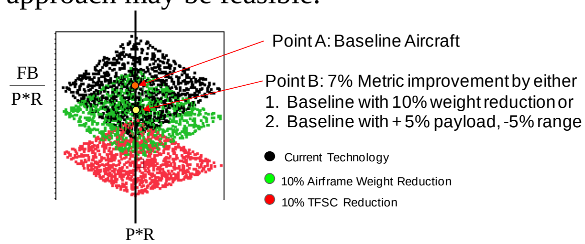


Fig. 12 FB/(P*R) against P*R

Two metric systems that include MTOW either in the metric or in the CP are presented in Fig. 13. The metric on the left, FB/(MTOW*R) vs. R, 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 meet EC1. The FB vs MTOW*R, depicted on the right side of Fig. 13, 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 the stringency line is parallel to the trend lines, this metric-CP pair does not distinguish improvements in technology generations.

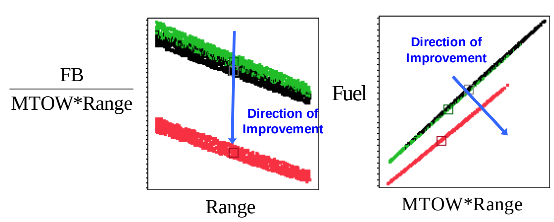


Fig. 13 Examples of Metric-CPs with MTOW Term

Two metric systems plotted in Fig. 14 show better characteristics of discriminating aircraft in different technology level without being compounded by mission effect. The FB/(UL*R) vs. (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 FB/R vs. P*R exhibits clear separation between technology groups. Both of these metric-CP systems exhibit similar behavior as the NO_x standard. However, the UL metric includes fuel in the numerator and denominator and thus tends to cancel out the fuel burn reduction impact; whereas the FB/R accurately reflects fuel burn reduction. For the baseline mission of the EDS STA, a 15% metric improvement implies 15% fuel burn reduction for the FB/R metric, and about 3% for the FB/(UL*R) metric.

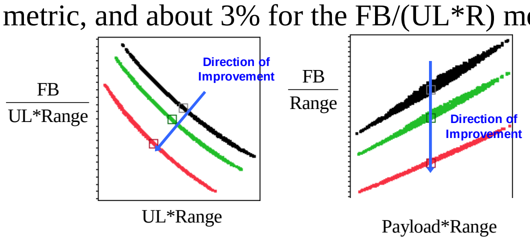


Fig. 14 FB/(UL*R) vs UL*R (Left) and FB/(P*R) vs P*R (Right)

Finally, all metrics and CPs were plotted simultaneously in Fig. 15. By comparing the plots within each row, it is observed that a metric's ability of differentiating technology generation (EC1 and EC4) is substantially affected by the choice of CP. Therefore, an assessment of metric and CP must be performed together. The key observations are:

- Metrics that include "load" terms [FB/P, FB/(P*R), and FB/(FL*R)] show large dispersion within a technology group scoring worst on EC1 and EC4
- Metrics that include empty weight in denominator [FB/(MTOW*R)] does not reward airframe weight reduction technology
- FB/(UL*R) and FB/(TOGW*R) exhibit substantially low sensitivity to technology improvement for fuel burn
- FB/R vs P*R and FB/R vs Floor*R among the metrics and CPs considered were identified to best support EC1 and EC4 for the STA aircraft.

4.2 Interpretation of the Results

Interestingly, the FB, FB/R, FB/P, and FB/(P*R) metrics with P*R as CP are all composed of the same parameters and yet perform so differently on the test. The cause of this phenomenon is investigated herein.

The degree of metric performance variation with respect to the mission variation is essentially determined by its sensitivity to each of the mission parameters. In Fig. 15, the first two columns show the metric sensitivities to range and payload, respectively. FB, in the top row, increases as range or payload increases as the positive slopes indicate. However, the steeper slope in the FB vs. Range plot indicates that FB is more sensitive to the variation in range than it is to the variation in payload. Observation of the FB/(P*R) metric in the fourth row shows its different sensitivity to range and payload. The metric value goes up as range increases and goes down as payload increases. This is due to the fact that fuel burn increase at a slower rate than payload increases whereas fuel burn increases at a faster rate than range does. When FB/(P*R) is evaluated against P*R, the metric performance varies significantly even when the P*R is fixed. Because of the different sensitivity of FB/(P*R) to payload and range, the metric can be reduced or increased by trading range and payload while keeping the productivity (e.g. P*R) the same. The FB/R metric in the second row, on the other hand, shows very similar sensitivity to payload and range. Therefore, for the FB/R vs. P*R, trading payload with range does not affect the metric value as significantly. The varying sensitivities explain that even though several metrics include the same parameters, they perform differently according to the evaluation criteria.

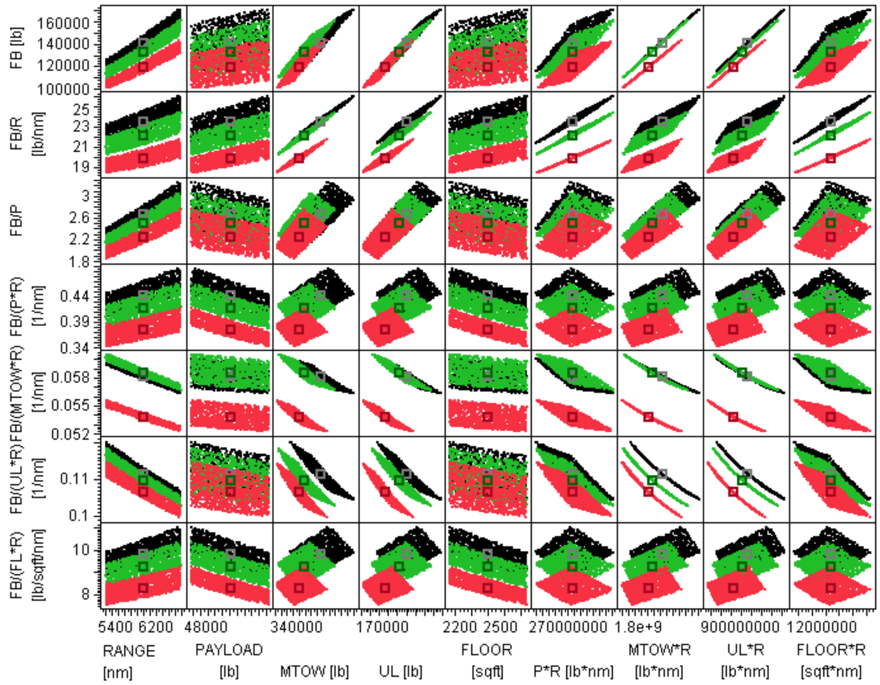


Fig. 15 Mission Performance Based Metrics and CPs – EDS Small Twin Aisle Analyses

In order to investigate how the current approach would affect the metric-CP performance, the metric systems were evaluated at three additional conditions: 1) changing design payload and design range by 5%, respectively, 2) changing design payload and design range by 10% while keeping the cabin floor area and number of seats the same, and 3) applying a 20% airframe weight reduction technology.

The first test considered a smaller change in payload and range. Changing payload and range at different percentages affected the degree of disparity only for the metrics that showed large changes with mission variation. For FB/(P*R) vs P*R, the size of the diamond within a technology group was reduced with smaller mission variations. For the metrics that previously showed a very tight collapse within in a technology group, the sensitivities were not affected. Overall, the ranking of the metric-CPs for EC1 and EC4 was not changed by how much the mission capability was changed.

In the second test, varying design payload without changing aircraft fuselage geometry reduced the sensitivity of fuel burn to the change in design payload. Since the metric performance with respect to EC1 and EC4 is determined by its relative sensitivity to payload and range change, this new assumption changed the metric performance. For example, the degree of dispersion in technology groups became even bigger for FB/(P*R). On the other hand, FB/R vs. P*R showed very good separation between the technology groups for all 5 EDS aircraft.

Finally, the purpose of the third test was to see if the trend observed for each metric vs. MTOW (e.g. FB vs MTOW*R as in Fig. 13) holds when the airframe weight was further reduced. The test showed that the aircraft group with 20% airframe weight reduction was still aligned with the current technology group. This simple metric-CP study with different sets of aircraft capability and technology assumptions confirmed that what matters most to the metric-CP performance on EC1 and EC4 is the relative sensitivity to each one of the mission capability parameters.

The analyses discussed for the STA was repeated for each of the EDS aircraft and is plotted together in Fig. 16. Since each aircraft has different sensitivities to design payload and range variations, some of the observations made for the STA aircraft were different for other vehicles. An aircraft with a 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 change in design range. Due to low sensitivity to design range change, some metrics for the RJ and SA aircraft performed quite differently. In the case of FB/R, its sensitivity to payload and range was quite similar to the STA, LTA, and the LQ aircraft. Therefore, FB/R vs P*R supported evaluation criteria 1 and 4. However, FB/R was much more sensitive to payload 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.

The key observations that are consistent on all five vehicles are summarized. Metrics that include “load” terms (FB/P, FB/(P*R), and FB/(FL*R)) showed 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. FB/R vs P*R and FB/R vs FL*R best support EC1 and EC4 for the STA, LTA, and LQ aircraft; however, they can potentially reward an aircraft with lower payload or floor area for the RJ and SA aircraft. FB/R vs. UL also showed medium level of dispersion within a technology group and should be considered as a metric-CP candidate. Finally, while FB/R vs. MTOW may not differentiate airframe weight reductions, it consistently showed tight collapse of aircraft in the same technology group while reducing the block fuel and should be considered as a metric-CP candidate.

4.4 Metric-CP Evaluation at the Fleet Level

All the discussions have been focused on the metric performance at each vehicle level. Expanding metric-CP evaluation to the fleet level is essential to answer the following questions:

- How can a stringency level(s) as a functional relationship between a metric and a CP be defined?
- What would be an evaluation point(s) within the payload-range envelop that is equitable to all stakeholders?
- What are the good CPs that represent aircraft capability? (EC3)

While not essential, a clear trend line formed for a metric-CP would be desirable under the following conditions: 1) all the aircraft plotted are of a similar technology level and 2) the evaluation point for all aircraft is fair. If a metric-CP shows a clear trend across the fleet, then defining the functional relationship for the potential stringency level and test procedures would be simple. If not, more complicated standard structure, e.g. multiple stringency levels, multiple applicability levels, and/or test procedures would be necessary. Complexity in a standard may not only increase the risk of introduction of such a standard being delayed but also the risk of being gamed.

In order to properly answer the research questions, a fleet level study including wide range of aircraft types and evaluation points is required. However, some preliminary observations based on the notional aircraft derived from the 5 EDS aircraft are made herein based on Fig. 16.

The FB, FB/R, FB/(MTOW*R), and FB/(UL*R) metrics show very good trend among the 5 aircraft for most of the CPs. On the other hand, FB/P and FB/(P*R), do not show a clear line with any of the CPs studied. These metrics are very sensitive to the evaluation point selection—especially the load factor—as such, further investigations on fair evaluation point should be conducted. For FB/(P*R), for example, the SA aircraft is the second group from the left and is out of the trend. The SA aircraft group show very good fuel efficiency based on the FB/(P*R) metric since load factor at design payload relative to the maximum payload is quite high for the SA aircraft. For the FB/(FL*R), while the variation due to mission change within aircraft types were large, the metric variation across the fleet seems to be quite uniform. The SA aircraft is not quite distinguished from the trend, since FB/(FL*R) is less sensitive to the load factor at the design point. Column by column comparisons suggest which CP represent aircraft capacity better. CPs with two parameters separates the five aircraft better than one parameter CPs. When range alone is used, the LTA and LQ aircraft are on top of each other, which indicates that using range alone does not represent aircraft capability well. Among one parameters CPs, MTOW and UL seem to represent aircraft capacity better than range, payload, or floor area alone. One should note that the CP consideration should also take into account what parameters are currently certified. Payload and range are not, MTOW is. If one were to plot MTOW vs. P*R, a clear linear trend would exist. As a consequence, although the P*R correlating parameter may appear to be a clear winner, using MTOW as a proxy for P*R may be more conducive to show compliance with a standard.

5 Analyses of the Point Performance Metrics and Correlation Parameters

The nautical air mileage (NAMS) based CO_2 metrics are investigated in this section. NAMS properties, advantages, and disadvantages when used as a CO_2 metric for a certification standard are discussed first. Then, evaluation results of the NAMS based metrics with respect to EC1 and EC4 are presented.

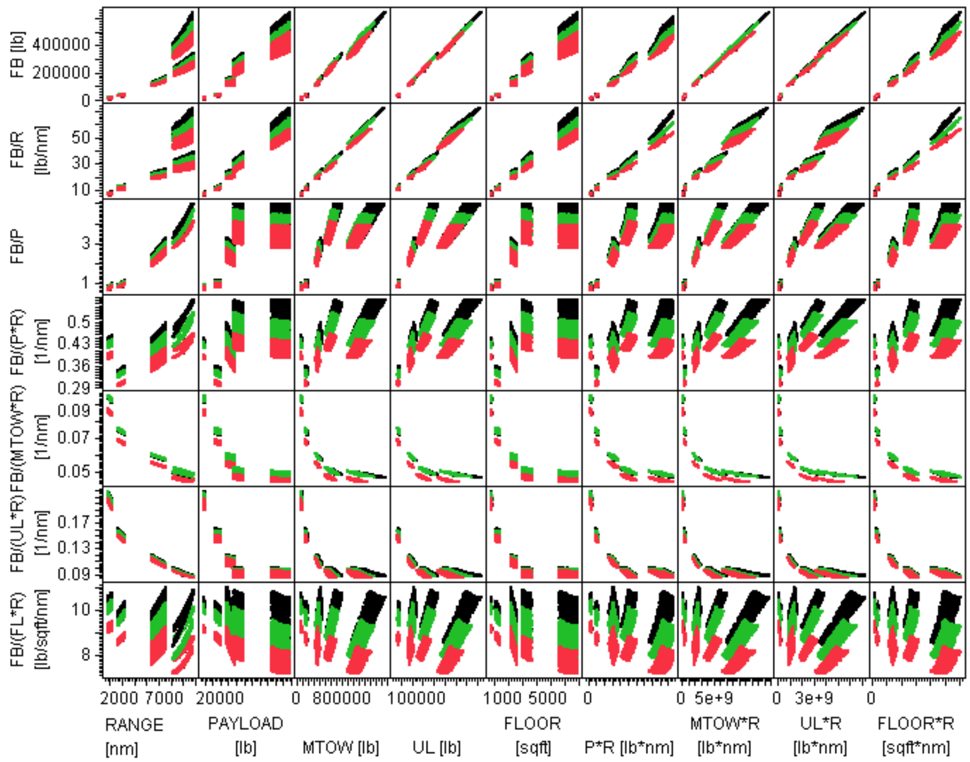


Fig. 16 Mission Performance Based Metrics and CPs – Five EDS Aircraft Analyses

5.1 Properties of Point Performance Metrics

Often, aircraft manufacturers provide guarantees to the customers. Historically, NAMS has been used as an aircraft fuel efficiency measure by the industry. A purchase agreement from the Airbus Industry and US Airways available publicly through the Security Exchange and Commission's database, also includes point performance guarantees including NAMS and mission guarantees such as block fuel, payload, and range [11]. In that legal agreement, a lower limit on NAMS value was required at a given speed, altitude, temperature, and aircraft weight. While only four parameters were necessary to measure NAMS, measuring any of the mission performance parameters such as range, fuel burn, and payload were very complicated. In order to measure fuel burn for a given range and payload, approximately 26 conditions had to be specified, ranging from fuel allowance for taxi-out to reserve fuel conditions. Agreement on all these conditions between two stakeholders for an aircraft would be feasible, but agreement on a consistent set of mission conditions that is equitable across multiple aviation stakeholders would be extremely difficult and potentially delay the introduction of a CO_2 emission standard based on mission performance parameters.

Another advantage of NAMS is its independence to utilization. NAMS is nearly inversely proportional to aircraft weight as defined in Eq. (2). While NAMS is sensitive to aircraft weight, the specific weight composition is not important. For example, a NAMS value measured at 100,000 lb of gross weight composed of either 50,000 lb of OEW, 40,000 lb of fuel, and 10,000 of payload or 55,000 lb of OEW, 15,000 lb of fuel, and 30,000 lb of payload is exactly the same. Therefore, NAMS can be measured at a certain percentage of MTOW, which is already certified, and it is not necessary to specify the OEW, payload, mission range conditions or anything else: only the weight is needed. Since mission payload and range as well as OEW itself can vary significantly after an aircraft is delivered to a customer, a metric that is independent to any of these parameters could greatly simplify the certification process of a CO_2 standard.

A potential drawback using point based NAMS metrics is that it may not completely capture fuel burn improvements away from that single test point. Since NAMS is measured at a single steady-state cruise condition, those technological improvements, specifically targeted for non-cruise mission segments such as taxi and climb, may not be directly captured by NAMS based metrics. This is a topic of further study by the authors, but not included herein.

5.2 Analysis Results on the Five EDS Aircraft

In order to evaluate the NAMS metric performance with respect to EC1 and EC4, the process formulated previously was utilized. NAMS 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 NAMS was calculated. The authors believe that this should be the choice of the manufacturers during compliance. In order to determine whether the specific weight condition selected would affect metric performance, three different weight conditions were tested. The same set of CPs used previously was used for this test.

Analysis results on the EDS STA aircraft are depicted in Fig. 17. The metrics are 1/NAMS85, 1/NAMS80, and 1/NAMS75. These three metrics are the inverse of NAMS in English Units measured at 85, 80, and 75% of MTOW, respectively. The units are pounds of fuel per nautical miles. Two other metrics in the bottom rows are 1/(NAMS*P), and 1/(NAMS*MTOW). The key observations from the STA aircraft performance are as follows:

- 1/NAMS metrics were found to exhibit very good quality that supports EC1 and EC4 when associated with either UL, P*R, or FL*R
- 1/(NAMS*P) show large dispersion within a technology group scoring worst on EC1 and EC4, especially
- 1/(NAMS*MTOW) does not reward aircraft structural weight improvements

General observations that were consistent for all 5 EDS aircraft were that 1/NAMS exhibit very similar characteristics to the FB/R metric. In addition, 1/(NAMS*P) showed very similar trend to FB/(P*R), and 1/(NAMS*MTOW) was very close to FB/(MTOW*R). Among the three different metrics, 1/NAMS seemed to be most desirable. Good CP candidates for this metric were P*R and FL*R based on EC1 and EC3 for the STA, LTA, and LQ. Again, for the RJ and SA aircraft, 1/NAMS vs. P*R and FL*R had a tendency to favor aircraft with low capacity.

Considering the fact that the key advantage of a NAMS based metric is its independence to mission and utilization, choosing a CP that is dependent on mission performance would not be desirable. When 1/NAMS is associated with MTOW, it shows best collapse of aircraft in the same technology group for all five aircraft. Moreover, this metric-CP combination has the great advantage of being much simpler than any other metric systems considered in this study. NAMS is potentially simpler to measure than mission parameters, and MTOW is already certified and mission and utilization independent, satisfying (EC2). However, as discussed previously, this pair may not reward aircraft improvements via better structural efficiency, but a similar trend is observed with EPNdB versus MTOW of noise certification. Thus, the authors pose a question to intended readers: is this also acceptable?

1/NAMS vs. UL showed very good behavior with respect to EC1 and EC4. 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 would be that OEW is not certified, and the degree of effort and information necessary to certify OEW is expected to be very high and potentially delay the introduction of the CO_2 emission certification standard.

Analysis results from all five EDS aircraft are depicted in Fig. 18. All metrics except for the 1/(NAMS*P) show good trend lines with most of the CPs. The 1/(NAMS*P) metric is very sensitive to the payload condition and needs to consider other test procedures.

As 1/NAMS85, 1/NAMS80, and 1/NAMS75 show very similar results, the ratio of airplane weight to MTOW at a measurement point makes no significant impact on NAMS metrics' behavior, only changing the scale. While further investigation is warranted, this study suggests that measuring NAMS at a certain consistent fraction of MTOW seem be fair and the most promising path forward to defining a new CO_2 standard.

6. Investigation of the Robustness of the Metric-CP to Unintended Consequences

One final investigation for this research was a qualitative assessment of the robustness of the metric-CP combination to potential unintended consequences. Many of these issues were discussed throughout this paper, but are summarized herein due to the importance of the topic. The use of poorly defined metric-CPs to establish policies used to set certification standards can result in negative or perverse effects 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 results need to be assessed during the development process of a standard to insure its effectiveness.

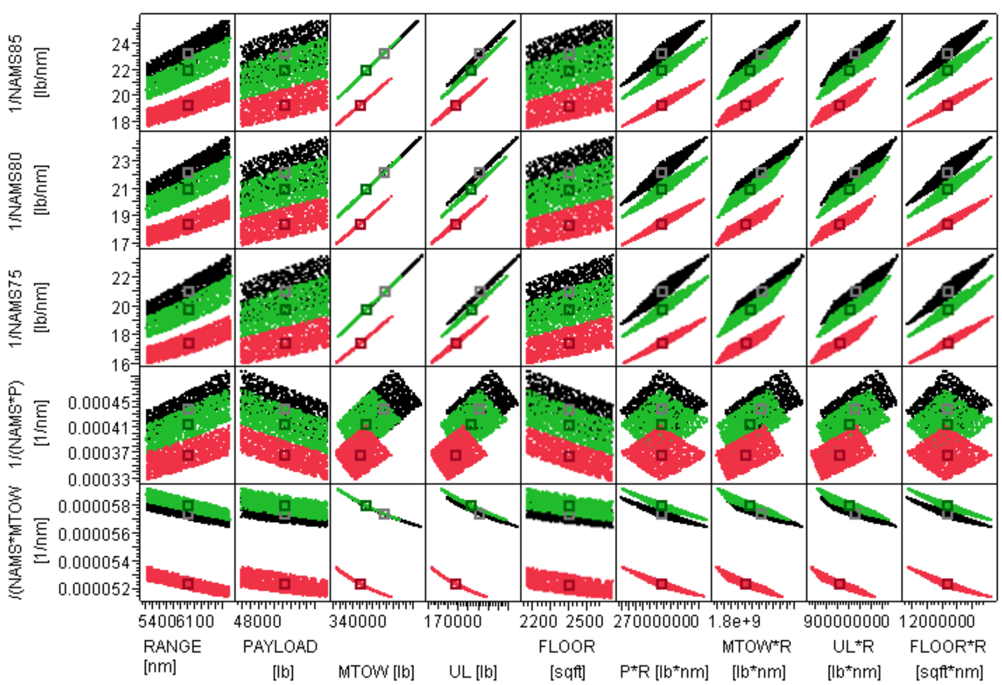


Fig. 17 NAMS-Based Metrics and CPs – EDS Small Twin Aisle Analyses

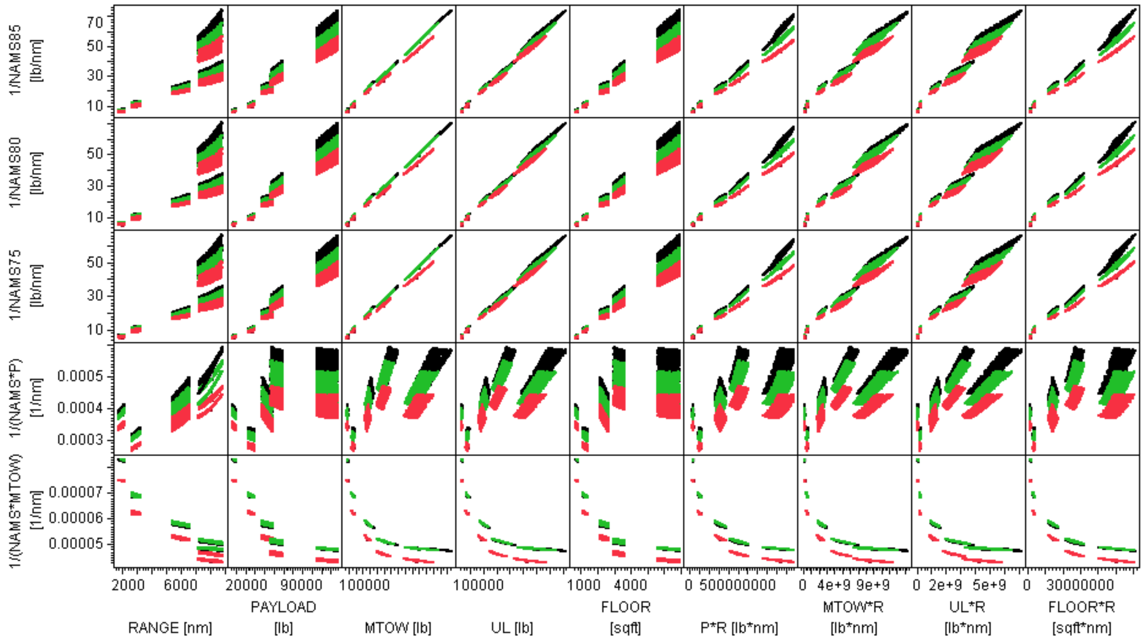


Fig. 18 NAMS-Based Metrics and CPs – Five EDS Aircraft Analyses

Using aircraft performance modeling and interviewing stakeholders, unintended consequences can be identified and include the implications of: (1) the metric-CP definition, (2) the certified level, (3) the scope of applicability of the standard, (4) the evaluation points (5) the test procedures, etc. This section addresses a few of the potential unintended consequences and is the focus of further research by the authors, but not included herein.

The definition of 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. As discussed earlier, a CO_2 standard could be based on a single parameter such as NAMS. Given that this metric measures the performance at one point of the cruise portion, it does not cover fuel burn performance during other phases of flights (e.g. climb and approach). As a result, there is the potential for designing aircraft that meet the certified level at cruise but would exhibit lower performance during other phases of flight.

Among the set of two parameter metrics, several potential unintended consequences can be envisioned. First, the inclusion of two parameters in a productivity term implies a relative trade-off between the two parameters (e.g. payload vs. range) as mentioned previously. However, while constructing a metric-CP for a future standard, it should be acknowledged that aircraft types are designed according to specific design philosophies and objectives that reflect market requirements. As discussed earlier, the choice of a metric-CP can result in the lack of adherence to the ECs outlined in this research since the same metric-CP values can be obtained via design choice or technology advancements. This conclusion is not in line with EC1.

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, for which this research has attempted to address.

The inclusion of specific aircraft characteristics (i.e. measure of what is transported) in the metric of the CP have the potential for unintended consequences. As highlighted earlier, the metric-CP based on UL*R could incentivize the development of aircraft with lower payload fraction and longer stage lengths (fuel fraction). The metric-CP based on MTOW*R, limits the incentives to reduce OEW, compared to other metrics such as payload-based metric. The FL*R based metric-CP 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),

The inclusion of speed in the metric-CP could provide different incentives to aircraft manufacturers. With speed included in the denominator of the metric (i.e. R*P*speed), manufacturers may be incentivized to evaluate and certify fuel efficiency performance at higher cruise speeds. A similar consequence may occur if MTOW is included in the denominator of the metric, such that the manufacturer would want to increase the MTOW to improve the metric. As further research is conducted on the metric and CPs, the unintended consequences, such as those mentioned here, will continue to be investigated given the significance highlighted here.

7 Conclusions and Future Work

Leveraging lessons learned from existing aviation environmental standards, a framework to evaluate aircraft CO_2 metrics and correlation parameters for a potential CO_2 standard was developed. Both block fuel and NAMS based metric candidates along with both one parameter and two parameter CPs were evaluated for notional aircraft derived from 5 EDS aircraft classes ranging from a regional jet to a 500+ passenger aircraft. While no single metric-CP fully satisfied all evaluation criteria across the fleet, several promising candidates were identified. While a judgment will be necessary to pick the best metric-CP, the 1/NAMS metric associated with MTOW as a CP seemed to be most promising. The 1/NAMS with either UL or P*R and FB/R with MTOW, UL, FL*R, or P*R are also recommended for further study. More conclusive recommendations shall be made through additional assessments of more metrics and CPs evaluations, which the authors are continuing.

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