Project 82a/b

Integrated Noise and CO_2 Standard Setting Analysis

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Objective:

This project will provide technical support to the FAA for the assessment of the 13th cycle of Committee on Aviation Environmental Protection's (CAEP/13) stringency analysis including cost estimation of various stringency options

The end result will provide the FAA with a data-driven process for decision-making, including the interdependencies between CO_2 and noise as well as the costs associated with their mitigation.

Project Benefits:

This project will provide the FAA with an understanding of the implications of different stringency analysis on the mitigation of the environmental impacts of aviation and the associated costs of achieving those benefits.

The work will support FAA engagement and decision-making at the International Civil Aviation Organization under CAEP and will enhance the cost analysis of stringency options

Research Approach:

- Development of an updated non-recurring cost model
- Assessment of the interdependencies of noise and CO_2 and the resulting costs associated with different stringency options across multiple aircraft classes
- Assessment of the interdependencies of CO_2 and NO_x emissions using engine and aircraft model coupled with fleet level environmental assessment
- Collaboration and dissemination of assumptions and results within the CAEP community
- Provide the US Research Team with necessary analysis to establish a data-driven decision

Major Accomplishments (to date):

- Developed an initial non-recurring cost model to quantify the economic implications of various stringency options
- Conducted an analysis on the noise margins as a function of takeoff mass and thrust
- Creating new technology response ranges across aircraft classes
- Quantified sensitivity of environmental impacts due to CO_2 and NO_x emissions to propulsion system design
- Contributed materials to various CAEP working groups

Future Work / Schedule:

- Finalize the technology responses
- Continue to develop the cost model and engage relevant stakeholders
- Collaborate with US Research Team to conduct the CAEP/13 stringency analysis

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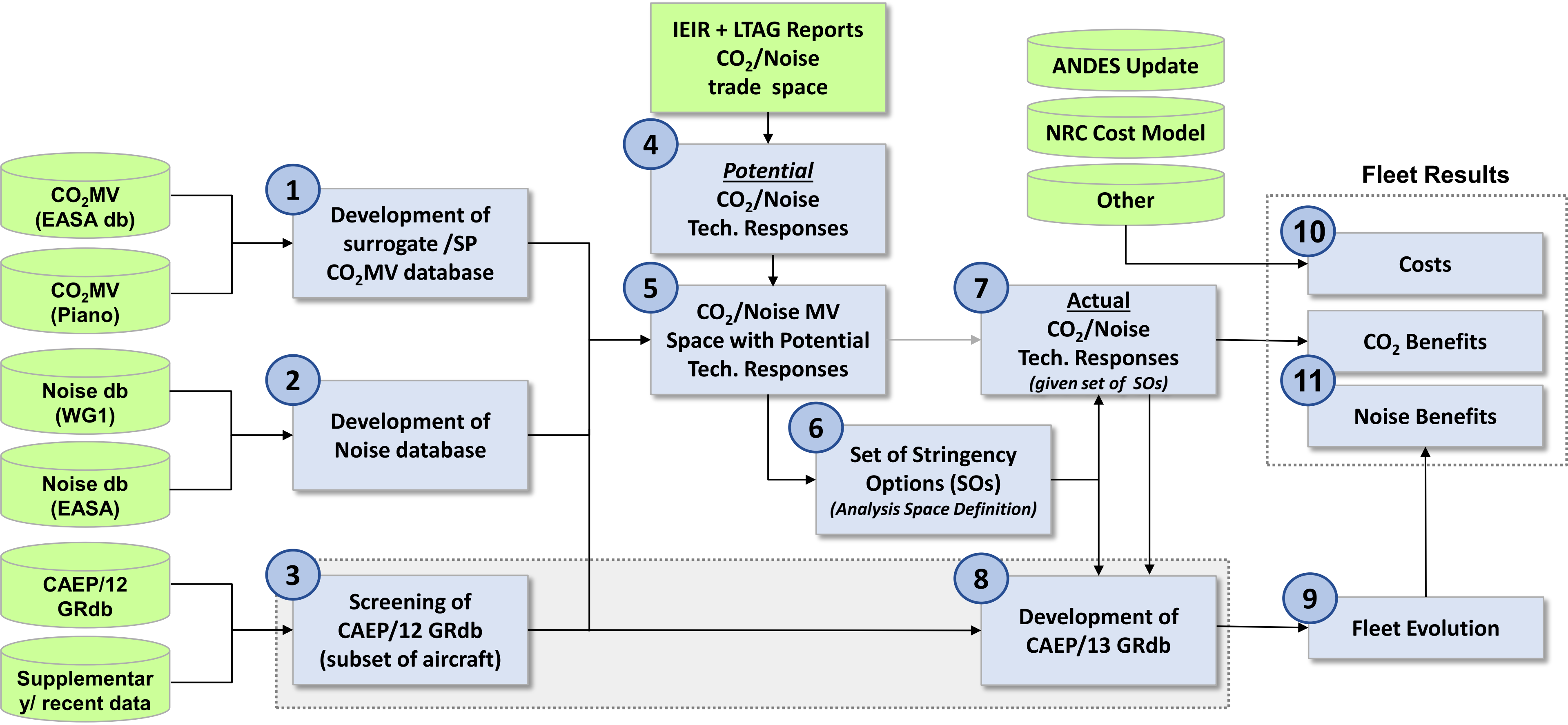
Objective

- This project will provide technical support to the FAA for the assessment of the 13th cycle of Committee on Aviation Environmental Protection's (CAEP/13) stringency analysis including cost estimation of various stringency options
- Provide the FAA with an understanding of the implications of different stringency analysis (CO_2 and noise) on the mitigation of the environmental impacts of aviation and the associated costs of achieving those benefits
- Research will support FAA engagement and decision-making at CAEP
- International implications on the future of aviation

High Level Overview of Approach



CO_2MV (EASA db)

CO_2MV (Piano)

Noise db (WG1)

Noise db (EASA)

CAEP/12 GRdb

Supplementary/ recent data

1 Development of surrogate /SP CO_2MV database

2 Development of Noise database

3 Screening of CAEP/12 GRdb (subset of aircraft)

IEIR + LTAG Reports CO_2/Noise trade space

4 *Potential* CO_2/Noise Tech. Responses

5 CO_2/Noise MV Space with Potential Tech. Responses

6 Set of Stringency Options (SOs) *(Analysis Space Definition)*

7 Actual CO_2/Noise Tech. Responses *(given set of SOs)*

8 Development of CAEP/13 GRdb

ANDES Update

NRC Cost Model

Other

Fleet Results

10 Costs

CO_2 Benefits

11 Noise Benefits

9 Fleet Evolution

Team Member Recent Highlights

- Georgia Tech
  - Non-recurring cost model development
  - Technology responses available to the current fleet
- MIT
  - Evaluated CO_2 – NO_x interdependencies
  - Calculated sensitivity of environmental impact to propulsion system design parameters
- Both universities are providing support to the US Research Team to accomplish the CAEP/13 workplan

Non-Recurring Cost Model Development

Summary of Models

Exponential

CAEP/10 model (Previously called the Sample Problem Approach)

- baseline cost
- exponential cost rise

$$\mathrm{NRC}_{\mathrm{Airframe}} = \left[\Delta + A\exp\left(Bx\right)\right] S$$

$$S = \left(\frac{m}{m_{\mathrm{ref}}}\right)^{0.5453 + \frac{0.6970 - 0.5453}{1+\exp\left(-25\left(x - 0.3\right)\right)}}$$

$$x = \alpha x_{\mathrm{CO_2}} + \left(1-\alpha\right) x_{\mathrm{Noise}}$$

Three-Tier Step and Exponential

A combination of:

- tiered stepped cost rise with three tiers:
  - small fix, derivative, new
- exponential cost rise

$$\mathrm{NRC}_{\mathrm{Airframe}} = \left[\Delta_{\mathrm{f}} + \frac{\Delta_{\mathrm{d}}}{1+\exp\left(-25\left(x_3 - \frac{1+2\beta}{4}\right)\right)} + \frac{\Delta_{\mathrm{n}}}{1+\exp\left(-25\left(x_3 - \frac{3-2\beta}{4}\right)\right)} + A\exp\left(Bx_3\right)\right] S$$

$$S = \left(\frac{m}{m_{\mathrm{ref}}}\right)^{0.5453 + \frac{0.6970 - 0.5453}{1+\exp\left(-25\left(x_3 - \frac{1+2\beta}{4}\right)\right)}}$$

$$x_3 = \begin{cases} \beta x & \text{for small fix} \\ 1/2 + \beta\left(x - 1/2\right) & \text{for derivative} \\ 1 + \beta\left(x - 1\right) & \text{for new} \end{cases}$$

$$x = \alpha x_{\mathrm{CO_2}} + \left(1-\alpha\right) x_{\mathrm{Noise}}$$

Two-Tier Step and Exponential

A combination of:

- tiered stepped cost rise with only two tiers (small fix vs. others)
- exponential cost rise

$$\mathrm{NRC}_{\mathrm{Airframe}} = \left[\Delta_{\mathrm{f}} + \frac{\Delta_{\mathrm{d/n}}}{1+\exp\left(-25\left(x_2 - {}^{1}/_{2}\right)\right)} + A\exp\left(Bx_2\right)\right] S$$

$$S = \left(\frac{m}{m_{\mathrm{ref}}}\right)^{0.5453 + \frac{0.6970 - 0.5453}{1+\exp\left(-25\left(x_2 - {}^{1}/_{2}\right)\right)}}$$

$$x_2 = \begin{cases} \beta x & \text{for small fix} \\ 1 + \beta\left(x - 1\right) & \text{for derivative or new} \end{cases}$$

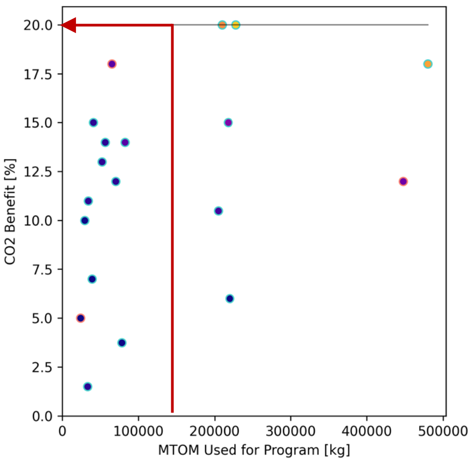
$$x = \alpha x_{\mathrm{CO_2}} + \left(1-\alpha\right) x_{\mathrm{Noise}}$$

Non-Recurring Cost Model Development

Summary of Normalization Methods

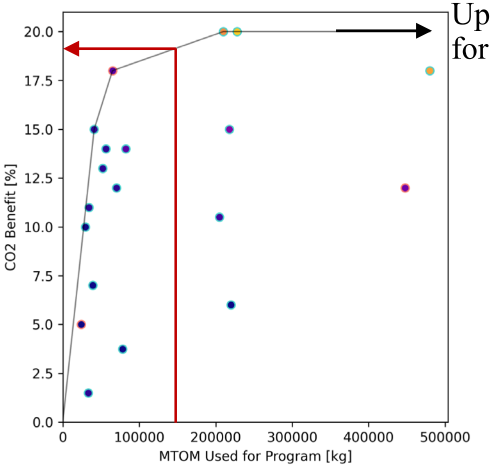
Simple Normalization

The largest metric value improvement in the data set is taken as the upper limit for the metric of interest.



Envelope Normalization

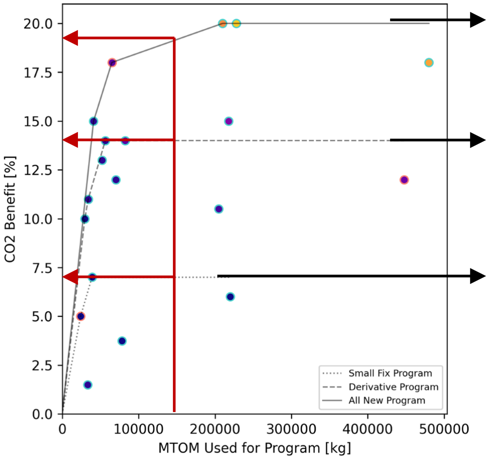
An envelope is created using max slopes from (0, 0) using points in the data set.



Upper limit for all aircraft

Tier Envelope Normalization

An envelope for each tier is calculated from the data set using max slopes from (0, 0)



All new

Derivative

Small change

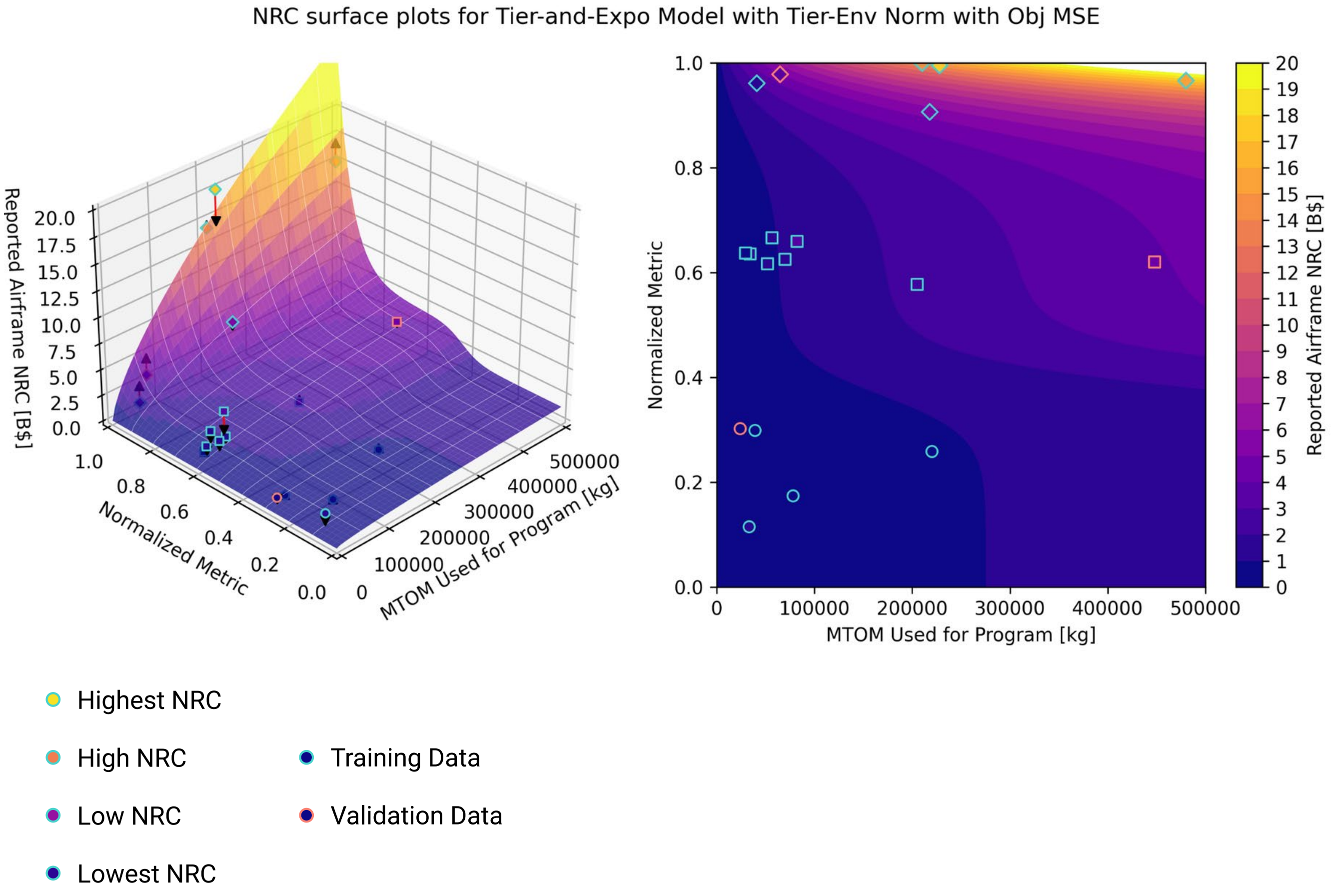
For a given MTOM, the upper limit of the metric value improvement is determined. The lower limits are assumed to be zero. The normalization is performed using:

$$x_{CO_2} = \frac{CO_2\ MV\ Improvement - \cancelto{0}{CO_2\ MV\ Lower\ Limit}}{CO_2\ MV\ Upper\ Limit - \cancelto{0}{CO_2\ MV\ Lower\ Limit}}$$

Similar approach is followed for noise as well.

Non-Recurring Cost Model Development

3-Tier Step and Exponential Model with Tier Envelope Normalization Results



- ✓ Overall, this model does a very good job of NRC prediction with small error
- ~ Normalized metric is mostly driven by CO2 as expected
  - 86% CO_2
  - 14% Noise
- ? The NRC is peaking very rapidly with normalized metric
  - The model is trying to thread the needle between low NRC new designs and high NRC new designs

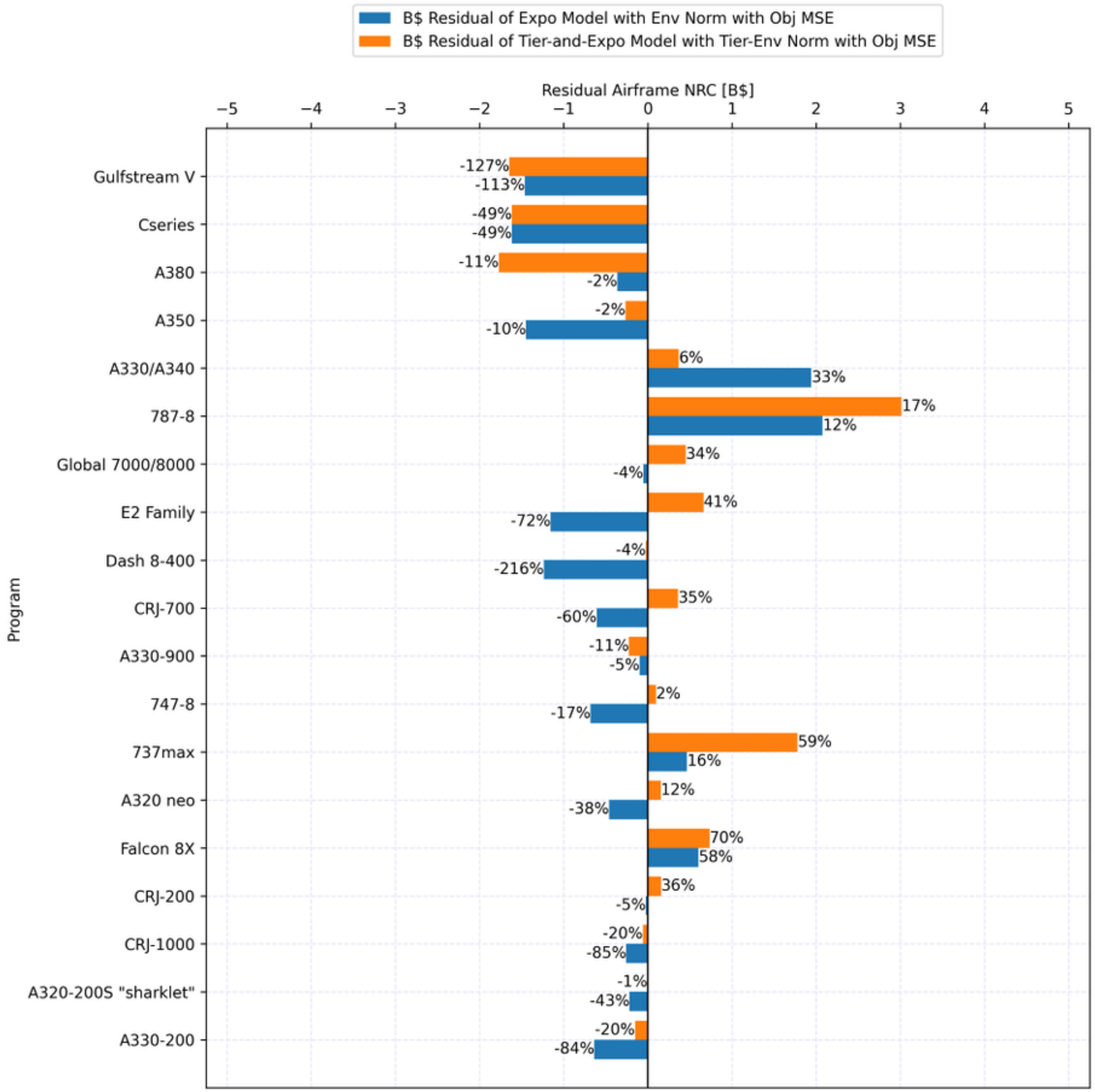
Non-Recurring Cost Model Development

3-Tier Step and Exponential Model with Tier Envelope Normalization Results

	Program (Program Specific Aircraft)	MTOM (kg) used for Program	Reference Aircraft	Fix Type	CO_2 MV Improvement (%)	Noise MV Improvement (EPNdB)	x_{CO2}	x_{dB}	x	Reported Airframe NRC (B$2010)	Predicted Airframe NRC (B$2010)	Error in Airframe NRC
T	A320-200S (A320-241 sharklets)	78000	A320-214	1	3.75	2.1	0.5357	0.4375	0.1740	0.5	0.5036	-0.0036
T	A330-200 (A330-203)	220000	A330-322	1	6	1.4	0.8571	0.2917	0.2593	0.755	0.9076	-0.1526
T	CRJ-1000 (CL-600-2E25)	38995	CRJ-900	1	7	1.3	1.0000	0.2708	0.2993	0.303	0.3637	-0.0607
V	CRJ-200 (CRJ-100/200)	24040	CRJ-100	1	5	1.2	1.0000	0.3443	0.3028	0.436	0.2795	0.1565
T	Falcon 8X (Falcon 8X)	33112	Falcon 7X	1	1.5	4.8	0.2414	1.0000	0.1158	1.046	0.3149	0.7311
T	737max (737-8)	82190	737-800	2	14	12.0	1.0000	0.8451	0.6594	3	1.2211	1.7789
V	747-8 (B747-8)	447695	B747-400	2	12	12.5	0.8571	0.8803	0.6201	4	3.9021	0.0979
T	A320 neo (A320-2xxN)	70000	A320ceo	2	12	14.2	0.8571	1.0000	0.6257	1.228	1.0747	0.1533
T	A330-900 (A330-941)	205000	A330-341	2	10.5	8.8	0.7500	0.6197	0.5773	2	2.2251	-0.2251
T	CRJ-700 (CRJ-200)	34020	CRJ-200	2	11	2.8	1.0000	0.3292	0.6354	1.012	0.6529	0.3591
T	Dash 8-400 (Dash 8-4xx ER)	29574	Dash 8-300	2	10	2.8	1.0000	0.3787	0.6377	0.571	0.5928	-0.0218
T	E2 Family (A190-E2)	56400	EMB-190-100IGW	2	14	14.1	1.0000	1.0000	0.6667	1.605	0.9433	0.6617
T	Global 7000/8000 (Global 7500)	52095	Global 6000	2	13	1.7	0.9685	0.1305	0.6171	1.322	0.8721	0.4499
T	787-8 (787-8)	227900	B767-300ER	3	20	13.6	1.0000	0.9067	0.9956	17.5	14.4864	3.0136
T	A330/A340 (A330-322)	218000	A300-B4-622R	3	15	8.0	0.7500	0.5333	0.9066	5.892	5.5255	0.3665
T	A350 (A350-941)	210000	A330-342	3	20	15.0	1.0000	1.0000	1.0000	14.166	14.4311	-0.2651
T	A380 (A380-842)	480000	747-400	3	18	13.5	0.9000	0.9000	0.9667	15.577	17.3485	-1.7715
V	Cseries (A220-100)	65000	CRJ-1000	3	18	7.6	1.0000	0.5366	0.9784	3.305	4.9215	-1.6165
T	Gulfstream V (GV-SP)	41050	GIV-SP	3	15	1.7	1.0000	0.1657	0.9611	1.293	2.9384	-1.6454

Non-Recurring Cost Model Development

3-Tier Step and Exponential Model with Tier Envelope Normalization Results



Developing Possible Technology Responses

- Utilize the fuel burn baskets from the LTAG study and the noise baskets form the IEIR report
- Representative fuel burn baskets depicted below
- Apply the baskets to each of the Technology Reference Aircraft (TRA) for a given date of applicability

Aerodynamics
- Excrescence Reduction
- Flow Control: HLFC / NLF, Riblets
- Active CG Control
- Advance Wingtip Devices
- MDAO – Configuration Integration

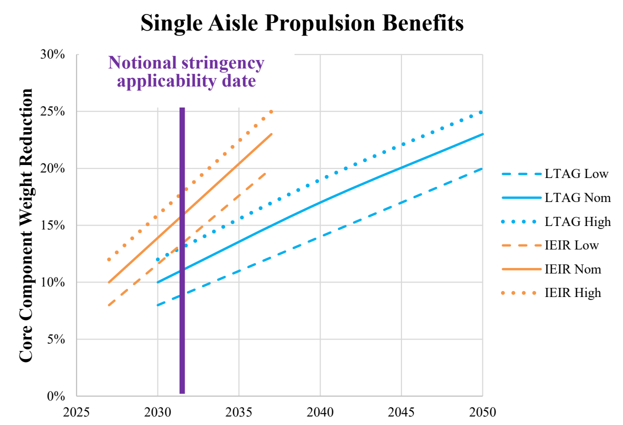
Structures / Materials
- Advanced Metallic Technologies
- Advanced Composite Technologies
- Optimized Local Design
- Multifunctional Design/Materials
- Advanced Load Alleviation
- Nacelle Improvements

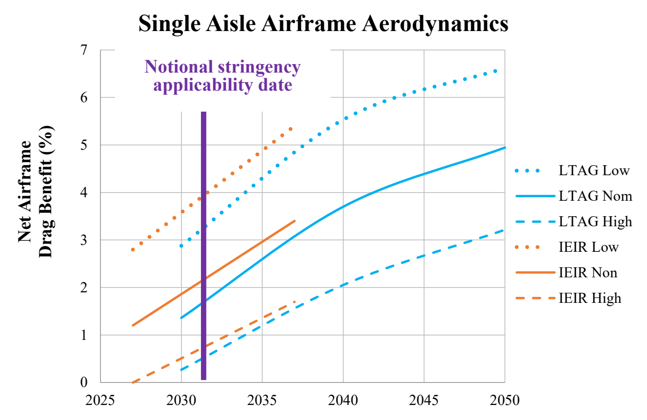
Systems
- More Electric A/C (replacement of various pneumatic systems with electrical equivalents)
- Adaptive ECS (Filtration and reconfiguration)

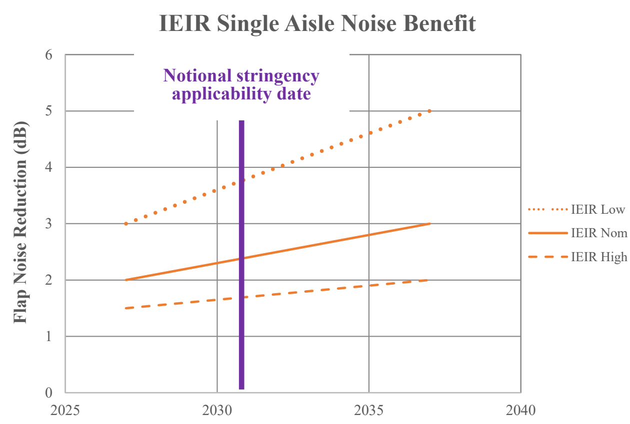
Propulsion
- Advanced Propulsion System
  - Higher OPR
  - Lower FPR
  - Component Weight Reductions
  - Component Efficiency Improvements

* Specific combination of technology baskets vary by aircraft class

Representative Technology Basket Response Data


Single Aisle Propulsion Benefits

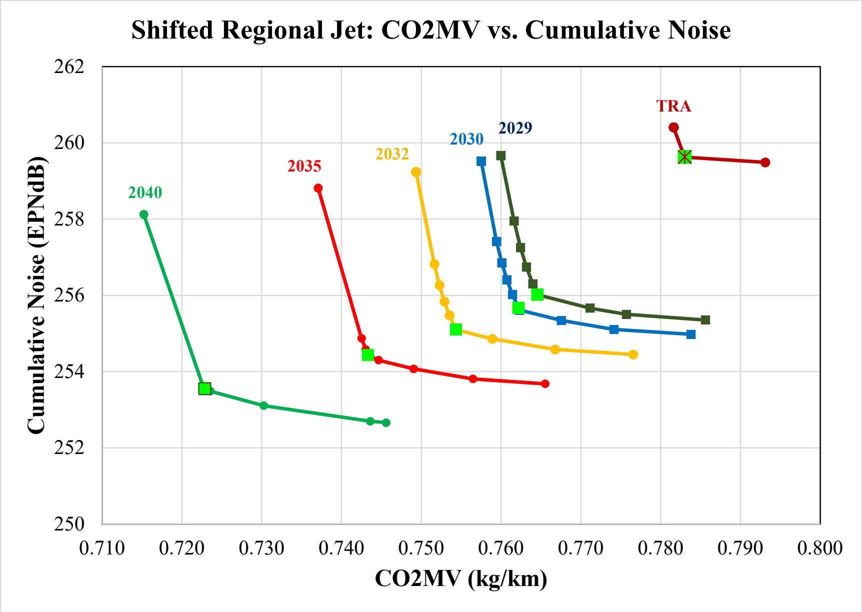

Single Aisle Airframe Aerodynamics

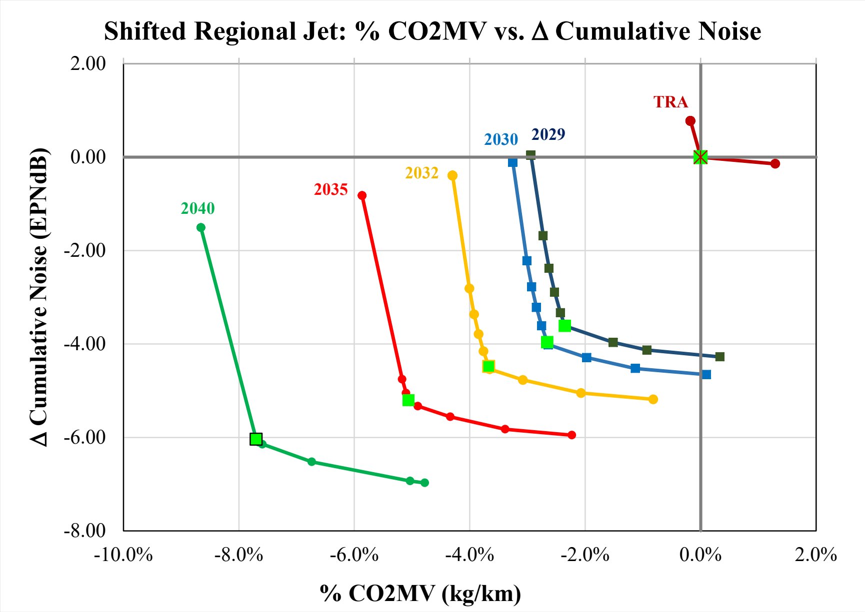

IEIR Single Aisle Noise Benefit

- Fuel burn airframe, propulsion, and systems fuel burn technology baskets and also design variables and constraints were updated from IEIR for LTAG
- No noise baskets in LTAG, will have to default to IEIR values, but don't have TP values
- **Each vehicle class has its own technology basket trends**
- Recommend to use the High Confidence level of technology baskets for the technology response, which represents an 80% level to achieve the value of the basket, which is the lower benefit

Possible Technology Responses: Regional Jet Class

- For 5 possible years of applicability, the 50/50 optimization weighed point was chosen to represent what is a possible technology response for that SO year
- Represents that maximum improvement possible for the RJ class for that year
- Can be used to establish the technology response of the existing fleet for the cost-benefit analysis if the OEMs cannot
- Also used as a sanity check if the OEMs can provide technology responses


Shifted Regional Jet: CO2MV vs. Cumulative Noise


Shifted Regional Jet: % CO2MV vs. Δ Cumulative Noise

Design drivers of CO_2 and NO_x emissions

- **CO_2** one of the dominant sources of aviation **climate impacts**
- **NO_x** dominant source of aviation **air quality** impacts
- There are known **interdependencies between CO_2 and NO_x emissions**
- Relevant metrics from an environmental standpoint are **full flight** (or fleet level) **emissions of CO_2 and NO_x**

CO_2 emissions

$$\mathrm{CO_2} \propto W_f$$

$$W_f = \underbrace{W_{\mathrm{land.}}}_{\text{Structural}} \left(\exp\left(\underbrace{\frac{1}{\eta_{\mathrm{ov}}}}_{\text{Propulsion system}} \times \underbrace{\frac{1}{L/D}}_{\text{Aerodynamics}} \times \frac{Rg}{\mathrm{LHV}} \right) - 1 \right)$$

Considering the engine only:

$$\eta_{\mathrm{overall}} = \eta_{\mathrm{propulsive}} \times \eta_{\mathrm{thermal}}$$

$$\eta_{\mathrm{thermal}} = f\left(\mathrm{OPR}, \frac{T_{t4}}{T_{t2}}\right)$$

NO_x emissions

$$\mathrm{NO_x} = \mathrm{EI(NO_x)} \times W_f$$

$$\mathrm{EI(NO_x)} = f(P_3, T_3, \mathrm{FAR}, \mathrm{combustor} \ldots)$$

$$P_3, T_3 = f(\mathrm{OPR}, \eta_{\mathrm{LPC,HPC}})$$

Approach to quantify interdependencies

- EI(NO_x) estimated using P_3T_3 method: $\mathrm{EI(NO_x)} = f(P_3, T_3)$
- Single-aisle class considered here with previous generation engine and aircraft model (think CFM56 generation)
- Emissions influenced by fuel, **aircraft + propulsion design** and operations
- Quantify the sensitivity of design variables on the monetized environmental impacts[1]
  - Climate damages modeled using APMT-Impacts Climate to estimate future GDP reductions due to climate change
  - Air pollution impacts modeled using APMT-Impacts AQ to calculate changes in exposure to $PM_{2.5}$ and ozone

NPSS model
(prev. generation engine for single aisle)

Aircraft model
(to capture airframe – engine interdependencies)

Fleet modeling
(capture spatial and temporal distribution of aviation emissions)

Monetized impacts
(both climate and air quality impacts)

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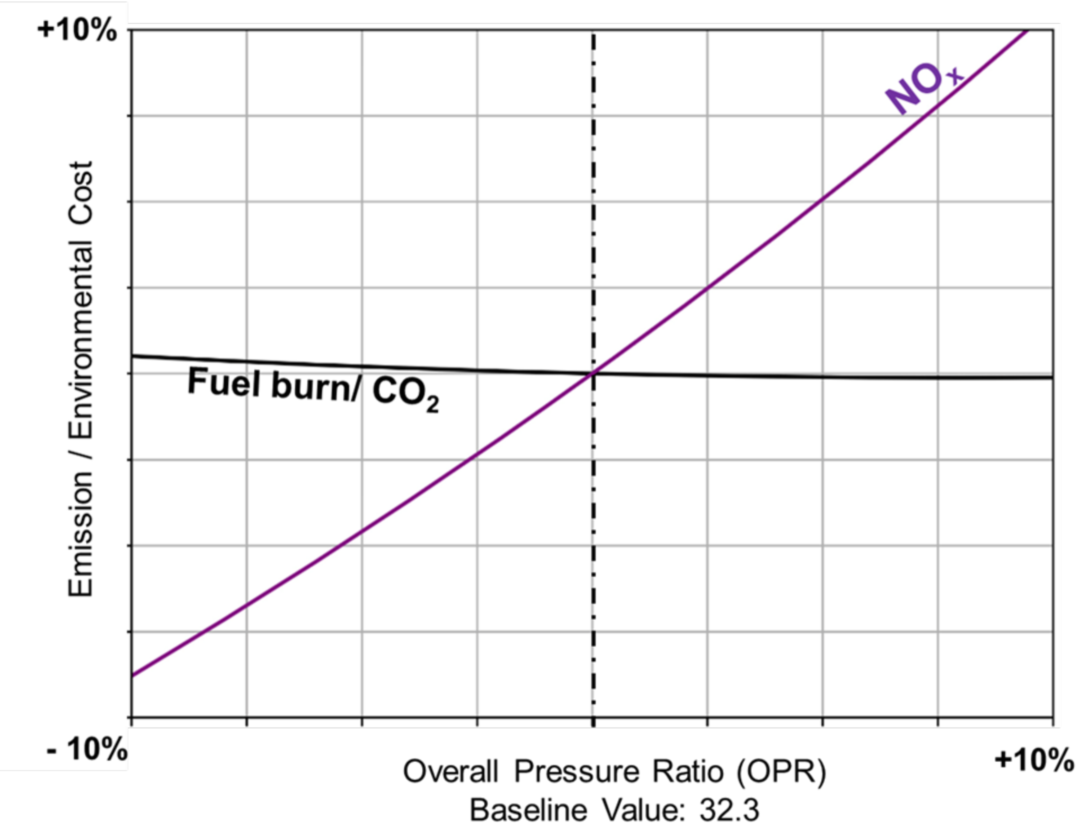
[1] Grobler et al. (2019) Marginal climate and air quality costs of aviation emissions. *Environmental Research Letters*. doi:10.1088/1748-9326/ab4942

Propulsion system: Impact of overall pressure ratio (OPR)

- **Increasing OPR reduces fuel burn** (and therefore **CO_2**) as the **thermal efficiency** of the engine **increases**
- **Increasing OPR increases the compressor exit temperature** which in turn **increases EI(NO_x)**
- **Increase in EI(NO_x) outpaces decrease in fuel burn →** NO_x emissions increase
- Need a **common basis** to compare the changes in CO_2 and NO_x



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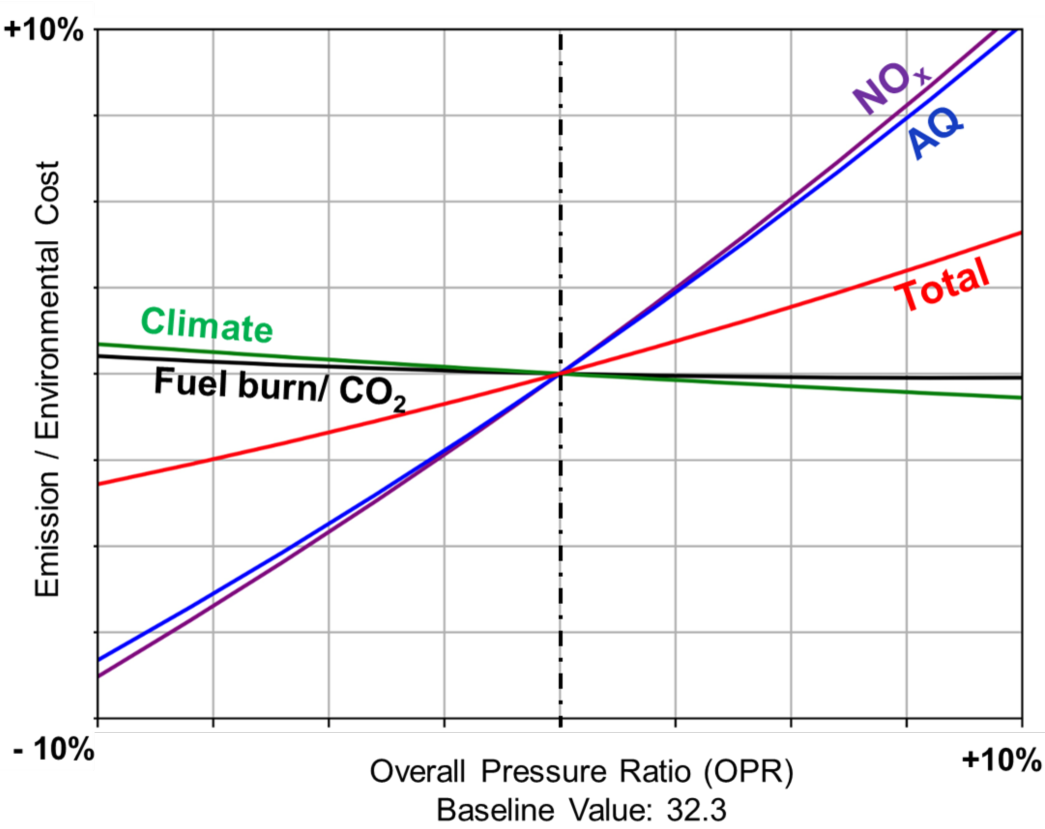
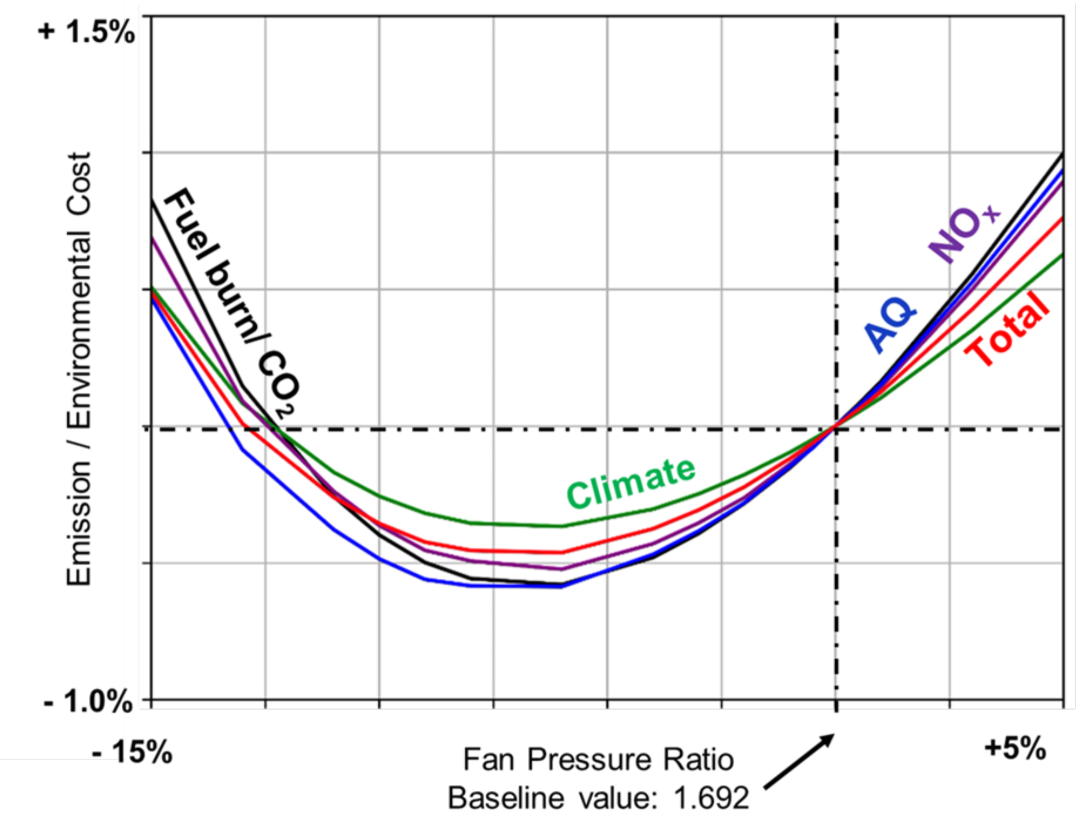
- **Increase in EI(NO_x) outpaces decrease in fuel burn →** NO_x emissions increase
- Need a **common basis** to compare the changes in CO_2 and NO_x
- **Only design variable which results in opposing fuel burn and NO_x emissions response**



Propulsion system: Impact of fan pressure ratio (FPR)

- **Decreasing FPR increases the propulsive efficiency** of the engine **reducing the fuel consumption and CO_2**
- Decreasing fan pressure ratio also implies a larger bypass ratio and a larger fan diameter which increases weight and drag
- EI(NO_x) relatively constant – NO_x follows CO_2 curve
- Results in non-monotonic behavior for fuel burn and NO_x emissions (relatively constant EI(NO_x))



Climate and air quality impacts can be compared on a cost basis

Design Parameter	Fleet fuel burn	Fleet NO_x	Climate cost	Air quality cost	Total Environmental cost
OPR	-0.033	$+0.96$	-0.078	$+0.91$	$+0.32$
FPR	$+0.16$	$+0.14$	$+0.10$	$+0.15$	$+0.12$
T_{t4}/T_{t2}	-0.18	-0.24	-0.11	-0.25	-0.17

Values indicate percent change in metric of interest to a percent increase in the design parameter

Next Steps

- Finalize the NRC model for the main analysis
- Identify the aircraft that could potentially respond to the stringency options under consideration
- Analyze sensitivity of environmental impact to airframe materials and improved aerodynamics
- Continue to support each of the CAEP Working Groups to meet an aggressive schedule
- Challenges exist in meeting the schedule due to international sanctions