ASCENT Project 47

Clean-sheet supersonic engine design and performance

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Objective

- Assessing the environmental performance of clean-sheet and derivative engines for supersonic transport (SST)
- Evaluating the suitability of LTO emission certification standards for supersonic transport using variable noise reduction systems (VNRS)

Project Benefits

- Development of roadmap for technology development to mitigate the environmental signature of supersonic transport engines.

Research Approach

- Identify the operating requirements for SST propulsion systems
- Develop framework for tracing the fuel burn, noise, and emissions of engines for SST to their design parameters
- Develop optimal control framework to design VNRS for SST
- Quantify and compare fuel burn, noise and emissions characteristics of clean-sheet and derivative engines
- Assess the certification noise reduction potential of various VNRS control strategies

Major Accomplishments (to date)

- Presented our work at SciTech 2021 Conference
- Submitted a working paper to WG3 (with Georgia Tech) on impacts of VNRS on emissions from supersonic aircraft

Future Work / Schedule

- Impact of technology assumptions on environmental performance of clean-sheet and derivative engines
- Assess the noise reduction potential of a *coupled* VNRS control strategy

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Motivation and approach

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Part 1: derivative vs. clean-sheet engines

Derivative engines:

- using existing cores without any modifications
- Turbomachinery & cooling flows sized by the donor engine cycle → design space constraints

Clean-sheet engines:

- Engine cycle & turbomachinery components are purpose-designed
- Turbine cooling flows are sized to meet material temperature limits

Research questions

1. What are the noise and emissions characteristics of clean-sheet and derivative engines designed for future SST aircraft?

2. What propulsion system requirements can be met using donor cores?

Part 2: VNRS for future SST aircraft

Variable noise reduction systems (VNRS) are suggested in the *NPRM for Noise Certification of Supersonic Airplanes (April 13, 2020)* to be used for certification noise reduction by the next generation SST.

Examples of VNRS:

- Programmed thrust cut-back (PTCB)
- Programmed high-lift devices (PHLD)

Operational strategies to reduce noise will affect engine operation and therefore take-off and climb-out emissions.

Research questions

1. What are the attributes of an effective VNRS for an SST aircraft?

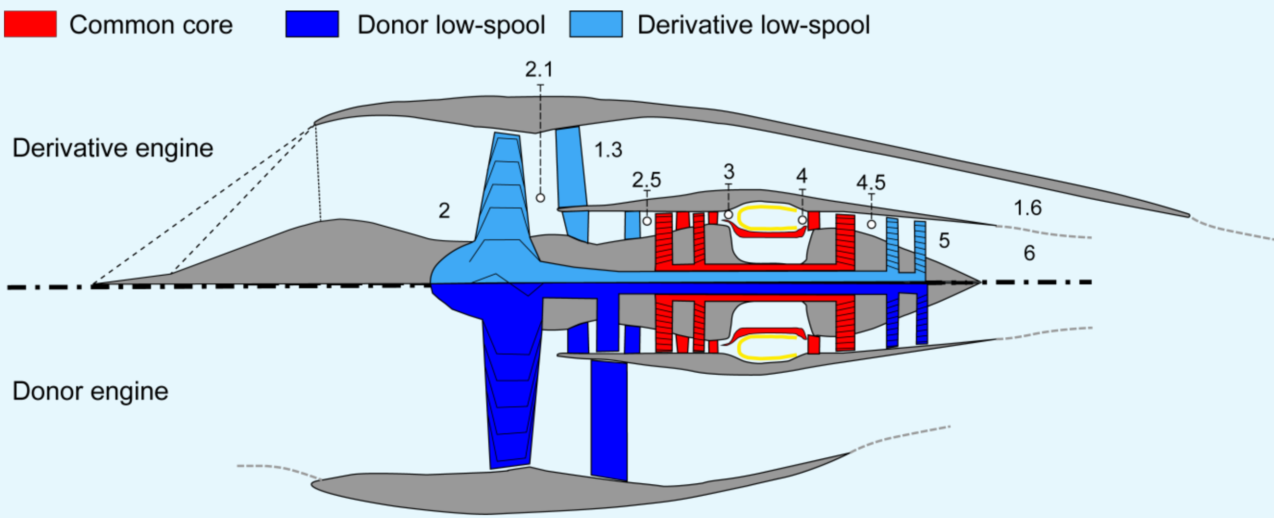
2. What are the effects of using VNRS on LTO emissions for SST engines?

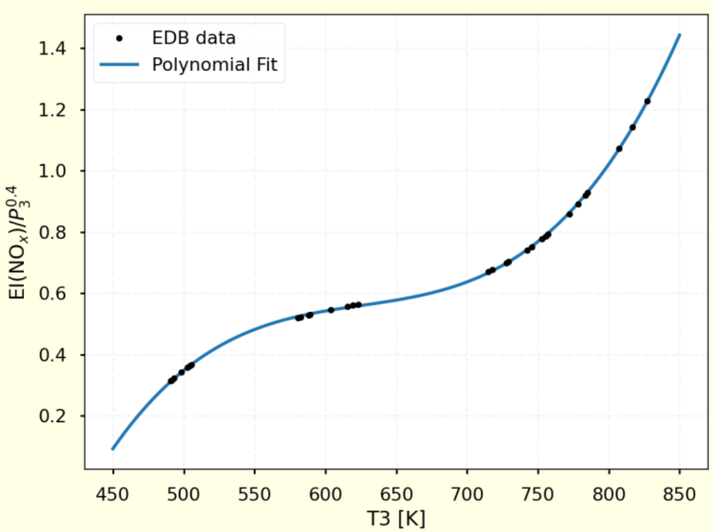
Methods – engine & emissions modeling

Engine modeling

NPSS is used to model the clean-sheet and derivative engines

A CFM56-5B3 model is developed based on publicly available data and used as the core for the derivative engine





Combustor emissions model

Focused on emissions of NO_x

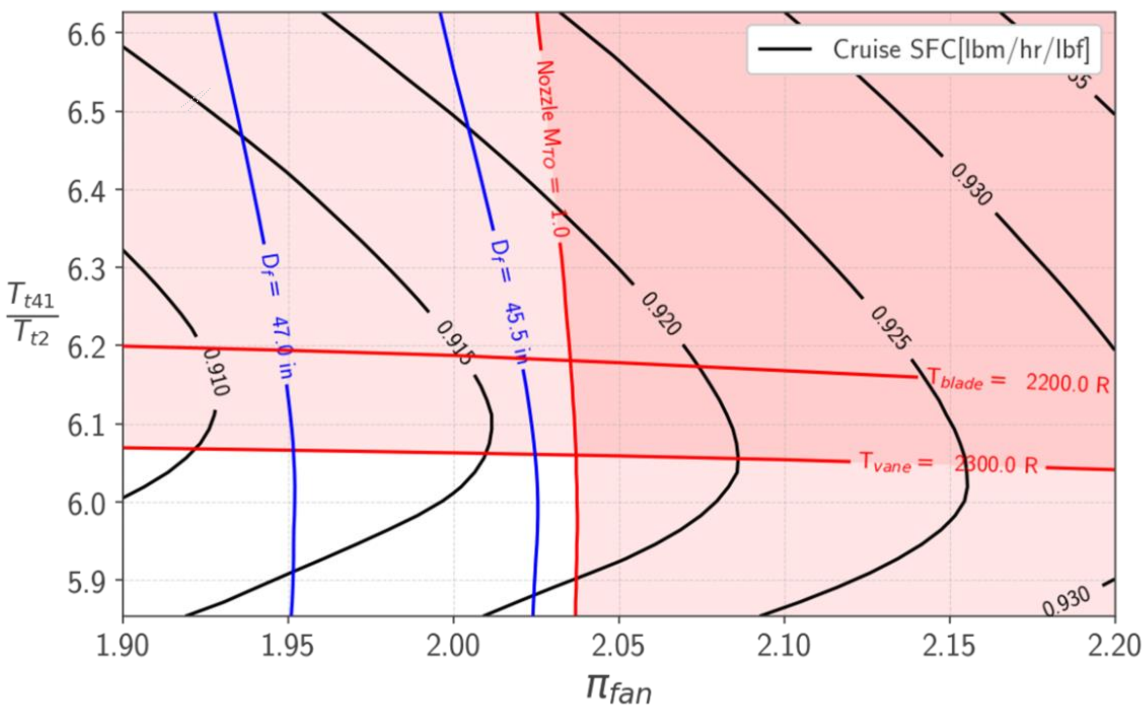
P_3T_3 methods adequate for RQL combustor NO_x emissions since T_3 is a good indicator of peak temperature and therefore NO_x production

EDB data and the above engine model is used to derive a P_3T_3 model for the CFM56-5B3 combustor

Design space of derivative engines are constrained by donor core characteristics

Derivative engine design space

- Two design variables: π_{fan} and T_{t41}/T_{t2} in derivative engine
- Core temperature limits (HPT and HPC) are determined by the donor core materials and cooling flows
- π_{HPC} is *only* an independent variable in clean-sheet engine (constrained by donor core characteristics in the derivative engine)
- Unshaded region represents feasible design space

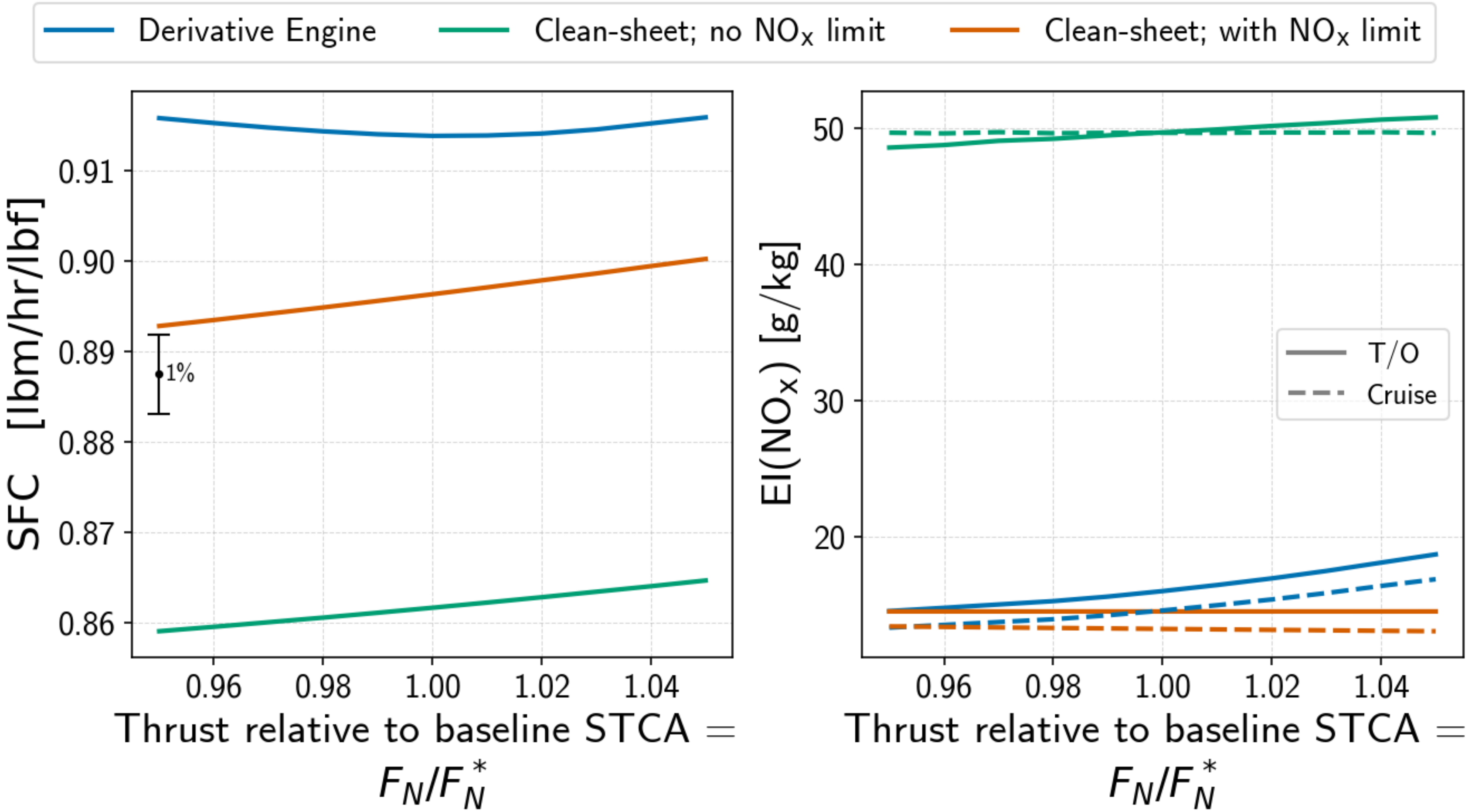


Optimization of performance as a function of propulsion system requirement

The required thrust (or specific thrust) can impact the relative performance of the clean-sheet and derivative engines.

Engine	Derivative engine	Clean-sheet engine without NO_x limit	Clean-sheet engine with NO_x limit
Objective function	SFC	SFC	SFC
Constraints	$T_{\text{blade}} \leq 2200\ \text{R}$ $T_{\text{vane}} \leq 2300\ \text{R}$ $T_{t3} \leq 1620\ \text{R}$ $\frac{P_{t9}}{P_{\text{amb}}} \leq 2.0$	$T_{\text{blade}} \leq 2200\ \text{R}$ $T_{\text{vane}} \leq 2300\ \text{R}$ $T_{t3} \leq 1620\ \text{R}$ $\frac{P_{t9}}{P_{\text{amb}}} \leq 2.0$	$T_{\text{blade}} \leq 2200\ \text{R}$ $T_{\text{vane}} \leq 2300\ \text{R}$ $T_{t3} \leq 1620\ \text{R}$ $\frac{P_{t9}}{P_{\text{amb}}} \leq 2.0$ $\text{EI}(\text{NO}_\text{x}) \leq 14.5\ \text{g/kg}$

Clean-sheet engine design strategy influences performance relative to derivative engine



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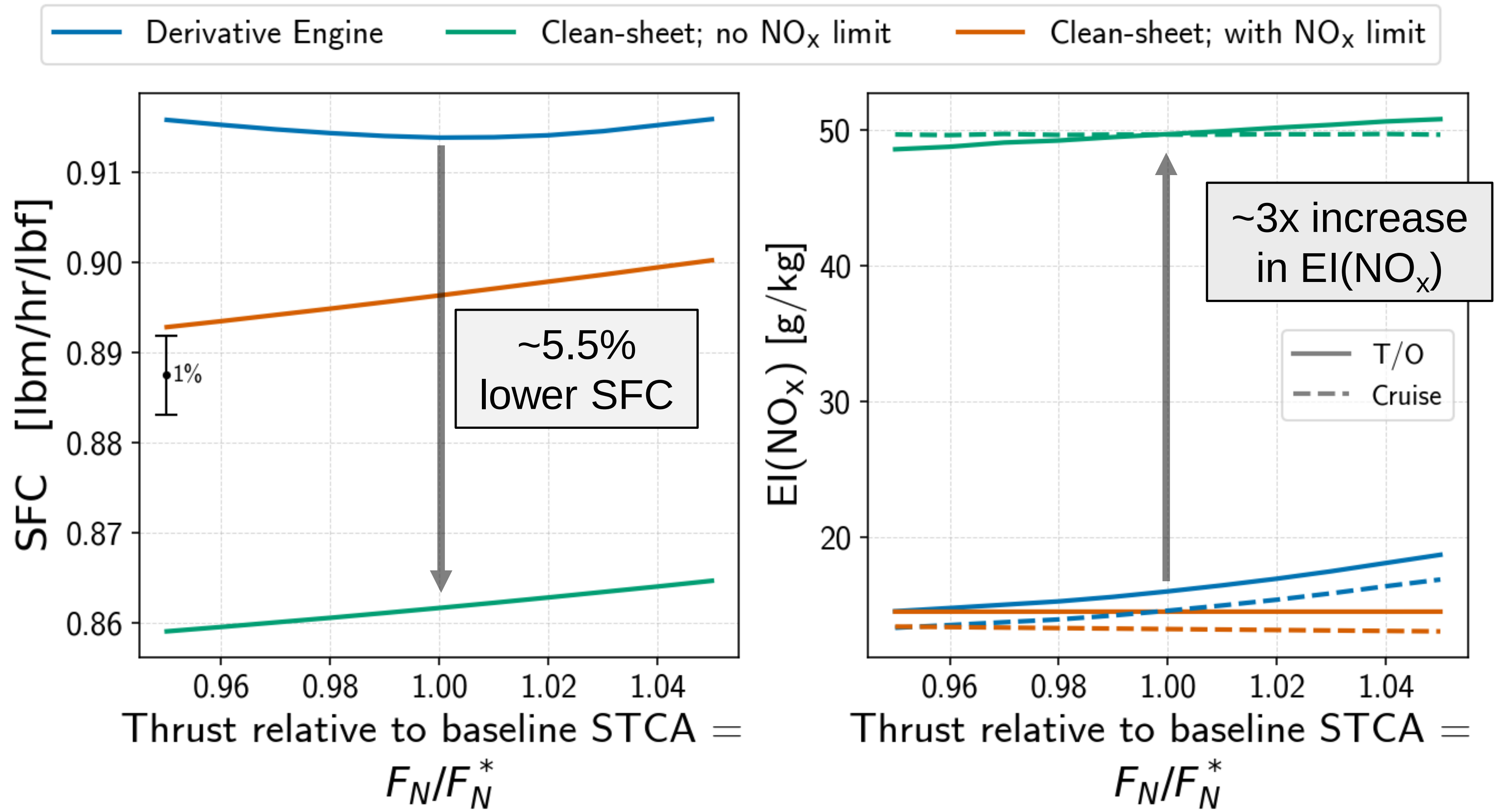

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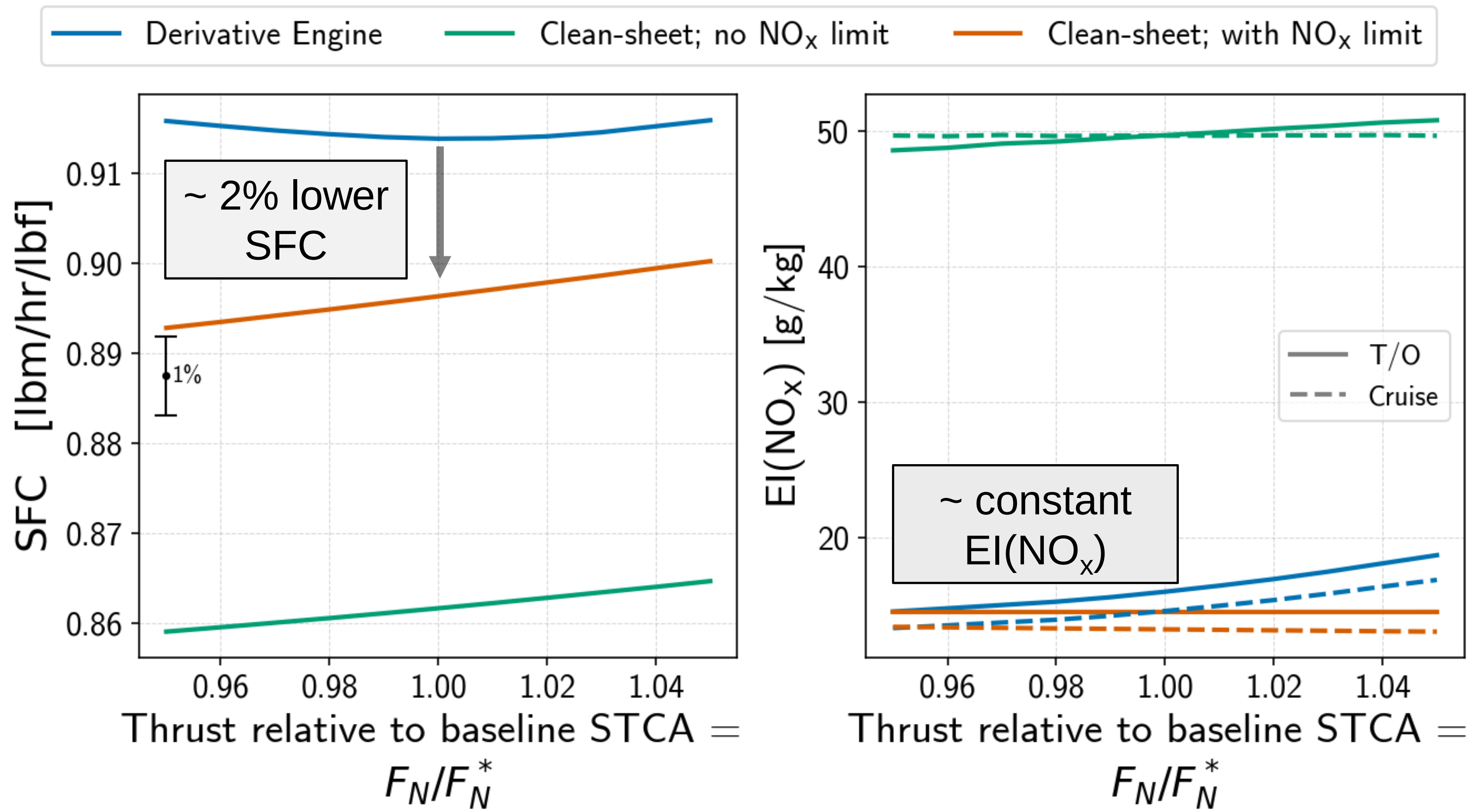
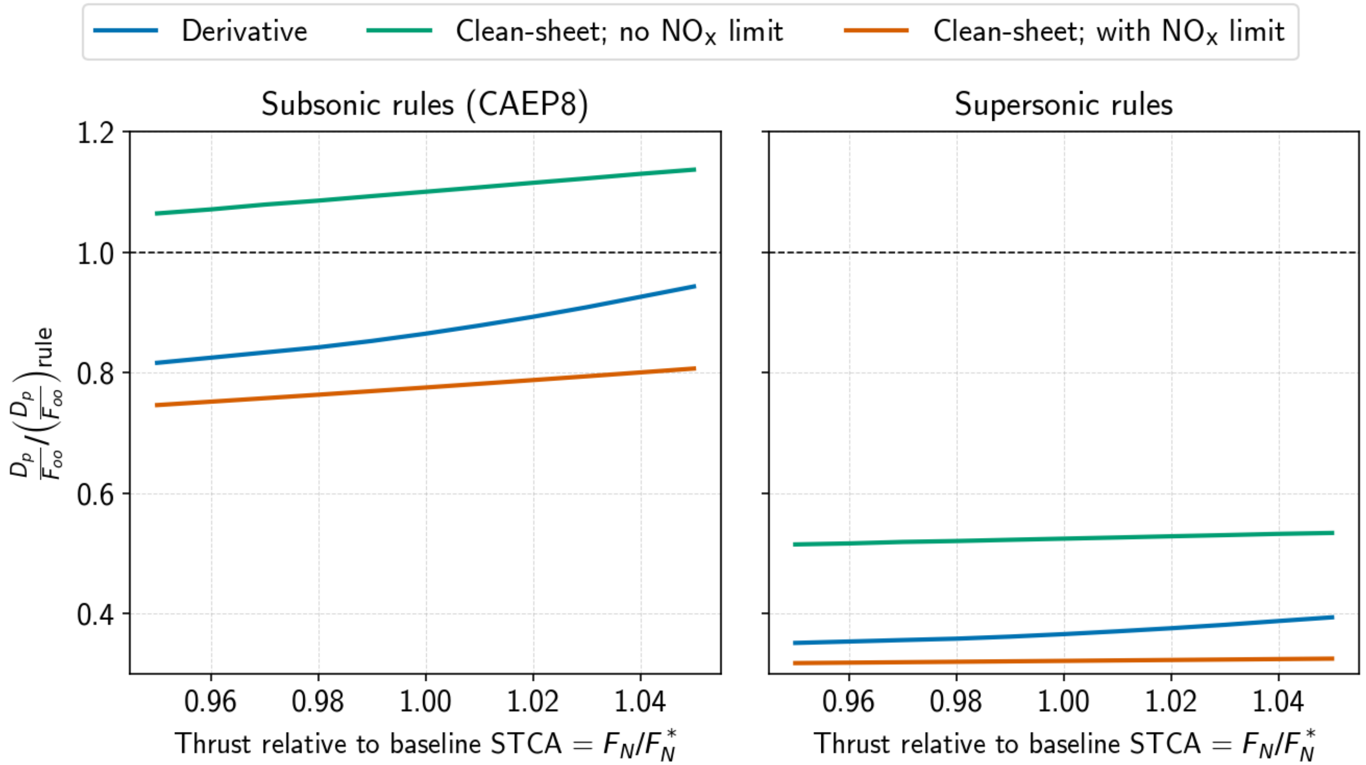


Derivative engine and clean-sheet engine with NO_x limits could meet CAEP8 standards



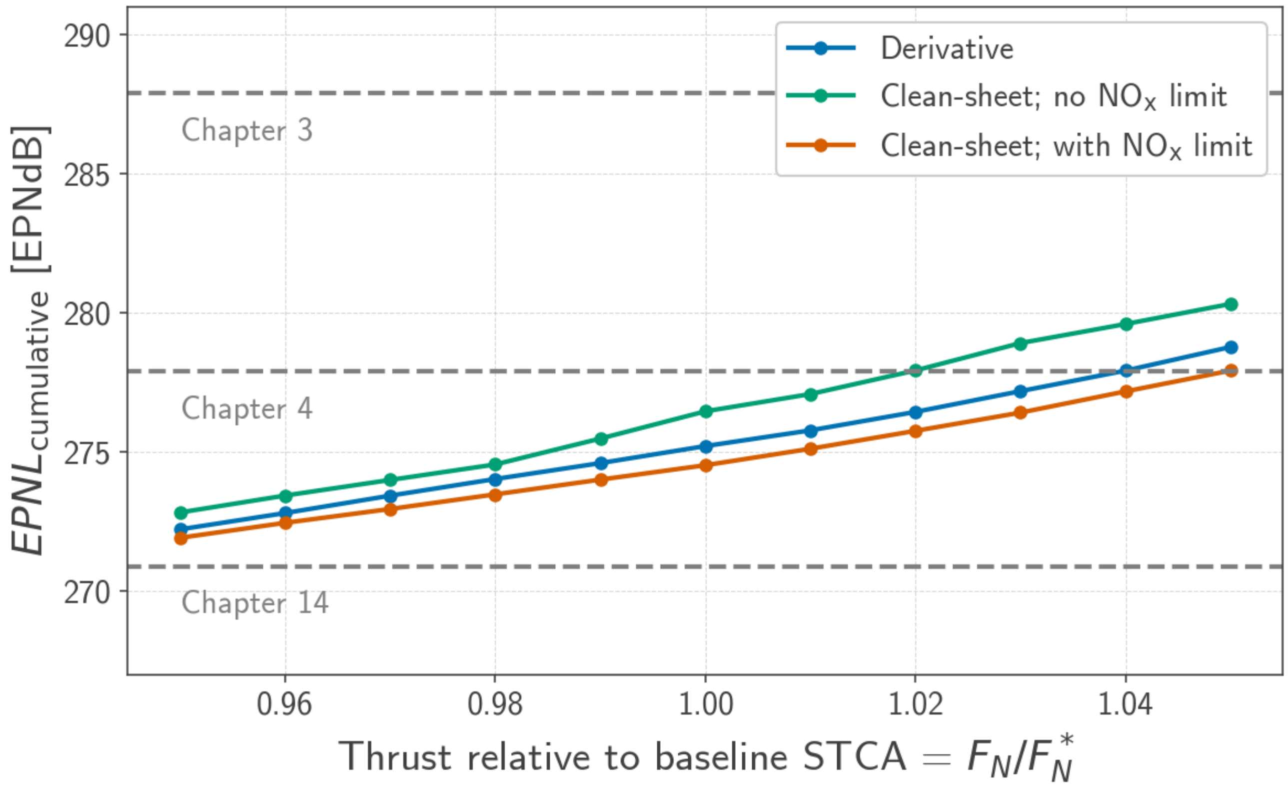
Derivative engine would meet the subsonic rules with a **6-16% margin**

Clean-sheet engine with CFM-56 combustor technology, simply optimized for minimum SFC **would not meet subsonic** NO_x limits.

*This does not include characteristic correction divisors or other development allowances.

Difference in certification noise levels between derivative and clean-sheet engines

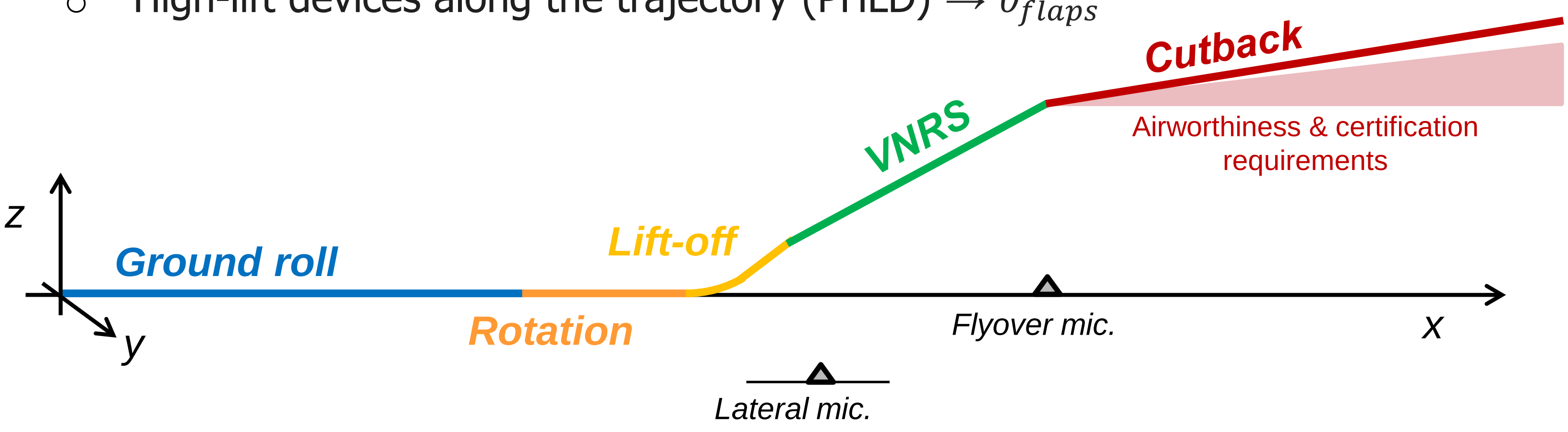
- Noise footprint is mainly governed by jet velocity for high specific thrust SST engines
- For given fan size and fan face Mach number: jet velocity is governed by the thrust requirement
- Core design parameters play an insignificant role in cumulative noise levels



Designing variable noise reduction systems for SST take-off trajectories

VNRS problem definition

- Objective to minimize sum of lateral and flyover EPNL ($EPNL_{TO}$)
- Subject to airworthiness & certification requirements
  - Speed constraints 250 kts < 10kft)
    - Noise certification: V_2+10kts < V < V_2+20kts
    - Airworthiness: V < 250kts (z < 10kft)
  - Cutback altitude constraints from noise certification requirements
- Independent control parameters:
  - Engine thrust along the trajectory (PTCB) $\rightarrow TS$
  - High-lift devices along the trajectory (PHLD) $\rightarrow \theta_{flaps}$

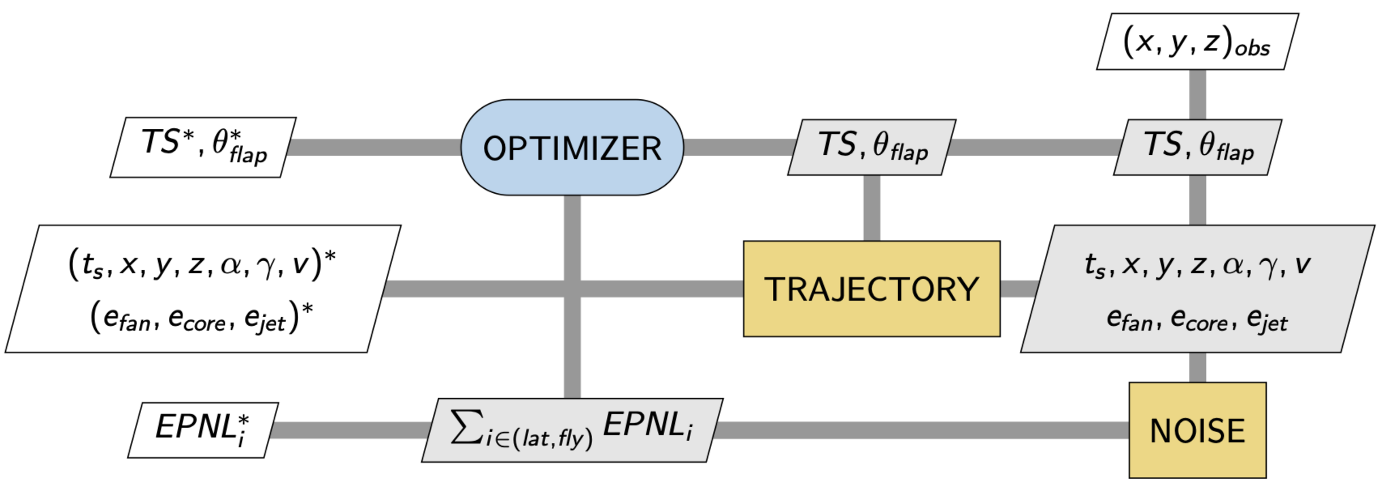


V_2: take-off safety speed

Methods – engine noise modeling

Framework for take-off noise assessment and minimization

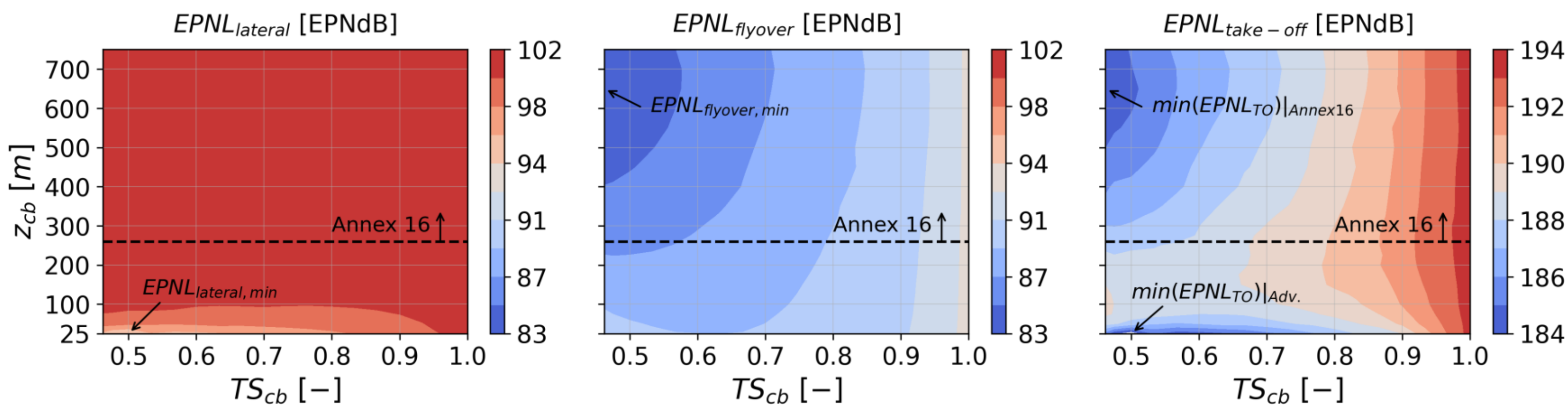
- Take-off trajectory model developed using NASA dymos within openMDAO
  - 5 phases: ground roll, rotation, lift-off, VNRS, cutback
- Noise model: Python Noise Assessment tool (PYNA)
  - Including fan, core, jet and airframe noise sources
  - Verified using NASA ANOPP noise assessment of NASA STCA
- Optimal control framework using gradient-based approach to minimize sum of lateral and flyover noise



Establishing a baseline trajectory for PTCB certification noise level comparisons

Single thrust cut-back trajectory (state-of-the-art)

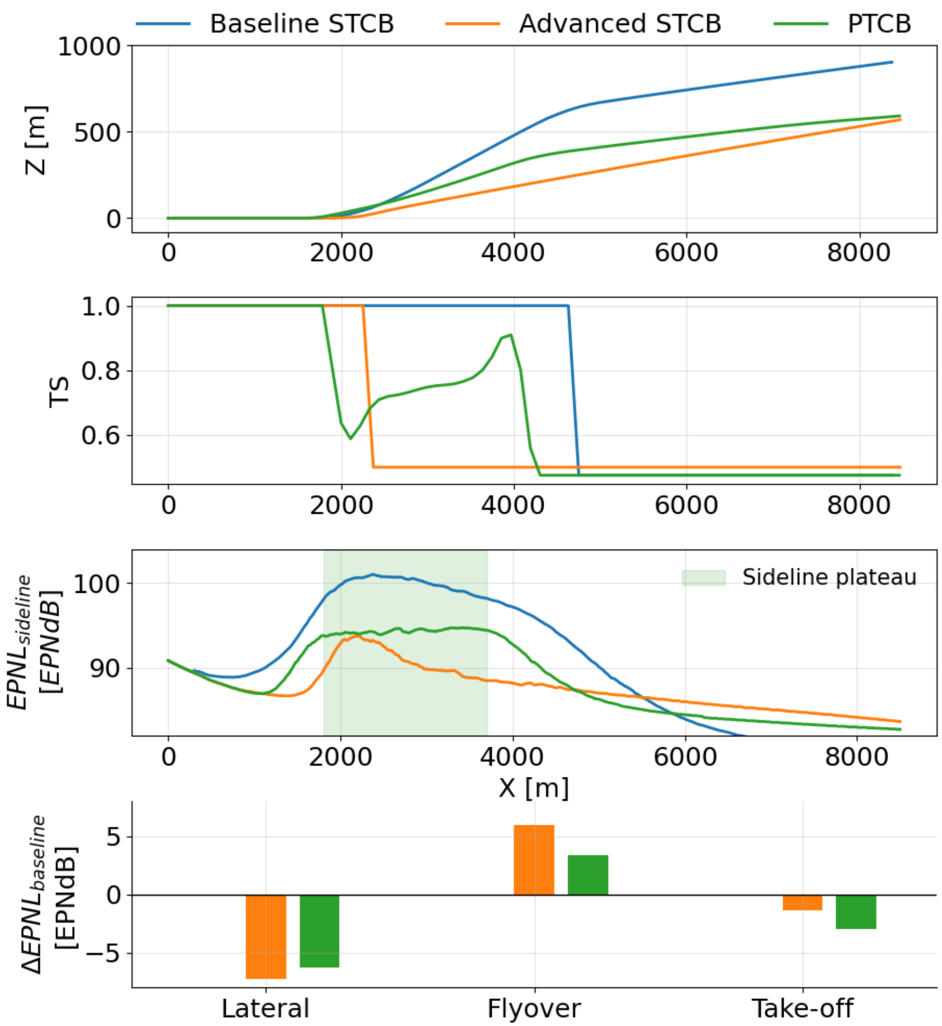
- Sweep of aircraft certification noise levels across (TS_{cb}, z_{cb}) design space
- Inherent trade-off between lateral and flyover noise for single thrust cut-back
- Minimum EPNL trajectory
    - Following Annex 16 guidelines on thrust cut-back: $EPNL_{baseline}$ = 184.8 EPNdB
    - Advanced trajectory: $\Delta EPNL_{advanced}$ = -1.6 EPNdB
- Hypothesis: higher degree of freedom thrust setting schedules can eliminate trade



Programmed thrust cutback eliminates trade between lateral and flyover noise levels

Programmed thrust cutback (PTCB)

- Thrust control schedule is characterized by:
  - Thrust cutback: to reduce lateral noise
  - Thrust bump: to increase flight altitude above flyover microphone
- Sideline noise is characterized by an EPNL *plateau*
- Compared to advanced STCB, PTCB results in small increase in lateral EPNL, but larger decrease in flyover EPNL
  - $\Delta EPNL_{\text{take-off, baseline}} = 2.6$ EPNdB

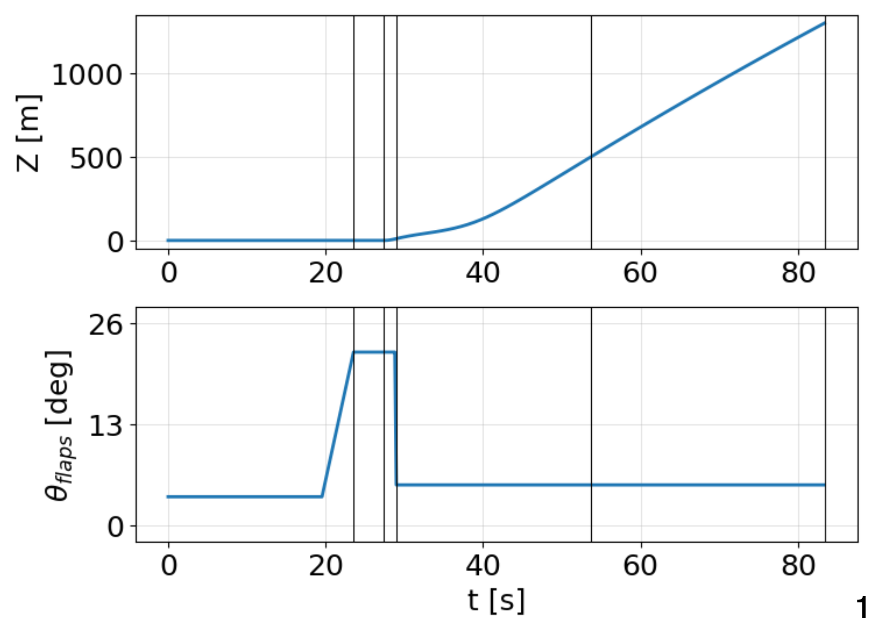


Programmed high-lift devices enable varying aerodynamic operating points during take-off

Programmed high-lift devices (PHLD)

- Objective: minimum take-off distance and maximum flyover distance
- Phases of the take-off trajectory have different aerodynamic requirements (table)
  - Ground roll: requirements are separable through a ramp function
  - Rotation and lift-off: optimized θ_{flaps} as a design parameter
  - PTCB and cutback: optimized θ_{flaps} as a design parameter
- Current research: assessing $\Delta \mathrm{EPNL}_{\mathrm{baseline}}$ for PHLD trajectories

Phase	Requirement for $\boldsymbol{\theta_{flaps}}$
Ground roll	min. c_d → fastest acceleration max. c_l → minimum V_{stall}
Rotation	min. c_d → fastest acceleration max. c_l → max. lift to get to $n = 1$
Lift-off	min. c_d → fastest acceleration max. c_l → max. lift to get to $n = 1$
PTCB	max. c_l/c_d → max. climb angle
Cutback	max. c_l/c_d → max. climb angle



Summary

Part 1: derivative vs. clean-sheet engines for SST

- SST propulsion systems have historically been derivative engines
- We identify the design space constraints imposed by the donor engines on the derivative cycle and quantify their impacts on environmental performance
  - A clean-sheet engine optimized solely for SFC results in a ~5% SFC reduction, but has a 3-fold increase in EI(NO_x)
  - An alternate design where an additional constraint on EI(NO_x) is applied results in a ~2% SFC reduction

Part 2: VNRS for future SST aircraft

- We estimate the certification noise reduction potential ($EPNL_{TO}$) of VNRS for NASA STCA (M1.4, 8pax)

$EPNL_{T0}$ [EPNdB]	$\Delta EPNL_{baseline}$ [EPNdB]		
Baseline STCB	Advanced STCB	PTCB	PHLD
184.3	-1.6	-2.6	current research

Next steps

As part of ASCENT Project 47

- What is the impact of technological improvements in turbomachinery components on the relative performance of clean-sheet and derivative engines? *(June 2022)*
- What is the VNRS noise reduction potential for different SST vehicle configurations, e.g. high-supersonic airliner? (*June 2022*)
- What is the impact of using VNRS on other aspects of aircraft certification, e.g. engine emission certification? (*July 2022*)
- Do the trajectories minimizing certification noise with VNRS align with trajectories minimizing noise footprint? (*August 2022*)

Beyond Project 47

- What are the impacts of improved combustor design (e.g., staged/lean combustion) and improved turbine material/cooling technology on the relative performance benefits of clean-sheet engine designs over derivative designs?
- How can VNRS for SST be integrated into the air transportation system, considering air traffic control, airworthiness, and certification requirements?