ASCENT Project 83

NO_x cruise/climb metric system development

MIT

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Cost Share Partner: NuFuels LLC

Objective:

- Support FAA decision-making regarding an engine emissions certification standard relevant to cruise and climb operations
- Provide a rational, scientific basis for decisions on the implementation of cruise- and climb-relevant emissions standards

Project Benefits:

- Analyses will be conducted that provide understanding of the costs and benefits of both current standards and policies which may be proposed in the future
- Contribute to an efficient implementation process and provide industry with regulatory certainty.

Research Approach:

To develop metrics relevant to cruise/climb NO_x emissions, we focus on:

- Assessing the relationship between landing/takeoff emissions and cruise emissions
- Evaluating the effectiveness of LTO emissions standards at limiting the amount of pollutants emitted at altitude
- Developing candidate emission metrics that would provide control over full-flight emissions
- Assessing the ability of new emissions metrics to limit environmental damage from full-flight emissions

Major Accomplishments (to date):

- Project was funded on September 19, 2022

Future Work / Schedule:

- First year's work is on quantifying limitations of existing metrics and developing potential metrics relevant to cruise climb.
- In future years, the environmental impacts of standards based on these metrics will be evaluated.

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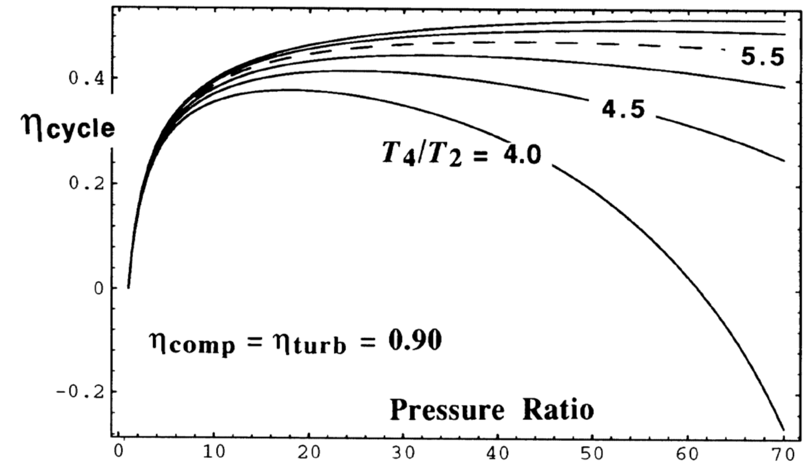
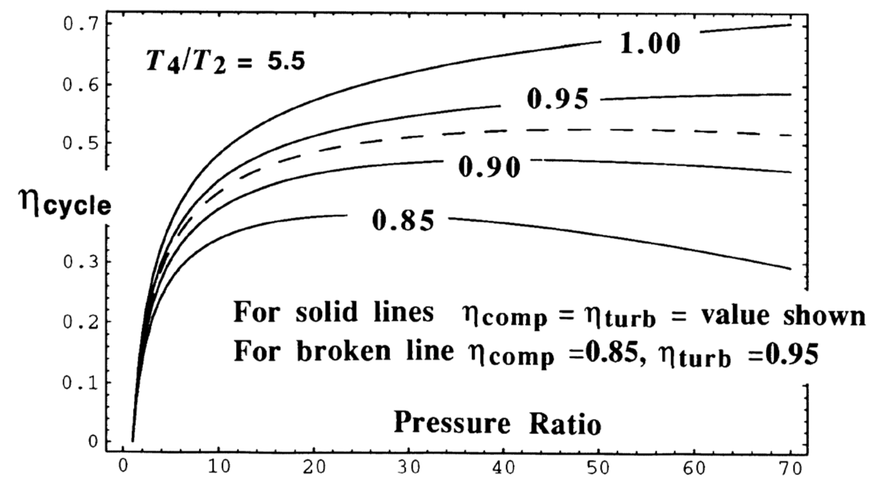
CO_2 and NO_x emissions depend on overall pressure ratio

- Cycle efficiency depends on:
  - OPR
  - Temperature ratio (T_4/T_2)
  - Component efficiencies (η_c, η_t)
- Technological improvements in component efficiencies and turbine temperature limits over time
  - Drives maximum efficiency to higher pressure ratios
- Higher OPR gives higher combustor inlet temperature (T_3)

$$\frac{T_3}{T_2} = 1 + \frac{1}{\eta_c}\left(\mathrm{OPR}^{(\gamma-1)/\gamma} - 1\right)$$

- For RQL combustors, higher T_3 gives higher NO_x emissions

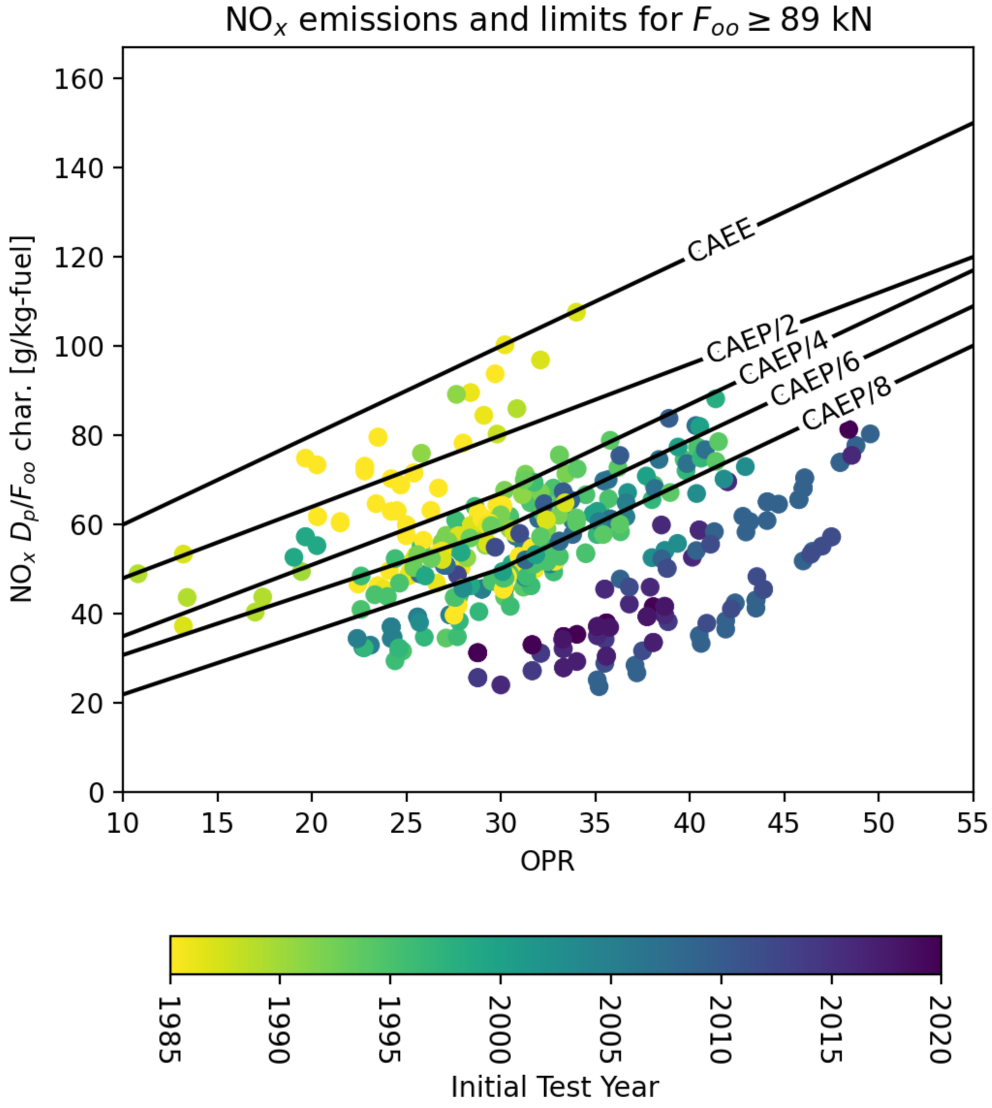




Cumpsty (2003)

NO_x limits & social costs of emissions

- ICAO emissions standards allow higher NO_x emissions at higher OPR
- This dependence on OPR implicitly defines an environmental tradeoff
- Questions from a social cost perspective:
  - **When operating at the CAEP/8 limit**, how does the social cost depend on OPR?
  - What would a NO_x limit that kept **social cost** constant look like?

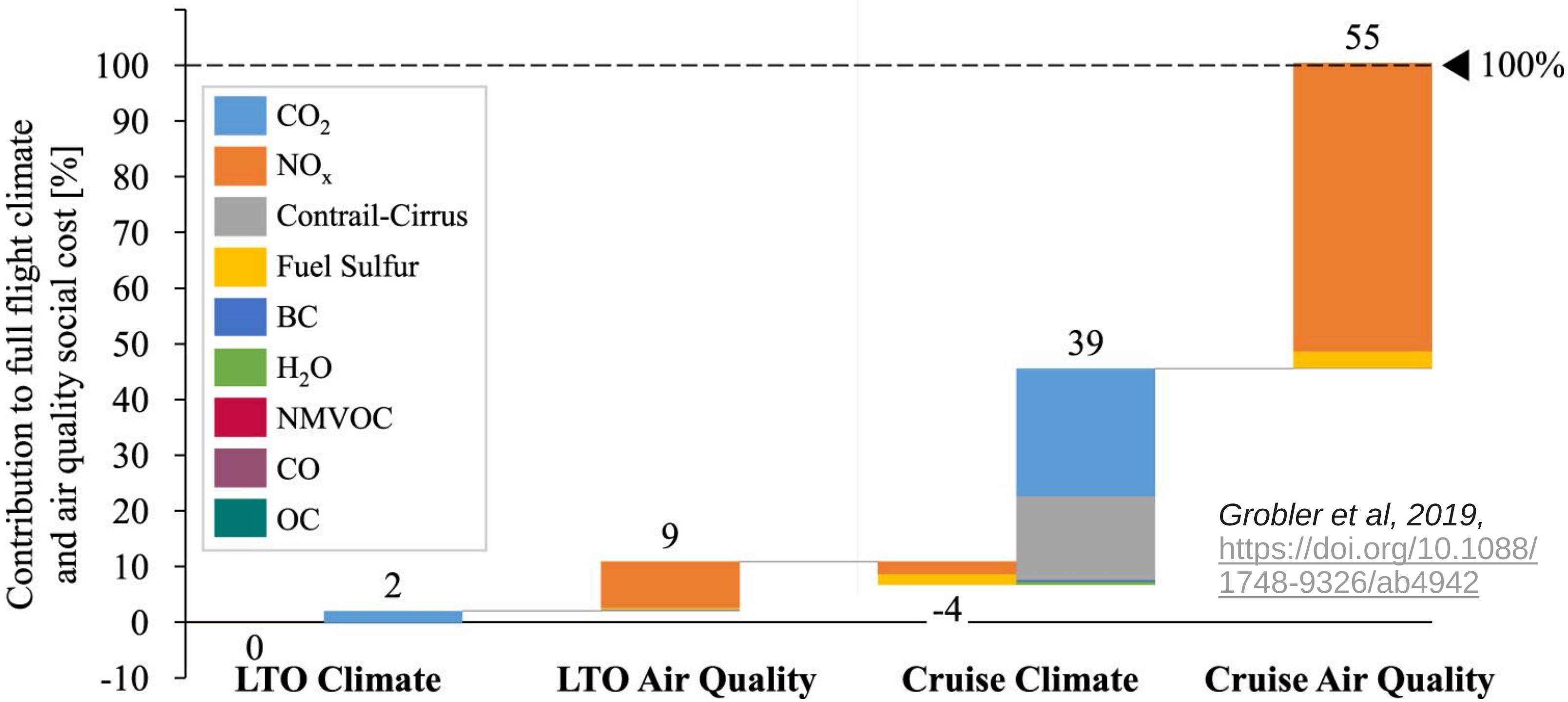


Defining the social cost of engine operation

- Social cost components considered:
  - NO_x climate and air quality impacts
  - CO_2 climate impacts
  - Marginal costs of fuel production

- NO_x standards set based on landing and takeoff (LTO) cycle
- Environmental impact comes from both cruise and LTO operations
- Basis of comparison: social cost per unit time per unit rated thrust ($/s/kN)

Monetized emissions impacts

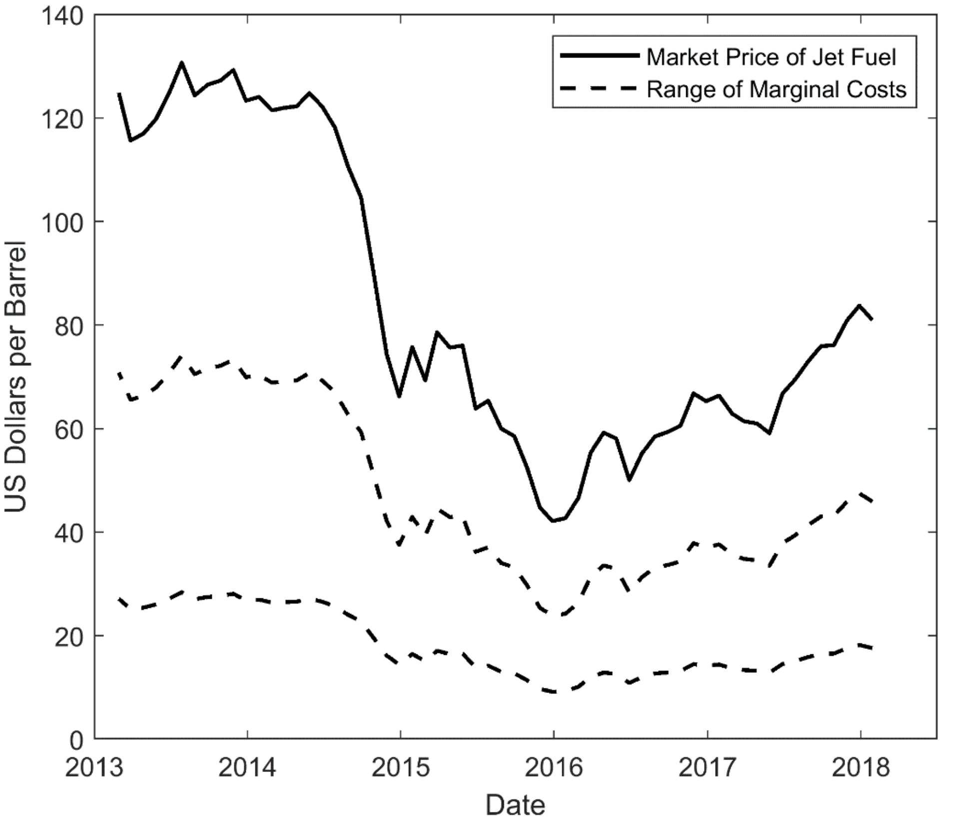


Grobler et al, 2019, https://doi.org/10.1088/1748-9326/ab4942

- Forward-looking approach, calculating impacts due to a unit of emissions in the present
- Climate impacts are primarily due to CO_2 and contrails
- Air quality impacts are primarily due to NO_x, which contributes to formation of $PM_{2.5}$ and surface ozone
- Approximately 90% of impacts are from cruise-altitude emissions

Social cost of fuel

- From a societal perspective, market price of fuel is a transfer, not a cost
- Production of fuel (extraction / upgrading) consume resources that could be used elsewhere, and therefore does represent a societal cost
- The Lerner Index relates the market price to the marginal cost of production

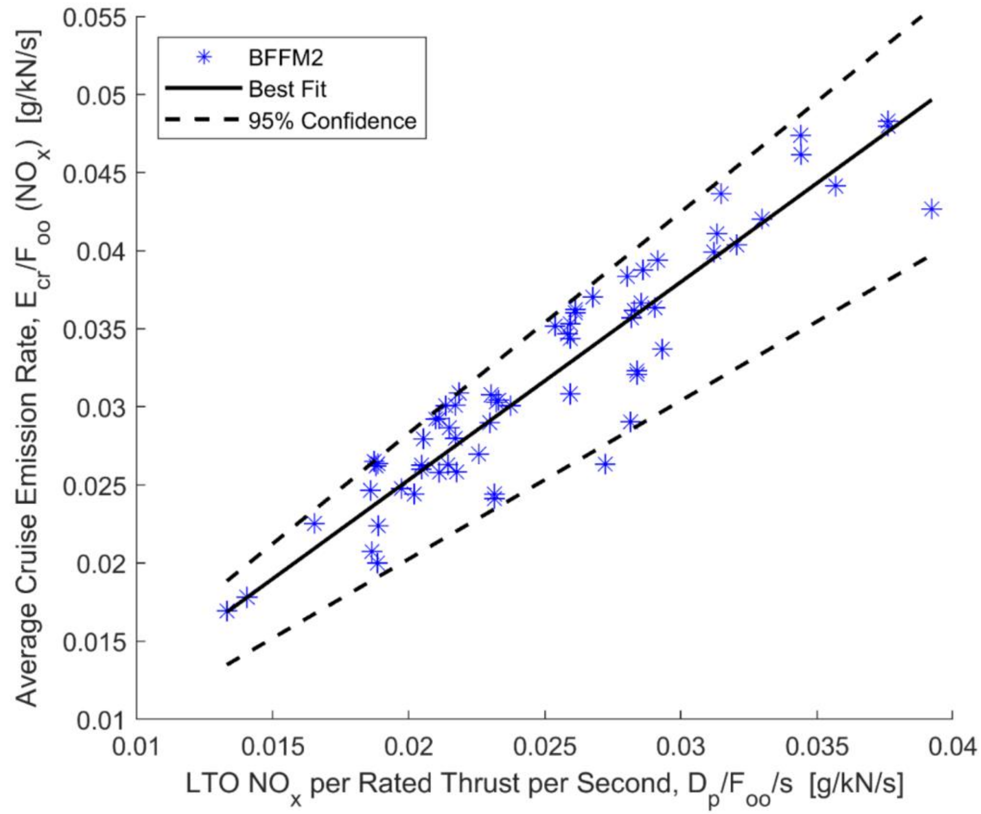


LTO and Cruise NO_x emissions

- NO_x emissions during LTO are given by the CAEP/8 limit by definition
- Cruise emissions for in-service engines calculated using BFFM2
- LTO NO_x metric and cruise NO_x emissions rate per unit rated thrust are correlated:

$$\frac{\mathrm{ER_{cr}}(\mathrm{NO}_x)}{F_{\mathrm{oo}}} = \frac{1.266}{t_{\mathrm{LTO}}} \times \left(\frac{D_{\mathrm{p}}}{F_{\mathrm{oo}}}\right)_{\mathrm{LTO}}$$

- Evaluating this relationship at the CAEP/8 limit gives an estimate of cruise NO_x emissions for an engine operating at the LTO limit as a function of OPR

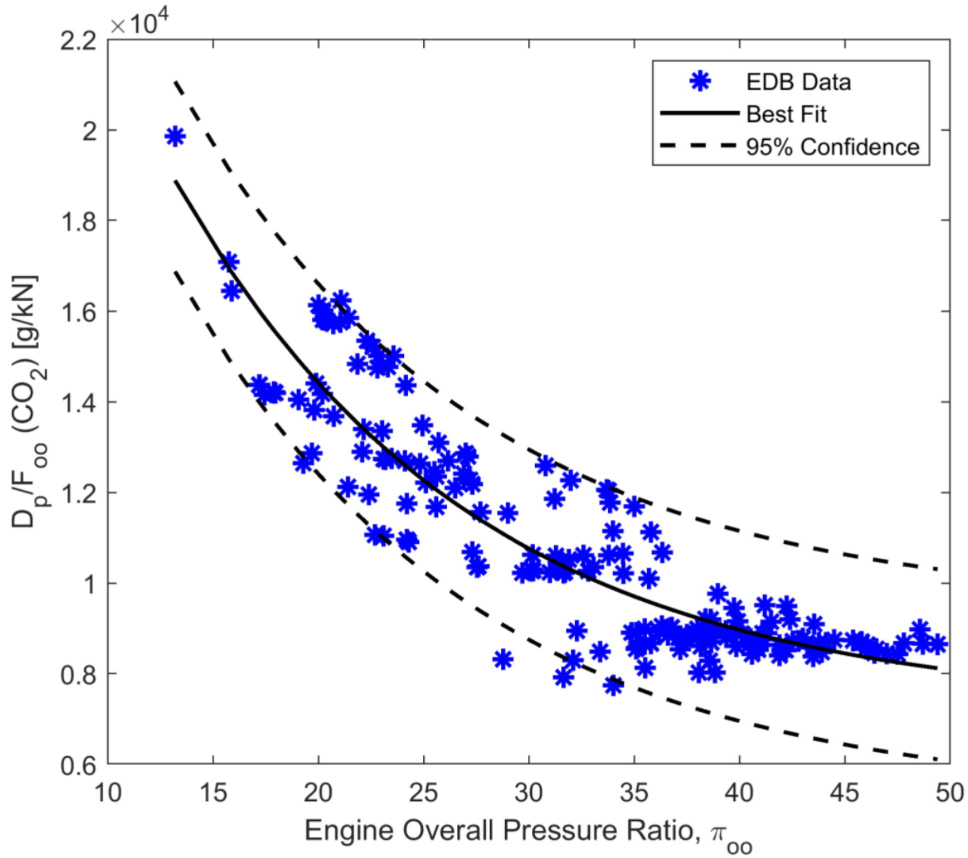


LTO CO_2 emissions

- Fit EEDB-reported LTO fuel consumption as a function of OPR for all in-production engines:

$$\frac{D_p(\mathrm{CO_2})}{F_{oo}} = 7233 + 29670\, e^{-0.0711\,\pi_{oo}}$$

- Likely an overestimate of the decrease in CO_2 emissions from going to higher OPR Confounding effects include:
  - Higher OPR for newer engines
  - Higher OPR for larger engines



Cruise CO_2 emissions

- Need the relationship between OPR and cruise CO_2 emissions rate per unit rated thrust
- Capturing trend with OPR is primary goal; uncertainty in absolute levels is acceptable

$$\dot{m}_f = \frac{F_N V}{\mathrm{LCV} \times \eta_{\mathrm{overall}}} = \frac{F_N V}{\mathrm{LHV} \times \eta_{\mathrm{cycle}} \times \eta_{\mathrm{propulsive}}}$$

$$\frac{\mathrm{ER}_{\mathrm{cr}}(\mathrm{CO}_2)}{F_{oo}} = \frac{\mathrm{EI}_{\mathrm{CO}_2} \times \mathrm{LR} \times V}{\mathrm{LHV} \times \eta_{\mathrm{cycle}} \times \eta_{\mathrm{propulsive}}}$$

- Thermodynamic analysis and dynamic scaling arguments give:

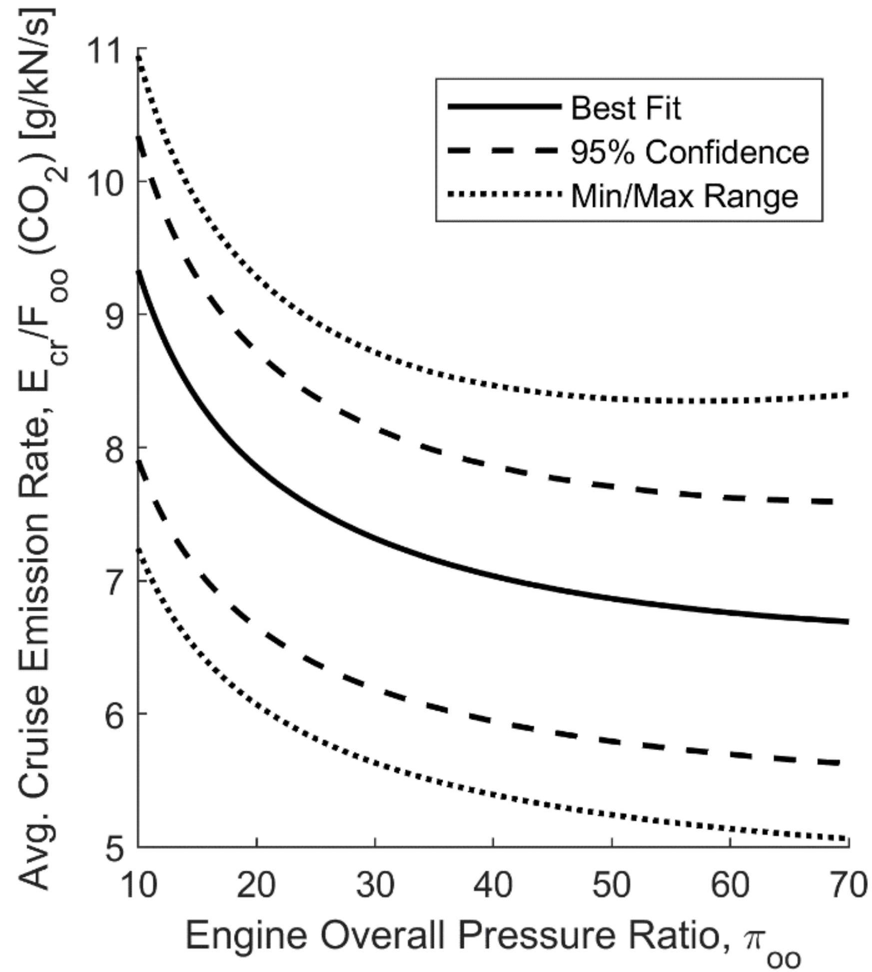
$$\eta_{\mathrm{cycle}} = f_1\left(\frac{T_4}{T_2}, \mathrm{OPR}, \eta_t, \eta_c\right)$$

$$\mathrm{LR} = f_2(M, p_{SL}, p_a, \pi_f, \eta_f)$$

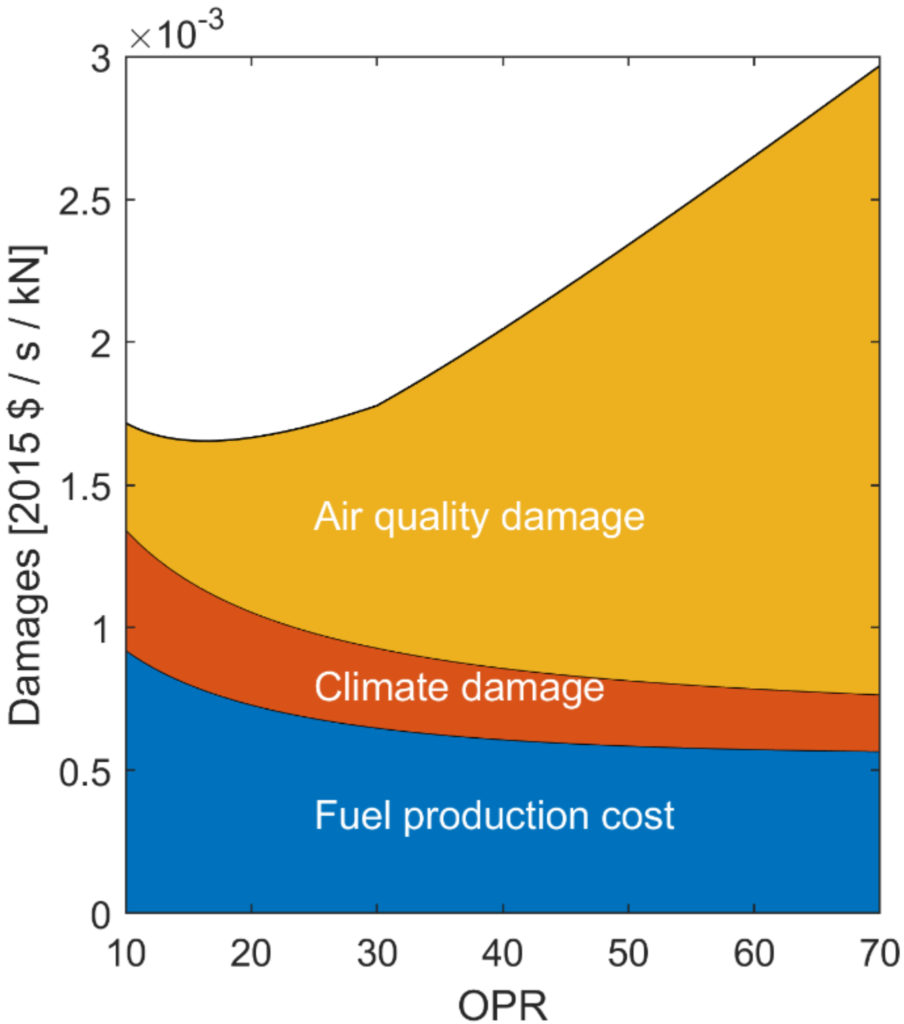
$$\eta_{\mathrm{propulsive}} = f_3(M, \pi_f, \eta_f)$$

Cruise CO_2 emissions (2/2)

- Use estimated ranges of cycle parameters:
  - T_4/T_2: 5.5 to 7.0
  - $\eta_{c,p}$: 0.89 to 0.915
  - $\eta_{t,p}$: 0.88 to 0.93
  - π_f : 1.4 to 1.9



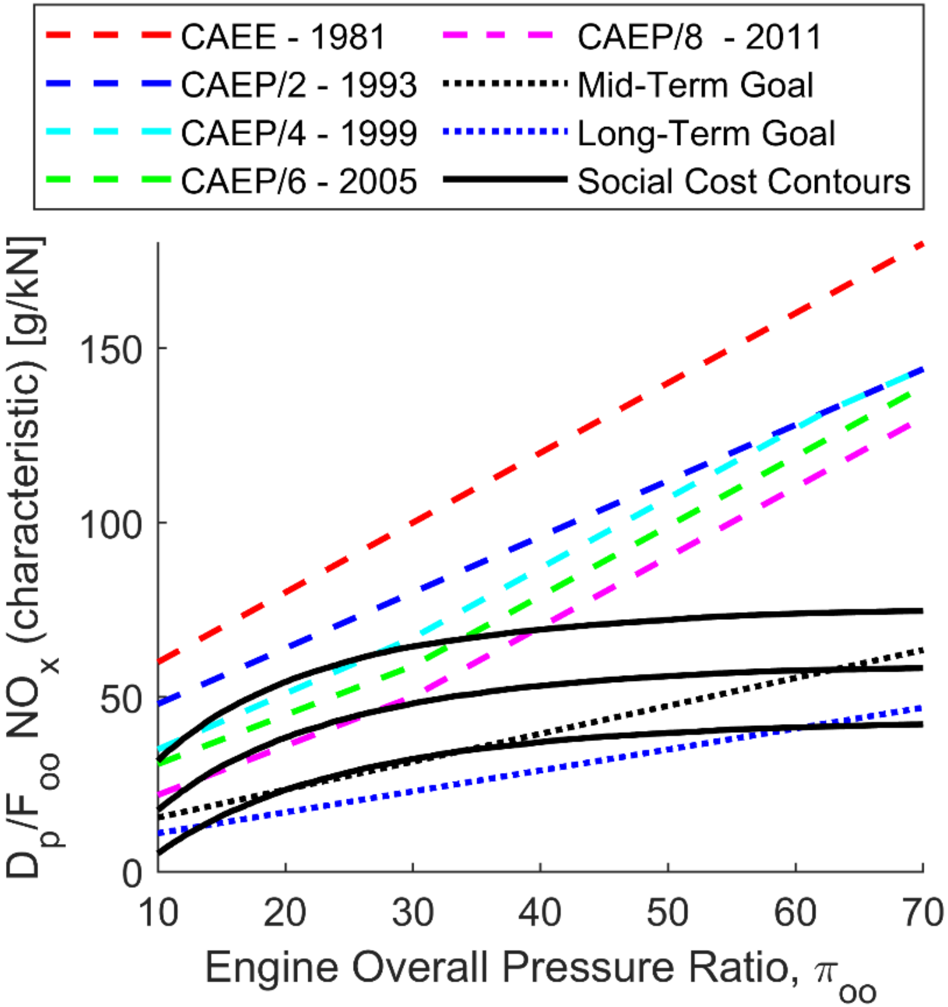
Social costs at the CAEP/8 limit



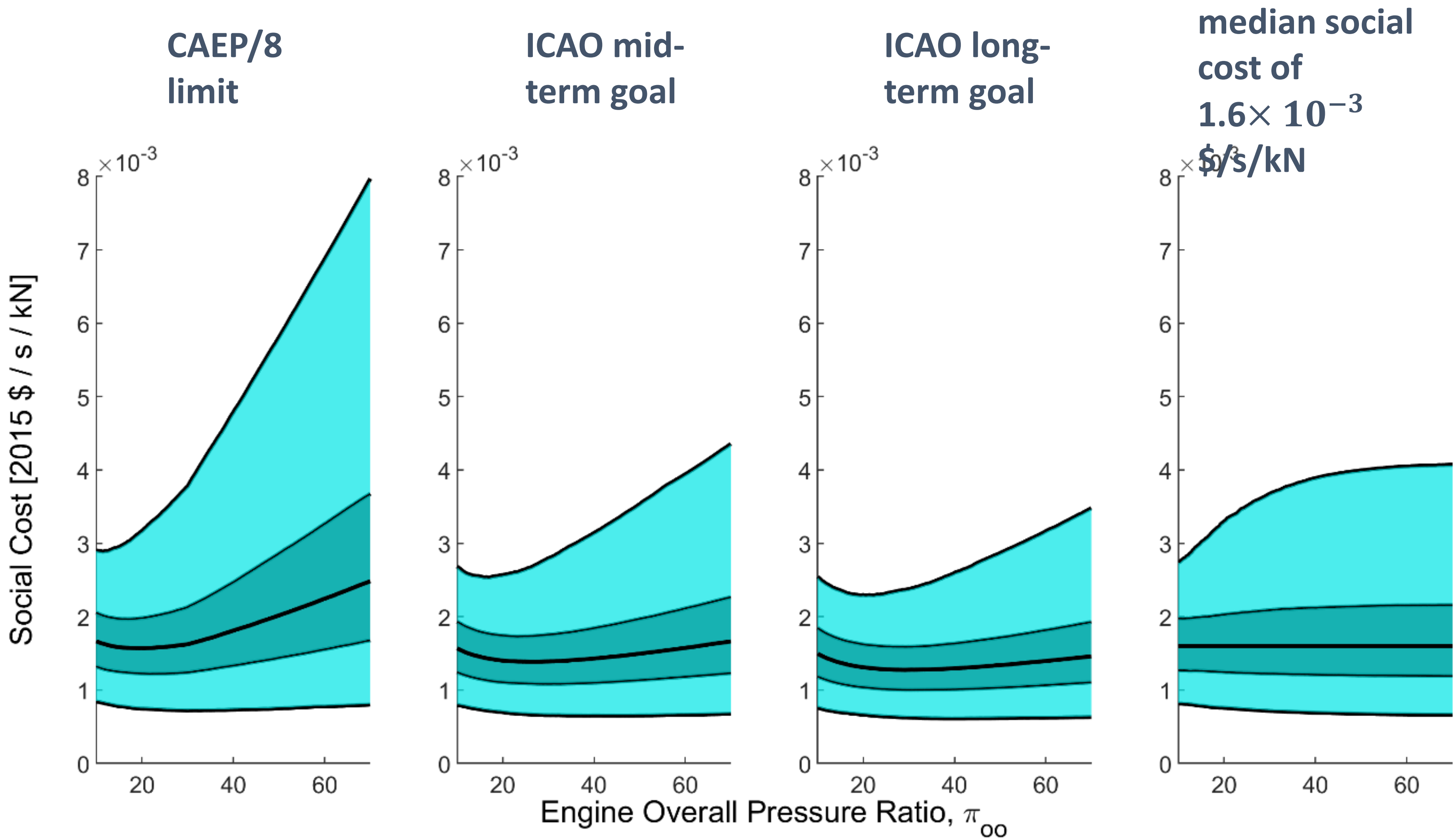
- Social cost analysis broken into marginal production cost of fuel, climate damage and air quality damage
- All results calculated at 3% discount rate
- Air quality dominates impacts at higher OPR
- Climate impact and fuel production costs continue to decrease, but with diminishing returns

NO_x limits with constant social cost

- Emissions limits with constant social cost can be expressed as a function of OPR
- Asymptotic behavior at high OPR corresponds to asymptotic behavior of efficiency-OPR relationship
- Lower slop of CAEP mid/long-term goals is more closely aligned with social cost optimal limits than existing regulations
- Technology that lowers NO_x independently of OPR shifts social cost optimum to higher OPR



Social costs for alternative NO_x limits



Challenges & Future Work

- Components of social cost vary over time
  - Scientific understanding of climate and air quality impacts is continuously being improved
  - Impacts per unit emissions depend on outside factors (e.g., background atmospheric state)
  - Fuel prices are volatile, and only partially linked to extraction/production costs
- Fuel cost and climate impacts differ when considering engines using SAF

Summary

- Climate impacts of aviation dominated by **contrails and CO_2**
- Air quality impacts dominated by **cruise NO_x** and **comparable in magnitude to climate**
- Consideration of both climate and air quality damages implies that a **different regulatory limit** may be optimal for **net damage minimization**
- Balance of climate and air quality damages is **discount rate dependent;** smaller discount rates mean larger climate contributions
- Environmental Research Communications paper available at https://doi.org/10.1088/2515-7620/ac6938