CLEEN II/III System Level Assessment

Project 37

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CLEEN Consortium

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CLEEN Overview

Purpose:

- Mature previously conceived noise, emissions and fuel burn reduction technologies for civil subsonic airplanes from Technology Readiness Levels (TRL) of 3-5 to TRLs of 6-7 to enable industry to expedite introduction of these technologies into current and future aircraft and engines.
- Assess the benefits and advance the development and introduction of "drop-in" alternative jet fuels, including blends.

CLEEN III technologies on a path for introduction into commercial aircraft by 2031.

	CLEEN I	CLEEN II	CLEEN III	
Noise	-25 dB (cumulative to Stage 5)			*and/or reduces the noise contour area in absolute terms*
LTO NOx Emissions	-60% *(margin to CAEP/6)*	*-70% (margin to CAEP/8)*		*and/or reduces absolute NOx production over the aircraft's mission*
Aircraft Fuel Burn	-33% (relative 2000 best in class)	-40% (relative 2000 best in class)	-20% (below CAEP/10)	*and/or supports the FAA's goal to achieve a net reduction in climate impact from aviation*

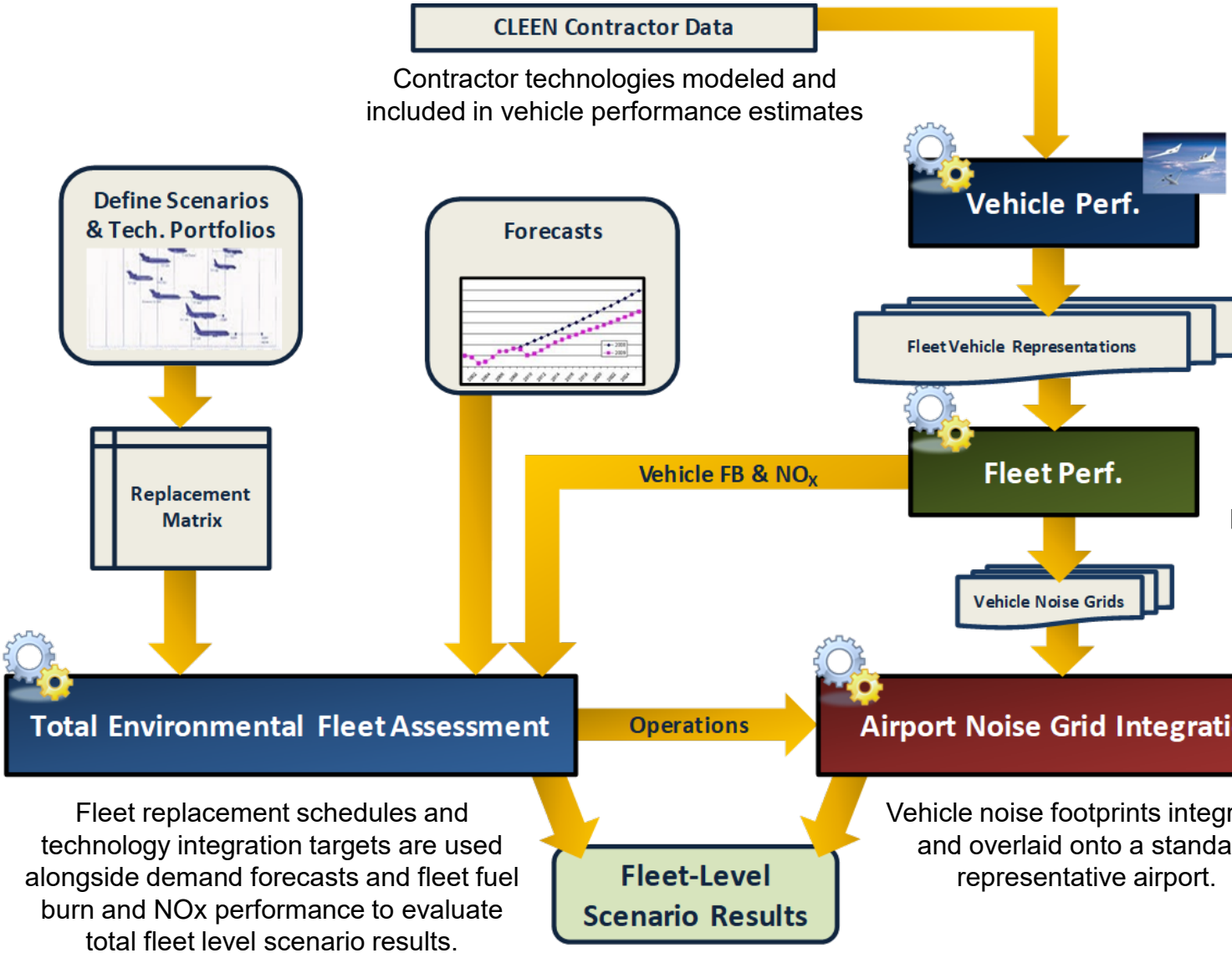
CLEEN II Technologies

Contractor	Technology	Fuel Burn	NOx	Noise	Status
Aurora	D8 Fuselage	X		X	Complete
Boeing	Structurally Efficient Wing	X			Complete
	Compact Nacelle	X			Complete
	Compact Nacelle (Noise liner)			X	Complete
Delta/MDS/America's Phenix	Leading Edge Protective Coating for Turbine Blades	X	X		Complete
GE	TAPS III Combustor		X		Complete
	MESTANG	X			Complete
	Flight Management System	X			Complete

CLEEN II Technologies

Contractor	Technology	Fuel Burn	NOx	Noise	Status
Honeywell	Compact Low Emissions Combustor	X	X		Complete
	Advanced Turbine Blade Outer Air Seal	X			Complete
	Advanced High-Pressure Compressor (CII+)	X			In Progress
	Advanced Acoustic Fan Rotor/Liner (CII+)			X	In Progress
Pratt and Whitney	Enhanced Efficiency Compressor	X			Complete
	Enhanced Efficiency High Pressure Turbine	X			Complete
Rolls-Royce	Advanced RQL Low NOx Combustor		X		Complete
Collins Aerospace	Short Inlet and Clean Fan Duct for HBR Engines	X		X	Complete
	Advanced Acoustics			X	Complete

System Level Assessment

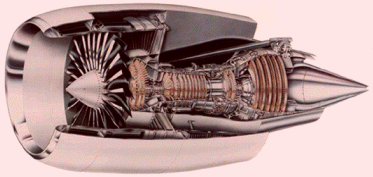


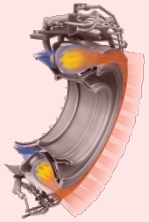
Modeling Process

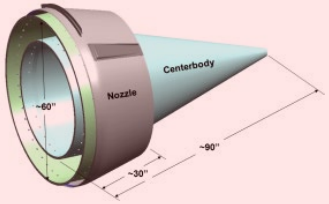
Proprietary

Technology Modeling

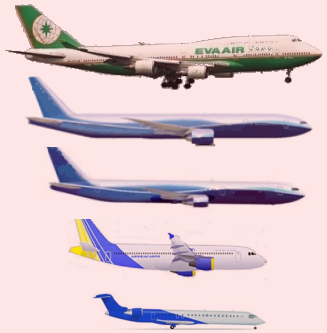
- Research Technologies
- Model Impacts



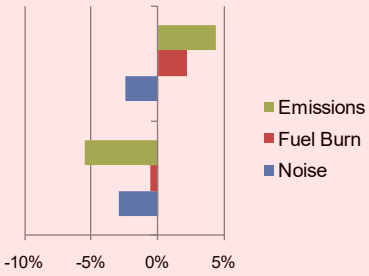




- "Fly" Vehicle Models

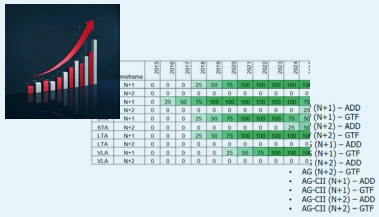


- Assess Technology Impacts

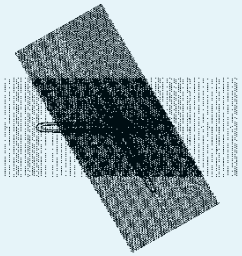


Publically Releasable

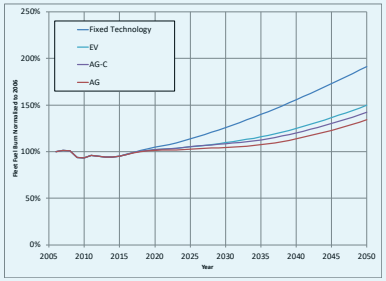
- Demand Forecasts
- Fleet Replacement Matrices
- Technology Integration Scenarios



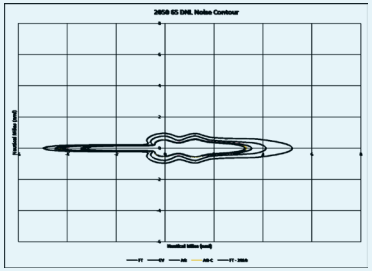
- Generate single event noise grids



- Fuel burn and emissions forecasting



- Generate airport noise contours



Fleet Replacement Matrix

- CLEEN fleet replacements defined using "known" vehicle introduction dates and historical trends of upgrades/performance improvement packages
- Used same schedule as CLEEN I for comparison.

CLEEN Replacement Matrix

Vehicle	Timeframe	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
RJ	N+1	0	0	0	25	50	75	100	100	100	100	100	100	100	75	50	25	0	0	0	0	0
RJ	N+2	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100
LSA	N+1	0	25	50	75	100	100	100	100	100	100	75	50	25	0	0	0	0	0	0	0	0
LSA	N+2	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100	100	100	100
STA	N+1	0	0	0	25	50	75	100	100	100	75	50	25	0	0	0	0	0	0	0	0	0
STA	N+2	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100	100	100	100	100
LTA	N+1	0	0	0	25	50	75	100	100	100	100	100	100	100	100	100	75	50	25	0	0	0
LTA	N+2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100
VLA	N+1	0	0	0	0	0	25	50	75	100	100	100	100	75	50	25	0	0	0	0	0	0
VLA	N+2	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100	100

Example: The Fleet Replacement Matrix assumes that in the year 2028, 75% of the regional jet replacements and new growth aircraft will consist of N+1 generation aircraft with the other 25% consisting of N+2 generation aircraft.

Fuel Consumption: CLEEN I and II

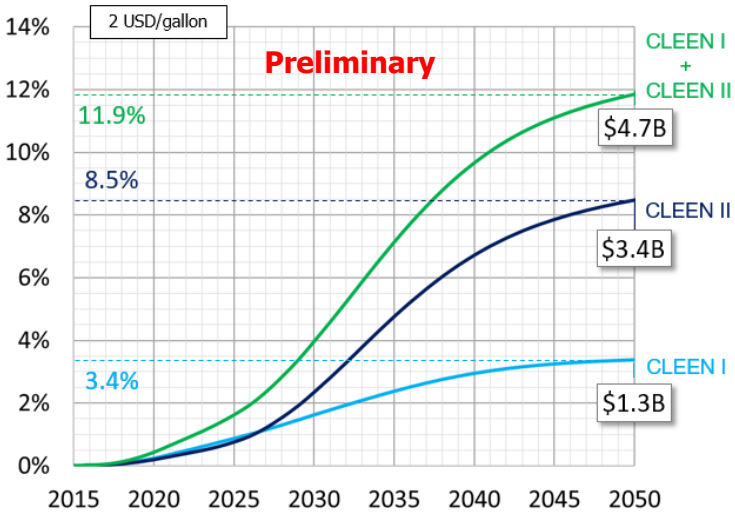
Assumptions

- Five generic vehicles assembled for analysis in EDS environment:
  - Regional Jet
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Very Large Aircraft

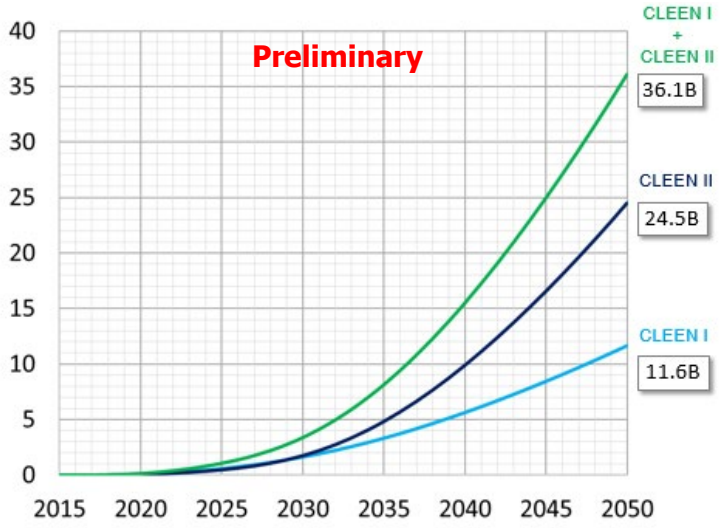
- Each vehicle has technology package varied for analysis across 5 technology integration scenarios:
  1. Frozen technology introduction (FTI)
  2. Evolutionary: Conservative performance and concrete entry into service plan
  3. CLEEN I Aggressive: Aggressive performance, including CLEEN I technologies and no entry into service plan
  4. CLEEN II Aggressive: Aggressive performance, including CLEEN I and II technologies and no entry into service plan
  5. Aggressive minus CLEEN: Scenario 3 or 4 without CLEEN technologies

- Difference between Scenario 5 and Scenarios 3 and 4 estimate the contributions of CLEEN I and II technology sets, respectively

CLEEN Cost Savings relative to Evolutionary Scenario



Cumulative CLEEN Fuel Savings (Billion Gallons)



Not all technologies are modeled/included at this time.

CO_2 emissions reduced by 420 Mt by 2050 - equivalent to removing 3.02 million cars from the road from 2020-2050

NOx Fleet Assessment

Assumptions

- Identical to fuel burn regarding:
  - Fleet replacement matrices
  - Demand forecast
  - Technology integration scenarios
  - Scope: Domestic + International departures
- Technologies included:
  - Traditional Combustors (GT Model)
  - CLEEN Combustors
    - GE TAPS II (GT Model) *[RJ, SA classes]*
    - GE TAPS III *[STA, LTA, VLA classes]*
    - Rolls-Royce RQL Combustor *[RJ, SA classes]*
    - Honeywell Compact Combustor *[RJ, SA classes]*
- Dp/Foo and SLS thrust to calculate NOx emissions throughout "LTO cycle"
  - Taxi
  - Takeoff
  - Climbout
  - Approach

*LTO NOx (g) = Dp/Foo (g/kN) * F_{SLS}(kN)*
(per engine)

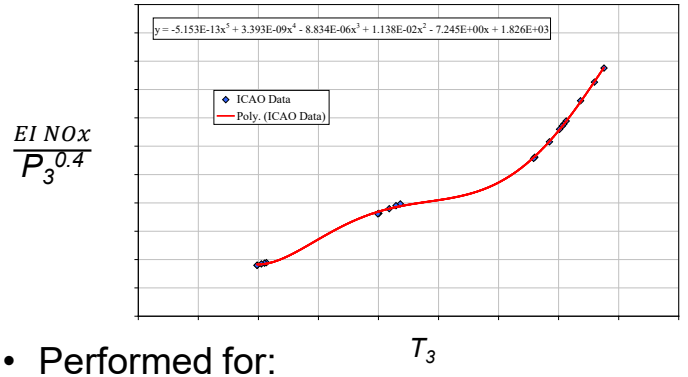
- Engine impacts mapped to five generic vehicles
- LTO cycle NOx emissions enumerated for estimated fleet operations

GT NOx Modeling

- Representative combustor models help define contrast between FTI and CLEEN I+II technology contributions
- P3T3 Correlation Developed:

$$EI\ NO_{X_{ALT}} = P_{3_{ALT}}^{0.4} * \frac{EI\ NO_{X_{SL}}}{P_{3_{SL}}^{0.4}} \left(T_{3_{ALT}}\right)$$

- NOx characteristic gathered from ICAO Aircraft Engine Emissions Databank (public)
- Cycle characteristic gathered from inhouse engine models calibrated against public data.

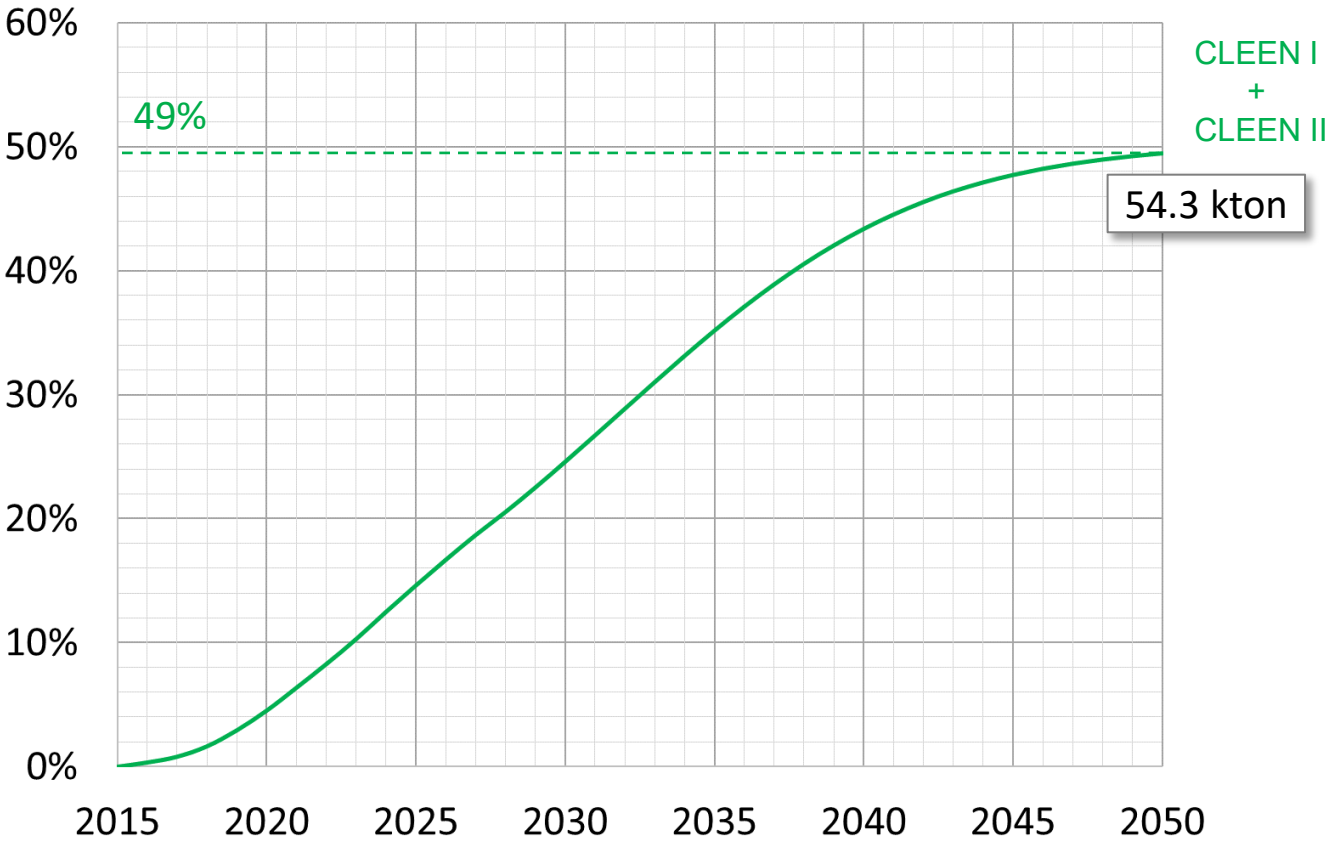


- Performed for:
  - Baseline vehicle combustors
  - TAPS I and II combustors
- Remaining combustors modeled using limited rights data directly with participating contractors

LTO NOx Emissions: CLEEN I and II

Preliminary

Annual LTO NOx Emissions Savings relative to Evolutionary Scenario



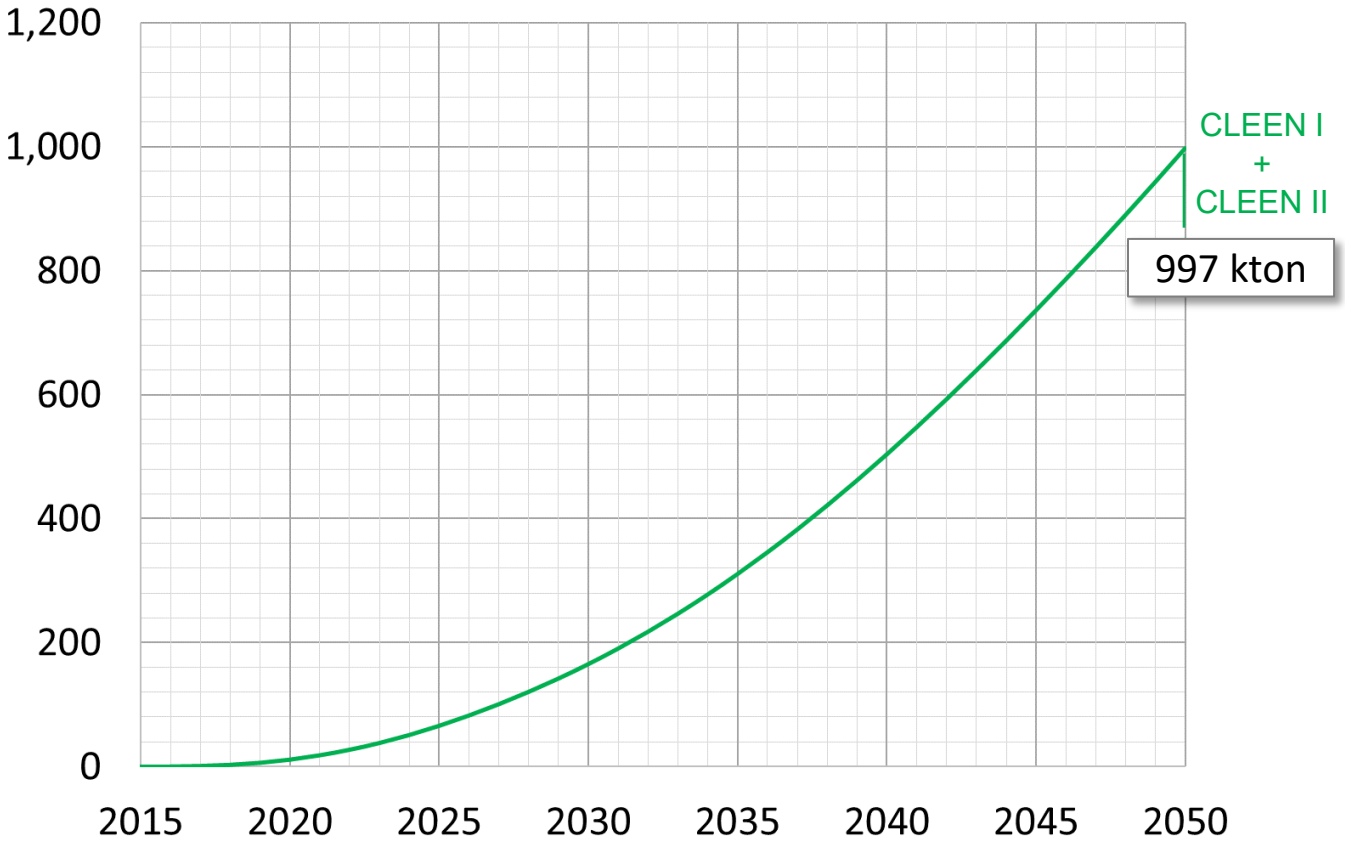
Not all technologies are modeled/included at this time.

Note: CLEEN II contributions are shown as annual and not cumulative benefit.

LTO NOx Emissions: CLEEN I and II

Preliminary

Cumulative LTO NOx Emissions Savings relative to Evolutionary Scenario (kton LTO NOx)



Not all technologies are modeled/included at this time.

Noise: CLEEN I and II

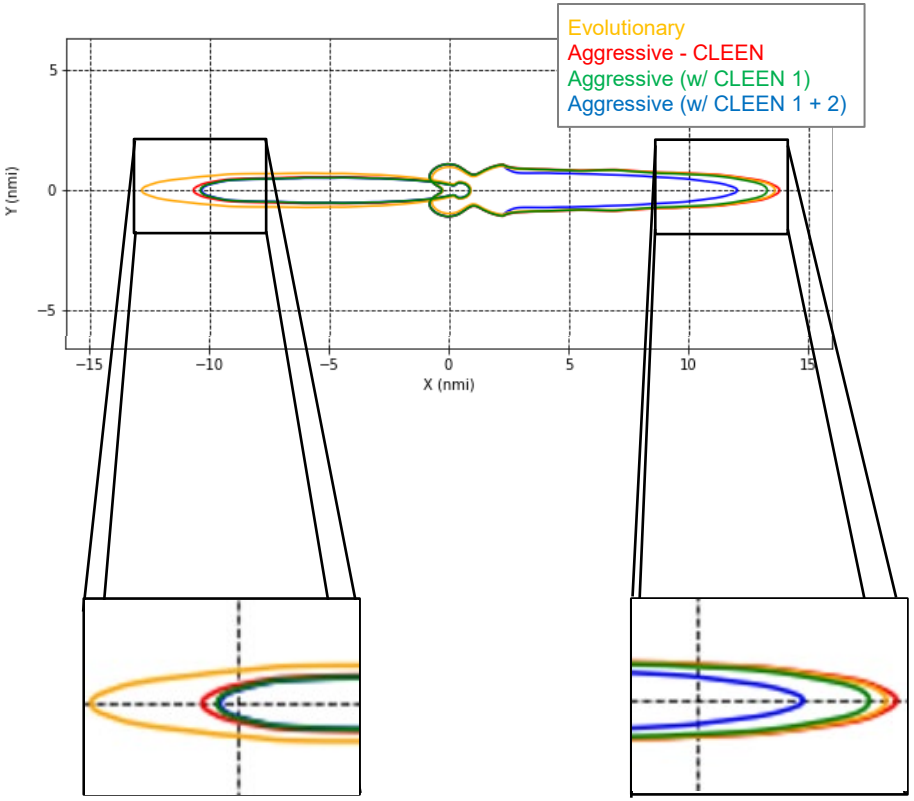
Assumptions

- Identical to fuel burn regarding:
  - Fleet replacement matrices
  - Demand forecast
  - Technology integration scenarios
  - Scope: Domestic + International departures
- Technologies included:
  - GT Public Set
  - All Fuel Burn/NOx Techs
  - CLEEN Acoustic Liners
    - Collins Aerospace Advanced Acoustics [RJ - GTF]
    - Boeing Compact Nacelle (Noise liner) [SA, STA, LTA, VLA]

GT Fleet Noise Modeling Process

- Generic noise contours generated for each vehicle class under each technology integration scenario
- For each scenario, the corresponding noise contours from all vehicle classes are summed by year
  - Output noise data for every 5 years, 2020-2050
  - Summation process follows demand forecast, scope, and fleet replacement matrix
- Result:
  - Predicted contour area for each scenario can be traced over 3 decades
  - Noise contours display impacts between scenarios and/or years

N+1 Generation Large Twin Aisle - ADD 75dB SEL Contours Max SL



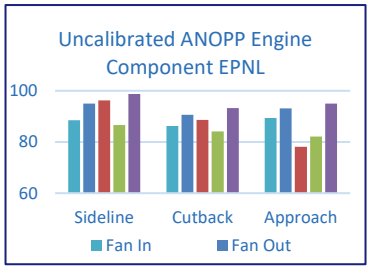
Baseline Source Noise Calibration

EDS Engine State Tables

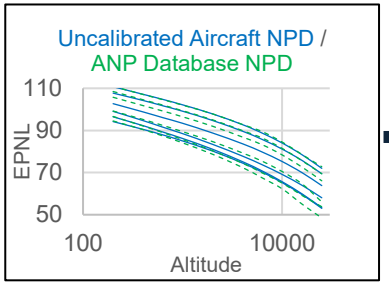
EDS Aircraft Size and Mission

NASA's ANOPP

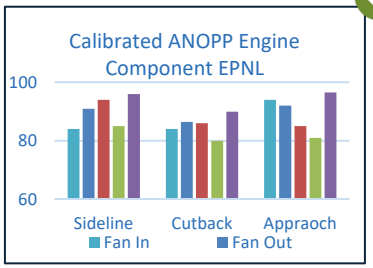
Component EPNL Level Calibration



Calibrated baseline vehicle component EPNLs for each vehicle class using NPDs from the ANP Database



Aircraft EPNL Level Calibration



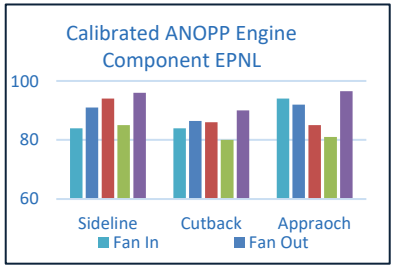
Baseline		
Cutback	Approach	Sideline
86.97	92.84	97.96

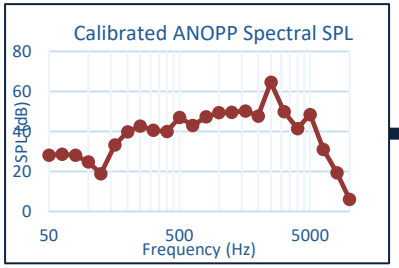
While preserving the component EPNL distribution, adjust calibration factors to match certification targets

Certification (B737-800)		
Cutback	Approach	Sideline
87.00	96.40	94.70

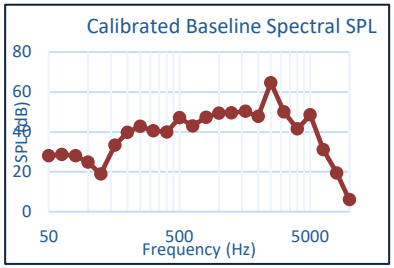
Calibrated Aircraft EPNL Level

Calibrated (Notional B737-800)		
Cutback	Approach	Sideline
87.00	96.40	94.70

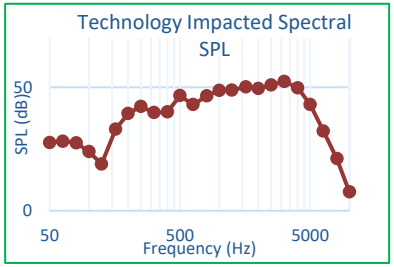




Technology Impacts to EPNL Level



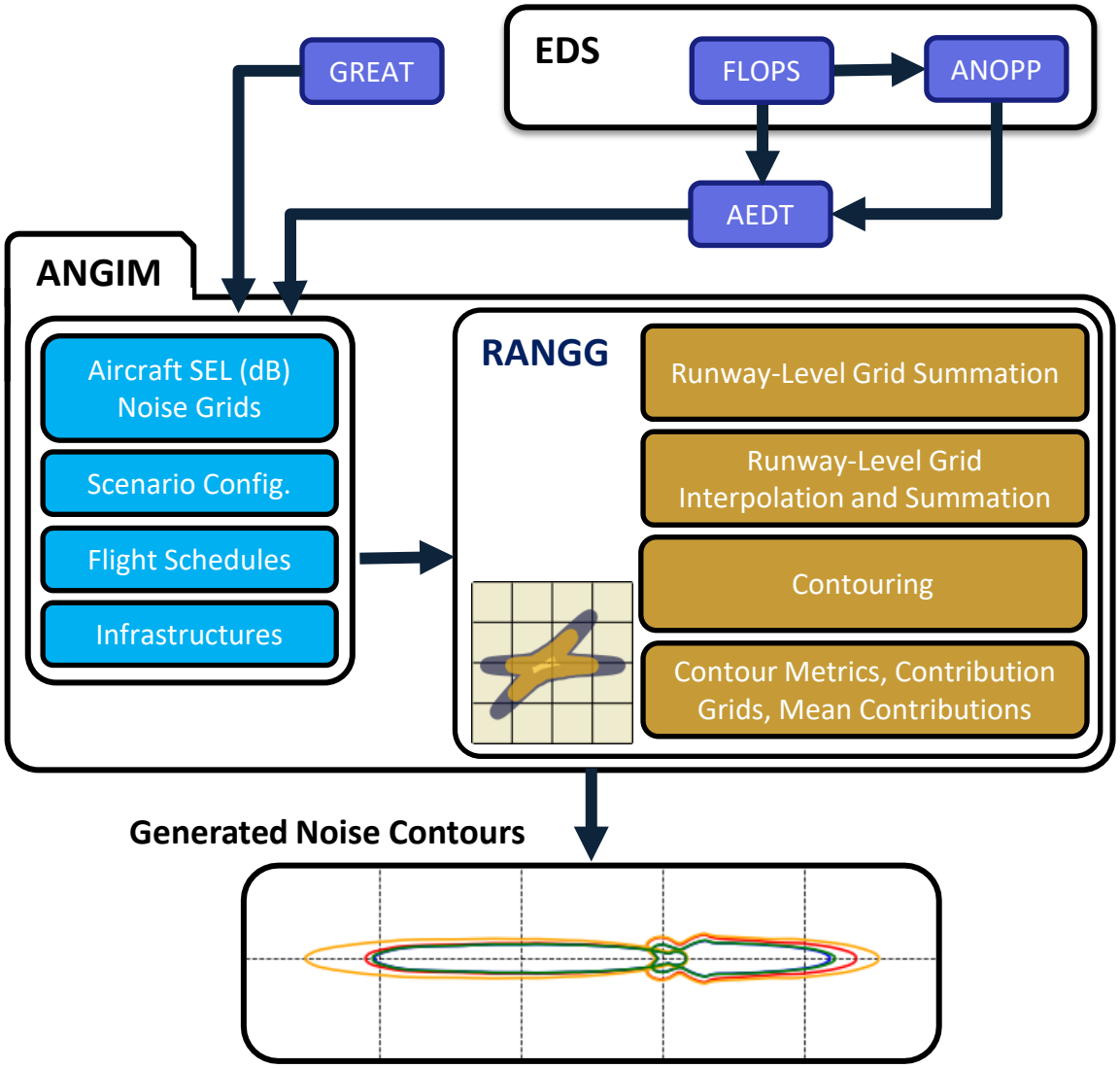
Apply suppression factors strategically inline with technology impacts



Airport Noise Grid Integration Method (ANGIM)

How does this translate to fleet noise contours?

- ANGIM applies individual vehicle noise grids under each scenario to a flight schedule and a runway configuration for a representative set of domestic airports
- ANGIM contains the C++ application Rapid Airport Noise Grid Generator (RANGG) that can perform grid summation, interpolation, contour generation, and metric computation
- Computes runway-level DNL noise, interpolates to airport-level DNL grids, and computes contours, areas, and other desired metrics for each airport
- Enables a rapid yet comprehensive analysis of fleet-level noise



Summary & Next Steps

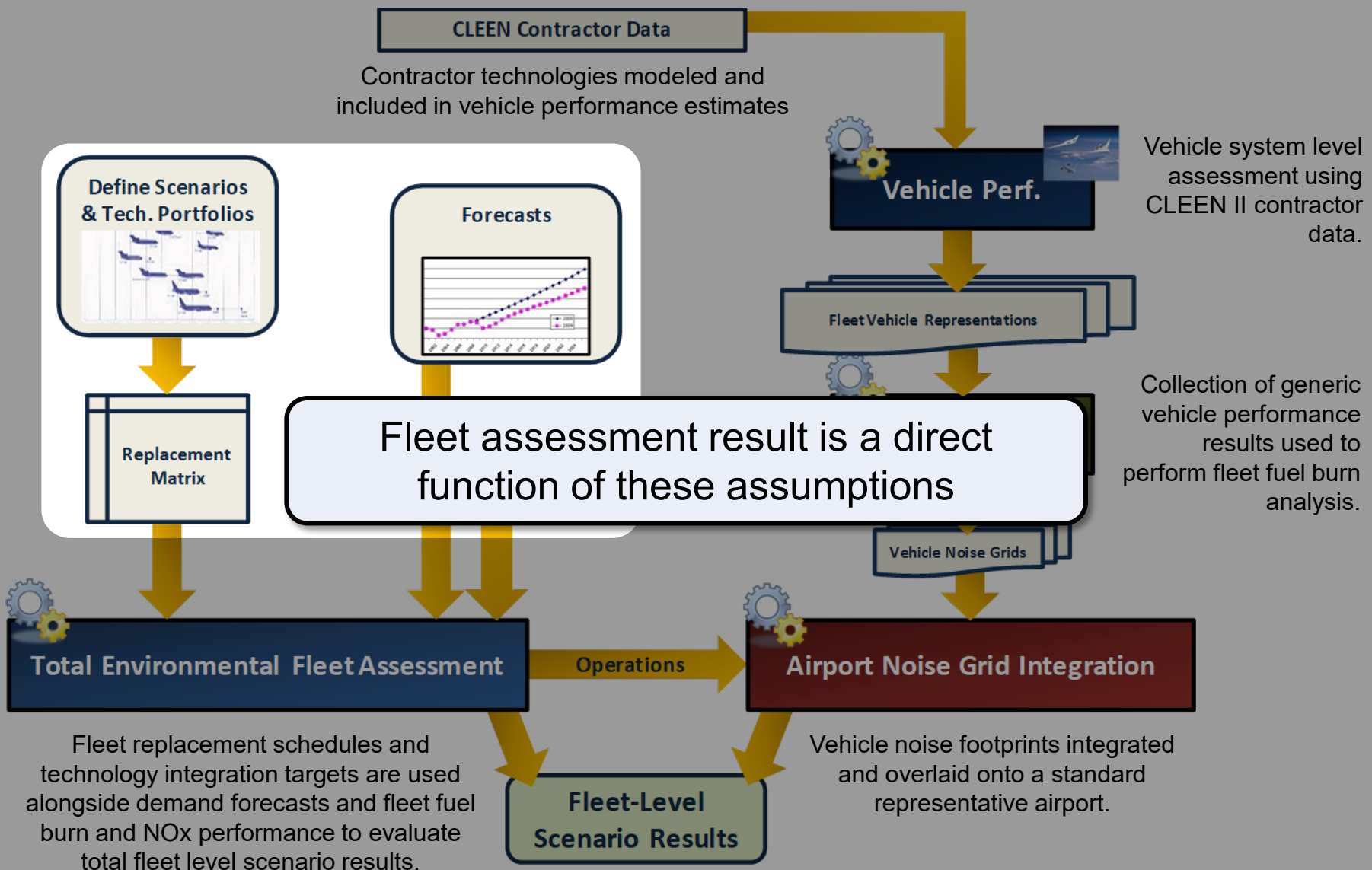
CLEEN II Technology Portfolio:

- Modeled
  - Boeing Aurora D8 Fuselage
  - Boeing structurally efficient wing, compact nacelle
  - Delta/MDS/America's Phenix Leading Edge Protective Cooling (FAA)
  - GE MESTANG, FMS, and TAPS III Low NOx combustor
  - Honeywell Turbine Blade Outer Air Seal
  - Pratt & Whitney Compressor and Aero-Efficiency Technologies
  - Collins Aerospace: Slim Nacelle
  - Honeywell Compact Combustor
  - Collins Aerospace: Noise Liner Technologies
  - Boeing compact nacelle acoustics
  - Rolls-Royce: Advanced Rich Quench Lean Low NOx Combustor
- Awaiting Data/Testing
  - Honeywell Acoustic Fan Rotor/Liner Technologies, Advanced HPC

Next Steps:

- Complete CLEEN II noise benefits assessment
- Complete technology modeling for CLEEN II
- Extend Current Fleet Level Assessments to include all CLEEN II technologies
- Establish working relationships with CLEEN III contractors and begin technology modeling
- Update Fleet assessment assumptions

Updating Fleet Level Assumptions



Updating Fleet Level Assumptions

Moving into CLEEN III:

- Fleet level assumptions to be updated (alongside FAA)
  - Demand forecast
    - US domestic travel and international departures to align with most recent, post-COVID, demand forecast
  - Replacement Matrix
    - Align with most relevant, post-COVID, fleet replacement forecasts
  - Technology Integration Scenarios
    - Align with recent international studies: IEIR, LTAG
    - Revisit the scope of included public technologies and their EIS plans
    - Realign the system level impacts of the included public technologies
    - Audit approach for drawing out the impact of CLEEN technologies at fleet level
  - Baseline vehicles
    - CLEEN III fleet composition better represented with different modeled vehicle collection
    - Assessment through CLEEN II uses 2010 best in class baseline vehicles
    - Updates for CLEEN III to potentially include vehicle upgrades:

Vehicle Class	CLEEN I & II (2010)	CLEEN III (2022)
RJ (50-100 pax)	CRJ-900	E190-E2
LSA (150 pax)	B737-800	B737-8
STA (210 pax)	B767-300ER	B787-8
LTA (300 pax)	B777-200ER	B787-10
VLA (400 pax)	B747-400ER	B747-8

Thank you.

GT-ASDL would like to thank Levent Ileri, Arthur Orton, and Roxanna Moores for their continued support in this work.

Demand Forecast

- 2017 FAA Aerospace Forecast + Terminal Area Forecast