Goal Setting Methodology and Existing Noise Technology Goals

Summary of Two Independent Expert Review Panels on Noise Technologies

Review 1: Reported at CAEP/8 in February 2010
Review 2: Reported at CAEP/9 in February 2013

Dennis Huff
NASA

CAEP11 Independent Experts Integrated Review (IEIR)
Review Workshop #1 – Washington-DC, United States, April 24-28 2017

CAEP Noise Technology
Independent Experts
Goals Review

ICAO – CAEP/8
Technology Task Group Project N29

WP09: Report of the Independent Experts on Noise Technology Goals

Presented by:
Philip Gliebe, Chair
Noise Technology
Independent Expert Panel
February 2010
Montreal, Quebec, Canada

Noise Technology Independent Expert Panel
N29 Membership

Philip Gliebe
Consultant, USA – Chair
(Fan Noise & Jet Noise)

Brian Tester
Consultant, England – Co-Chair
(Jet Noise, Liners and Advanced Concepts)

Dennis Huff
NASA, USA – Co-Chair
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Jean Beslon
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Wajid Chishty
NRC, Canada
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Hirokazu Ishii
JAXA, Japan
(Airframe Noise, Fan Noise)

Yuri Khaletskiy
CIAM, Russia
(Core Noise, Fan Noise)

Independent Experts Review CAEP Remit

Using the independent expert process, to examine and make recommendations for noise, with respect to aircraft technology and air traffic operational goals in the mid term (10 years) and the long term (20 years).

The **Independent Expert Panel (IEP)** was directed to carry out the following, per CAEP-Memo/70, Attachment A, dated 1/4/08 (IEP1.1):

- "**Summarize the status of technology developments for aircraft noise** reduction that could be brought to market within 10 years from the date of review, as well as the 20-year prospects for noise reduction suggested by research progress, without disclosing commercially sensitive information;
- "**Assess the possibility of success for each technology**, based on experience from past research and development programs;
- "**Comment on the environmental, efficiency, and other economic tradeoffs** resulting from adopting the candidate noise reduction technologies;
- "**Define a noise level baseline**; and
- "**Recommend mid term and long term technology goals** for reducing aircraft noise relative to the defined baseline."

IER – Independent Experts Review
IEP – Independent Experts Panel

Goal Setting Process

- **Two major approaches identified for reducing aircraft noise:**
  - Advanced noise reduction design features or Noise Reduction Technology (NRT) of propulsion system and airframe, and
  - Advances in propulsion system design which provide increased Bypass Ratio (BPR) and therefore lower exhaust velocities and lower component source noise

- **Four categories of aircraft addressed:**
  - Regional Jets (RJ)
  - Small-Medium Range Twins (SMR2)
  - Long-Range Twins (LR2)
  - Long-Range Quads (LR4)

Technologies not Included in Goal Setting Process

- **Blended Wing-Body and "Silent Aircraft" Concepts**
  - Considered premature for 2018
  - Unlikely to be in service by 2028
- **Open rotor technology**
  - Insufficient Data Available to Review
  - The IEP Recommends future review when new data becomes available

Noise Goal Evaluation Methodology

- The IEP identified two contributors to aircraft system source noise reduction:
  - **Advances in propulsion system cycle – i.e., increases in Bypass Ratio (BPR)**
  - **Component Noise Reduction Technology (NRT) development**
- IEP members reviewed Noise Reduction Technology Concepts presented in the IER and made assessments of recommended benefits – see CAEP/8 - IP/10 for details
- Pilot Studies defined to provide system noise impact benefits for “packages” of noise reduction technologies – ICCAIA provided study results to IEP and the IEP carried out a separate Pilot Study of BPR effects
- Trends developed for cycle change (bypass ratio or BPR) effects from pilot studies, NASA AST studies, supplemented with Best Practices Database information
- Noise Reduction Technology (NRT) effects on Aircraft System Noise extracted from pilot study results and NASA AST study results

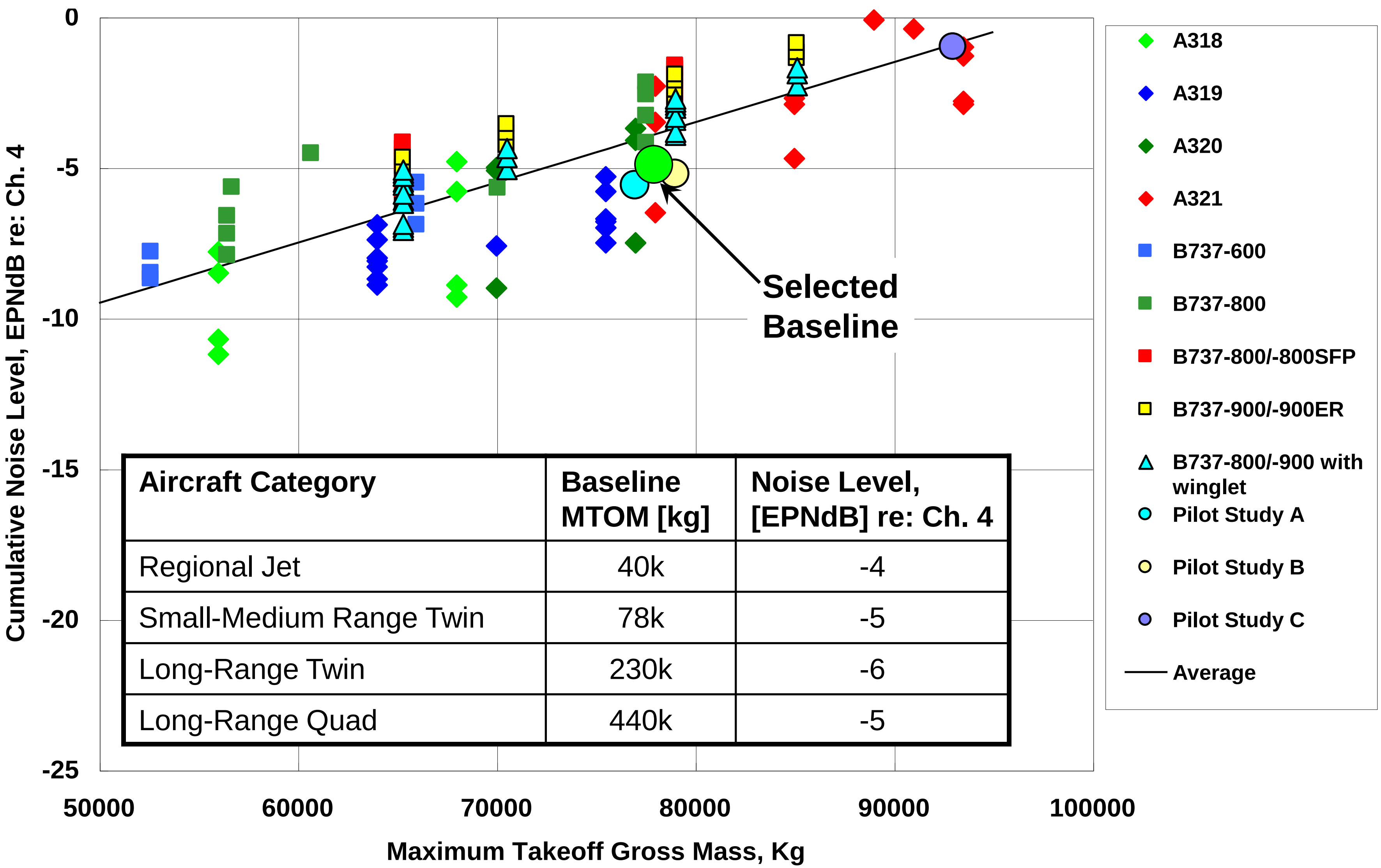
Noise Goal Methodology, Cont'd.

- Total Noise Reduction = combined effect of BPR effects and Noise Reduction Technology (NRT) effects
- Representative Baseline aircraft (2008 technology) selected for each aircraft category from which to apply noise reduction goals
- Noise Reduction Goals Established for Each Aircraft Category, for:
  - Mid Term (year 2018) – Technologies at TRL 5 to 6 or higher (TRL 8 within 10 years)
  - Long Term (year 2028) – Technologies at TRL 3 to 4 (TRL 8 within 20 years)
- Uncertainties in Goal Estimates evaluated
- Approximate Realization Factor applied to recognize potential noise reduction benefit shortfall as technology transitions from TRL 6 to TRL8

Baseline Aircraft Selection

- Best Practices Database certification data examined to select “typical” aircraft in each class
  - establish aircraft Takeoff Maximum weight (MTOM)
  - cumulative noise level relative to Chapter 4
  - with guidance from WG1 N29 Planning Committee
- IEP selected potential bypass ratio improvements for each class baseline, utilizing:
  - Guidance from WG1 N29 Planning Committee
  - IEP member expertise and experience
  - Needed for estimating future advanced cycle noise benefits

Sample Baseline Selection – SMR2

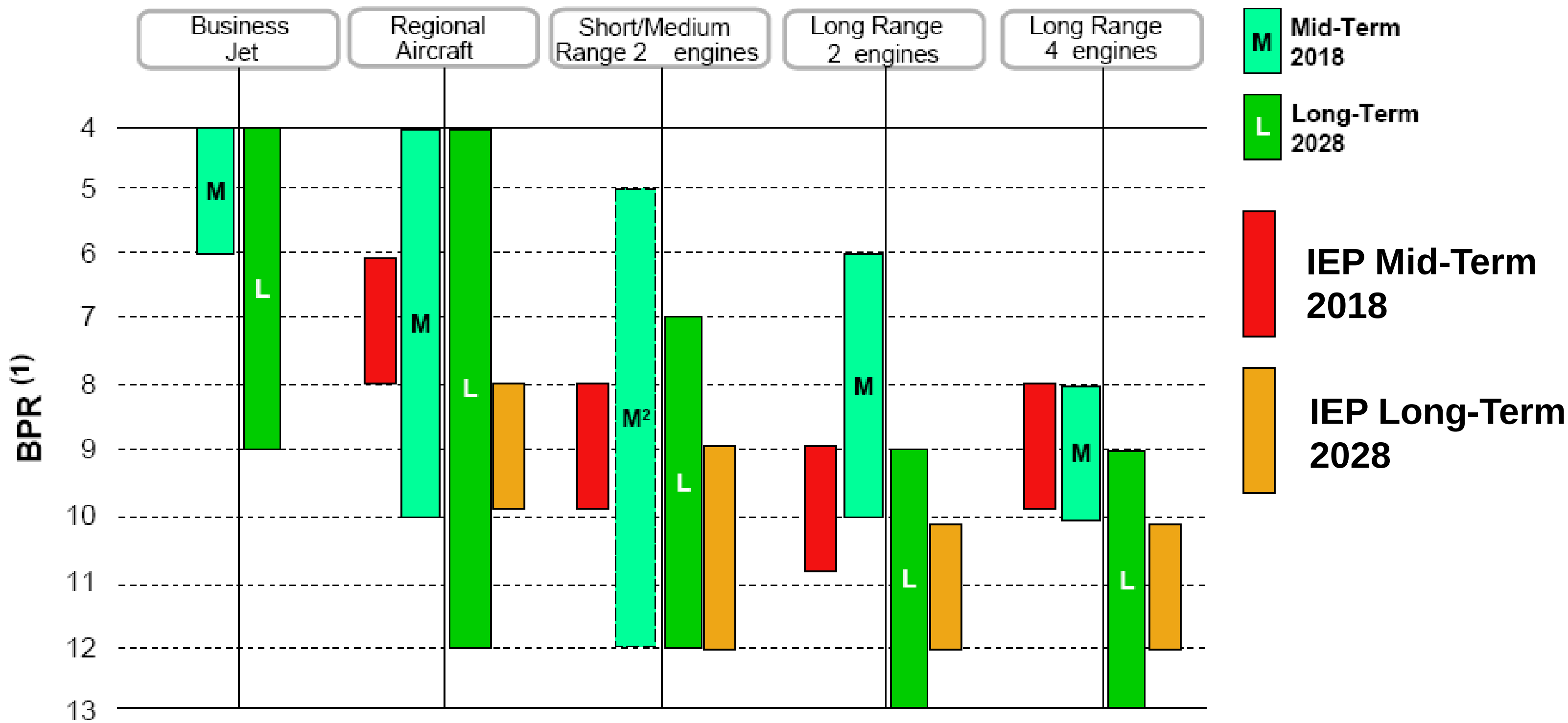


Aircraft Category	Baseline MTOM [kg]	Noise Level, [EPNdB] re: Ch. 4
Regional Jet	40k	-4
Small-Medium Range Twin	78k	-5
Long-Range Twin	230k	-6
Long-Range Quad	440k	-5

Bypass Ratio Range and Likely Future Target Values

Predicted Evolution of Bypass Ratio (BPR) enabled by engine technology - Open Rotors excluded

CAEP Noise Technology Independent Experts Goals Review



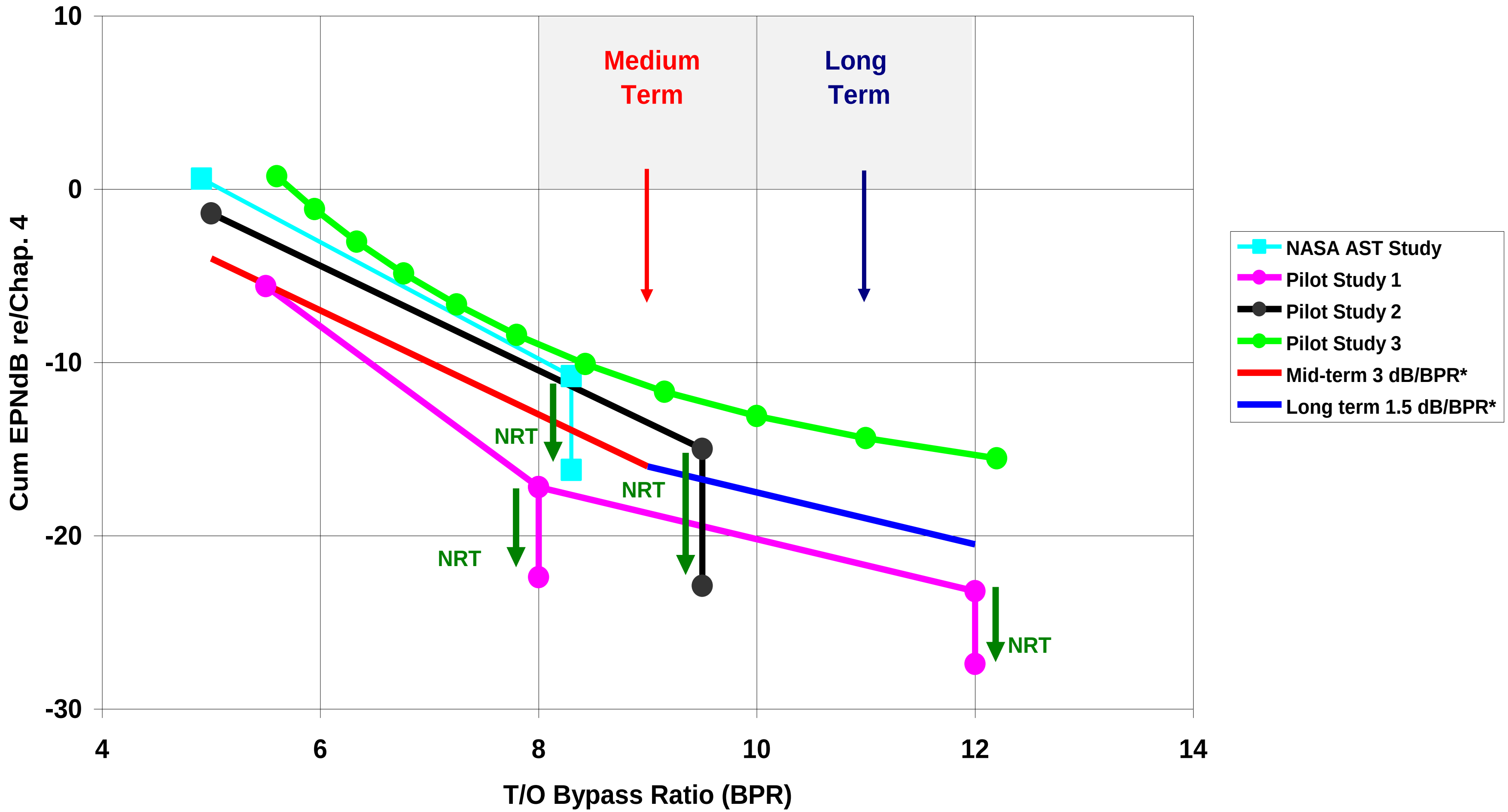
(1) All BPR correspond to sea level static rated thrust conditions

(2) Entry in service of most products in this category is not certain as of 2008

IEP Goal Methodology Details
Based on 3 'Pilot' Studies & NASA AST Studies

- Pilot 1 (industry) – SMR2 at BPR = 8 & 12 re. baseline at BPR = 5.5 (resized but similar MTOM) - with and without NRT
- Pilot 2 (industry) – SMR2 at BPR = 9.5 re. baseline BPR = 5.0 (resized but similar MTOM) - with and without NRT
- Pilot 3 (IEP) – SMR2 at BPR = 5.5 in steps to 12 (same MTOM) - no NRT
- NASA AST SMR2 study at BPR = 8.5 re. baseline BPR = 5 (same MTOM) - with and without NRT
- BPR & NRT trends deduced from SMR2 compared & adjusted for other classes using BP Database + NASA Studies on Long Range Quad & Long Range Twin

Example Noise Trends with Bypass Ratio and Noise Reduction Technology – SMR2



IEP Noise Reduction Goals
Mid-Term (Yr. 2018)

(BPR + NRT = Total)

Aircraft Category	Approach	Flyover	Lateral	Cumulative
Regional Jet	0.5+1.5=2.0	2.0+1.5=3.5	3.5+1.0=4.5	6.0+4.0=10.0
Small-Med. Range Twin	1.5+2.0=3.5	4.0+2.0=6.0	6.5+1.5=8.0	12.0+5.5=17.5
Long Range Twin	1.5+2.0=3.5	4.0+2.0=6.0	6.5+1.5=8.0	12.0+5.5=17.5
Long Range Quad	1.5+2.0=3.5	4.0+2.0=6.0	6.5+1.5=8.0	12.0+5.5=17.5

BPR – Bypass Ratio Benefit (Surrogate for Advanced Engine Cycle Design)
NRT – Noise Reduction Technology Package

IEP Noise Reduction Goals
Long-Term (Yr. 2028)

(BPR + NRT = Total)

Aircraft Category	Approach	Flyover	Lateral	Cumulative
Regional Jet	1.5+2.0=3.5	4.0+2.0=6.0	6.5+1.5=8.0	12.0+5.5=17.5
Small-Med. Range Twin	2.0+2.5=3.5	4.5+2.5=6.0	7.0+2.0=8.0	13.5+7.0=20.5
Long Range Twin	2.0+2.5=3.5	4.5+2.5=6.0	7.0+2.0=8.0	13.5+7.0=20.5
Long Range Quad	2.0+2.5=3.5	4.5+2.5=6.0	7.0+2.0=8.0	13.5+7.0=20.5

BPR – Bypass Ratio Benefit (Surrogate for Advanced Engine Cycle Design)
NRT – Noise Reduction Technology Package

Noise Reduction Goals Uncertainties

- **Statistical Analysis of available System Study Results carried out – separating BPR effects from NRT effects**
- **Total = RMS sum of BPR and NRT uncertainties**
- **Applied to Cumulative Noise Levels**
- **Uncertainty Estimates the same for all aircraft categories**

Time Interval	St'd. Deviation	80% Confidence
Mid Term (2018)	±3.6 dB	±4.6
Long Term (2028	±4.3 dB	±5.5

Realization Factor

- Factor to be applied to bring noise reduction estimates from TRL 6 to TRL 8
- IEP Settled on 90% Realization – Applied to Cumulative Noise Reduction

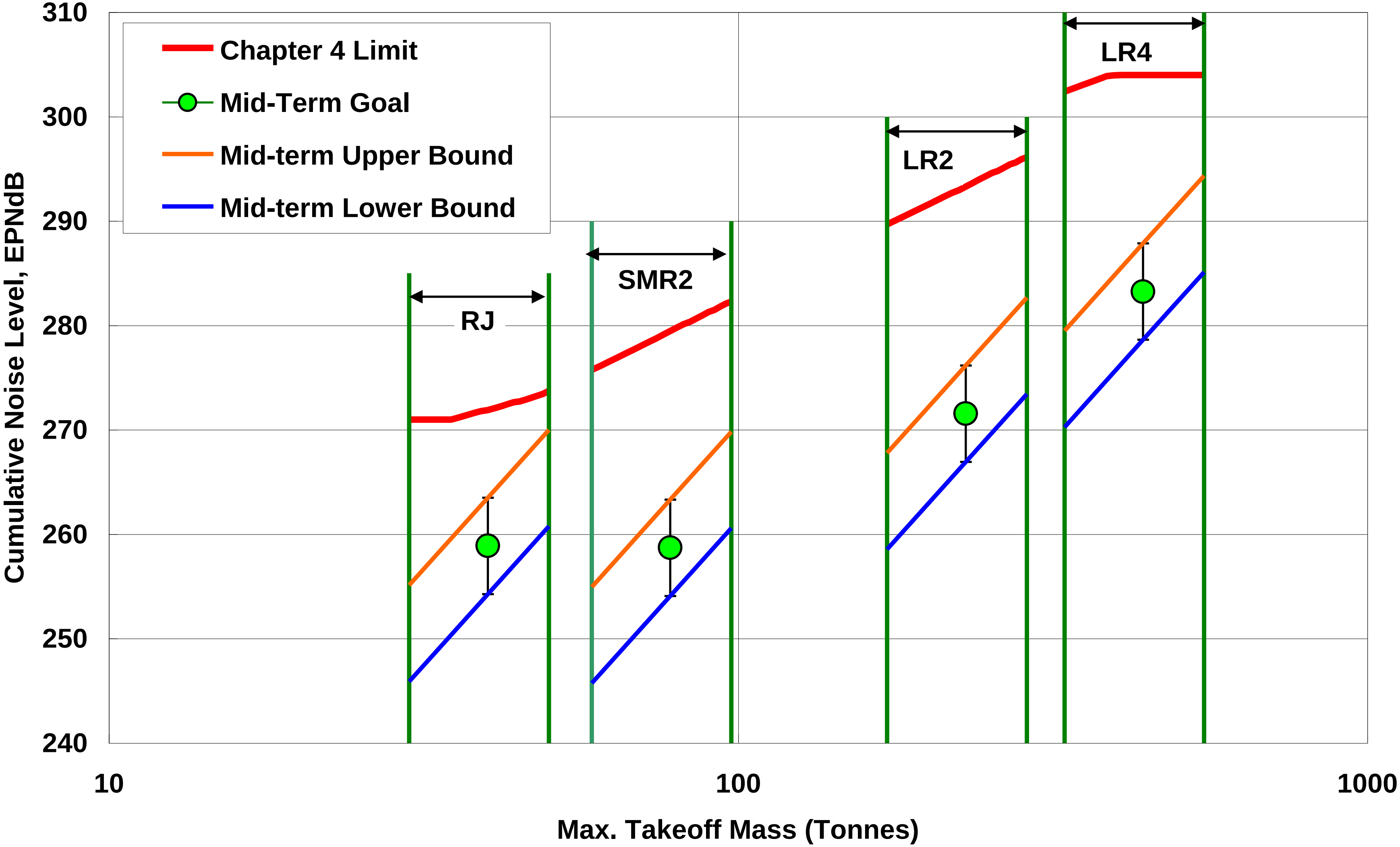
Estimated Cumulative EPNL Noise Reduction Goals (Relative to Current Reference Aircraft)

Aircraft Category	Mid-Term TRL 6	Mid-Term TRL 8	Long-Term TRL 6	Long-Term TRL 8
Regional Jet	10.0	9.0	17.5	16.0
Small-Med. Range Twin	17.5	16.0	20.5	18.5
Long Range Twin	17.5	16.0	20.5	18.5
Long Range Quad	17.5	16.0	20.5	18.5

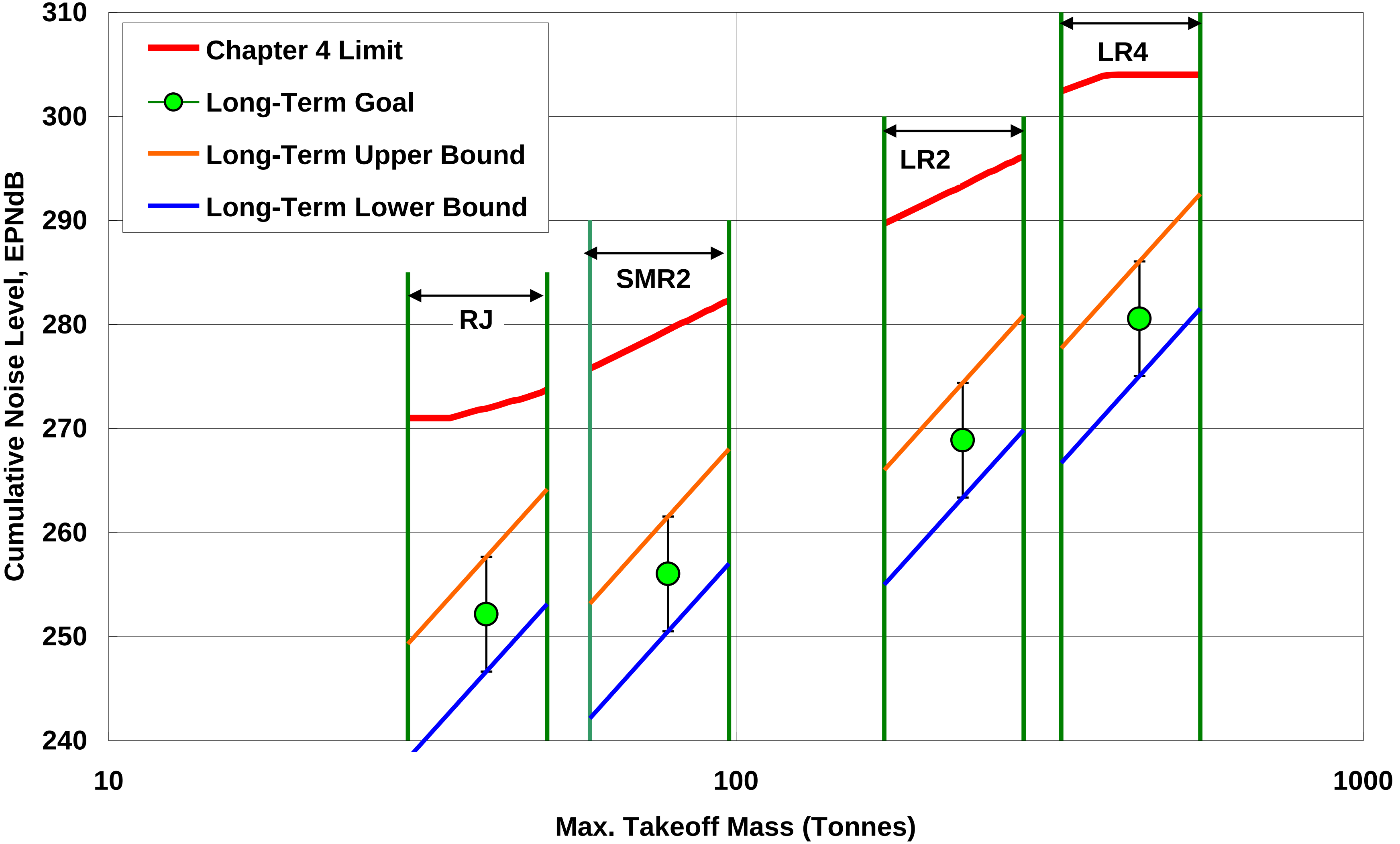
Noise Goal Presentation

- Noise Goals were developed in the following format, in agreement with WG1:
  - Absolute cumulative noise level
  - Show Chapter 4 limits
  - Show all 4 aircraft categories on same plot vs. MTOM
  - Indicate uncertainty band around goals – 80% CI
  - Realization Factor applied to noise reduction goal estimates – 90%
  - Indicate MTOM sensitivity to introduction of either lighter or heavier aircraft versions using historical MTOM sensitivity trends – provided by ICCAIA

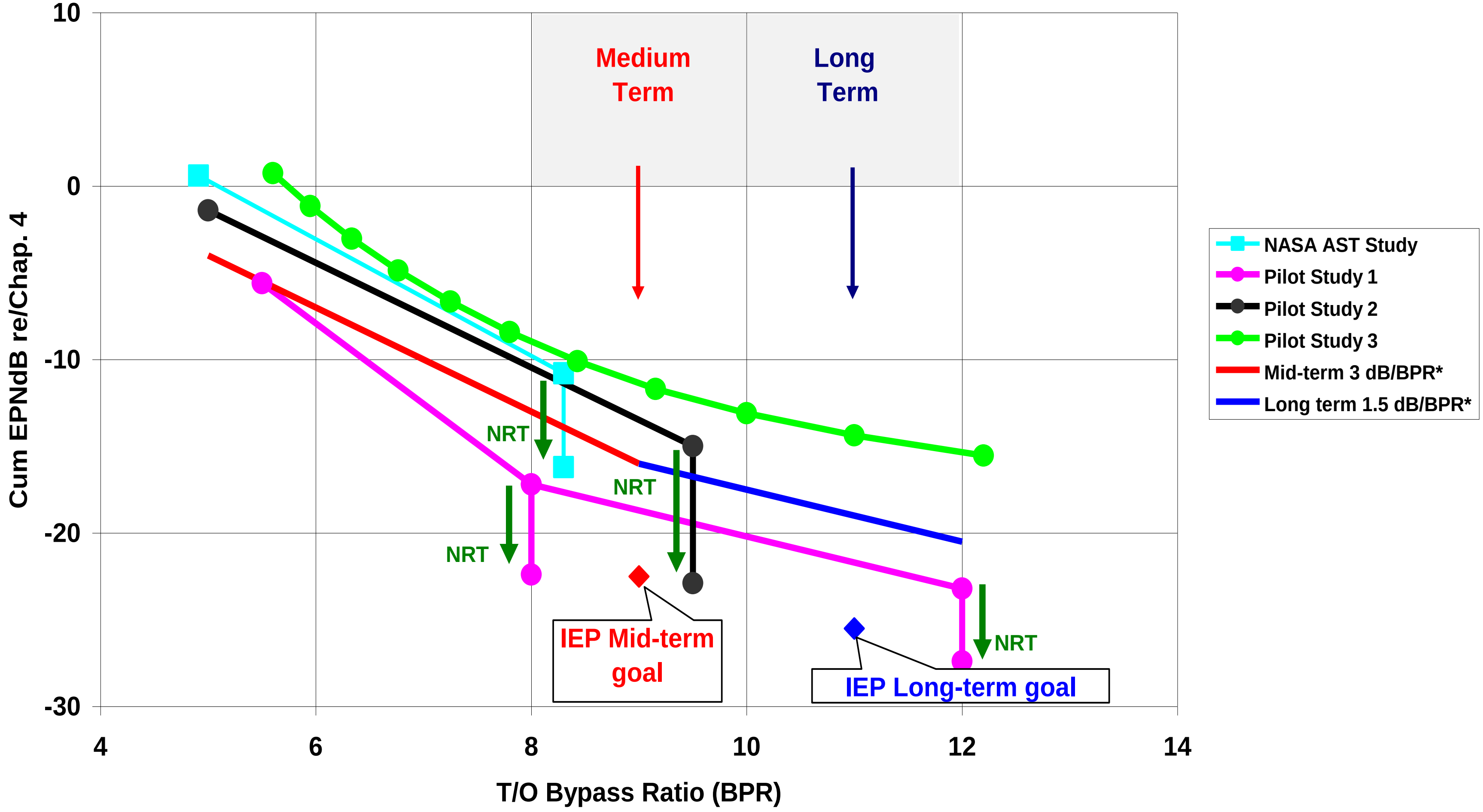
Noise Reduction Goal Summary
Mid-Term (2018)



Noise Reduction Goal Summary Long-Term (2028)



SMR2 Pilot Study Results with IEP Goals



Recommended Future Work Items

- Conduct “Pilot Studies” for other aircraft categories to refine present recommended goals
- Incorporate Open-Rotor Technology in Goal Setting Process as Data becomes Available
- Conduct study of “Realization Factor” to quantify influence of aircraft type, size, BPR, etc.
- Refine Goal Setting Uncertainty estimations as data becomes available

IEP Lessons Learned

- The CAEP Committees charged with defining IER’s should define and understand the resources needed to carry out the remit and objectives of the IEP review, and ensure that these resources and time to execute are adequate before launching a review.
- Written reports of IER material submitted prior to the Review would have been helpful to the IEP, would have provided the IEP with the written text & tables that the IEP needed.
- Consistency on part of the ICCAIA presenters in terms of noise reduction units, definition of TRL and BPR would have helped.

2nd CAEP Noise Technology
Independent Experts
Goals Review

ICAO – CAEP/9
Technology Task Group Project

Final Report of the Noise Technology Independent Expert Panel (IEP2)

February 5, 2013
Presentation to ICAO CAEP/9
Montreal, Canada

Noise Technology Independent Expert Panel Membership

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NASA, USA
Chair

Brian Tester
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Fernando Catalano
University of São Paulo,
Brazil

Magdy Adib Istafanous
ECAA, Egypt

Jim Hileman
FAA, USA

Independent Experts Review CAEP Remit

The **Independent Expert Panel (IEP2)** was directed to carry out the following, per CAEP-Memo/80, Attachment A, dated January 21, 2011:

<u>Task 1</u> - Summarize the status of new *technological advances* (novel aircraft and engine concepts) (e.g., open rotor, geared turbofan, blended wing body, etc.) that can be brought to market within 10 years (mid-term, 2020) from the date of the review, as well as the 20-year (long term, 2030) prospects suggested by research progress, without disclosing commercially sensitive information;

<u>Task 2</u> - Assess the possibility of noise reduction for each *technology* (novel aircraft and engine concepts);

<u>Task 3</u> - Comment on the environmental efficiency, and other economic tradeoffs resulting from adopting the candidate technologies; and

<u>Task 4</u> - Recommend updated mid-term and long-term technology goals for reducing aircraft noise relative to the defined baseline, also considering an improved definition of the realization factor when applied to noise technology development.

IER – Independent Experts Review
IEP – Independent Experts Panel
"1" – First Review/Panel
"2" – Second Review/Panel

Task 1 – Technological Advances

- IEP2 decided to use a Technology Scenario for Noise (TSN) approach similar to the Fuel Burn IEP.

  TSN-1: Pressure on the aviation industry to reduce noise will remain the same as it is today. Evolution of the conventional tube and wing aircraft will continue but the pressure will be insufficient to achieve the higher Technology Readiness Level (TRL) required for unconventional noise-driven aircraft concepts by 2030.

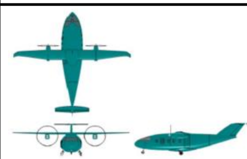
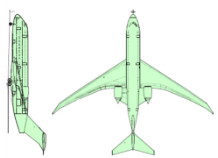
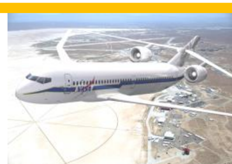
  TSN-2: Increased pressure to reduce noise, but balanced with reduced fuel burn and reduced emissions. Noise reduction would be a primary design objective that may require unconventional aircraft concepts, such as those that incorporate engine noise shielding.

- Reviewed NASA advanced aircraft studies and NACRE Pro-Green concepts (European project on "New Aircraft Concepts REsearch").

- Utilized independent systems analyses available from NASA Ultra High Bypass (UHB) turbofan and Open Rotor (CROR) studies.

- Interviewed several organizations who have conducted novel aircraft studies to determine feasibility for Entry Into Service (EIS) by 2030.

Sample of Novel Aircraft and Engine Concepts

Aircraft Concept	Picture	Mission	Reference	Fuel Burn (% below reference)	Noise (cum EPNdB under Chapter 4	NOx (% under CAEP/6)
NASA SFW General Electric 2035		20 pax 800 nm M=0.55 39,000’	B20/GE4600B	68.9	75	77
Novel Tube & Wing				**Reported Benefits**		
NASA ERA Boeing 2025		224 pax 8000 nm M=0.85 35,000’	B767 (1998 Technologies)	42.5	32	72
NACRE Proactive Green		Not Available	Single Aisle	-	4 below unshielded configurations	-
NASA ERA Lockheed Martin Box Wing		224 pax 8000 nm M=0.85 39,000’	1998 Technologies with Scaled Trent 800	>50	33 to 39	>85
NASA SFW MIT D8.1 Double Bubble		180 pax 3000 nm M=0.72 43,300’	B737-800	49	43	53

Selected for interviews by IEP2 to investigate feasibility for long-term 2030 EIS (entry into service), but deemed not likely.

Estimated by IEP2 to be feasible for long-term 2030 EIS based on interviews, but no current plans for product launch.

Task 2 – Noise Reduction Technologies

- The IEP2 revisited the noise reduction technologies (NRT) list from the first review. Several technologies shifted in time based on knowledge of current research activities.
- IEP2 used NASA studies on Short/Medium Range Twin (SMR2) Open Rotor and UHB turbofans to evaluate noise reduction technologies.
- TSN-2 concepts that used engine noise shielding were compared with each other to determine reasonable range of noise reduction benefits.

Noise Reduction Technologies

Small Twin Vehicles – Regional Jet to A321 size

Component	**Technology**	**Medium Term** (TRL 8 by 2020)	**Long Term** (TRL 8 by 2030)	**Longer Term** (TRL 8 post 2030)
Fan	Rotor Sweep	X		
	Stator Sweep & Lean	X		
	Fan Speed Optimization	X		
	Variable Area Nozzle	X	X	
	Acoustically Lined “Soft”		X	
	Vane		X	
	Over The Rotor Treatment		X	
	Active Stator			X
	Active Blade Tone Control			X
	Zero Hub Fan			X
Jet	Fixed Geometry Chevrons	X		
	Variable Geometry		X	
	Chevrons	X		
	Higher BPR Cycle	X		
	Advanced Long-Duct Mixer		X	
	Fluidic Injection, Microjets		X	
	& High Frequency		X	
	Excitation		X	
	Bevelled Nozzle			
	Off-set nozzles			
Nacelle/Liner	Zero Splice Inlet	X		
	Scarf Inlet		X	
	Nose Lip Liner	X		
	High Temp. Lightweight	X		
	Liner			
	LDMF (CNA) Liner		X	
	HQ Tubes		X	
	Optimized Zone Liner		X	
	Aft Cowl Liner		X	
	Acoustic Splitter		X	
	Active/Adaptive Liner		X	

Small Twin Vehicles – Regional Jet to A321 size (continued)

Component	**Technology**	**Medium Term** (TRL 8 by 2020)	**Long Term** (TRL 8 by 2030)	**Longer Term** (TRL 8 post 2030)
Turbine	Blade/Vane Ratio	X		
	Optimisation	X		
	Optimized Aerodynamics	X		
	Speed Optimisation		X	
	Over The Rotor			
	Treatment			
Combustor	Combustor Liner			
	(Baffles/Cavity Acoustic			
	Plugs/			
	Micro-Perforated Liner	X		
	Cavity Septum)		X	
	Staged injection			
Compressor	Blade/Vane Ratio	X		
Bleed Valve	Teeth Design	X		
	Exit Screen	X		
Landing Gear	Fairing & Flaps	X		
	Low-Noise Design	X		
	Flow Control		X	
Slats	Low-Noise Design		X	
	Slat Cove Filler		X	
Flaps	Low-Noise Design		X	
	Continuous Mold Line		X	
	Flap	X		
	Porous Side Edge			

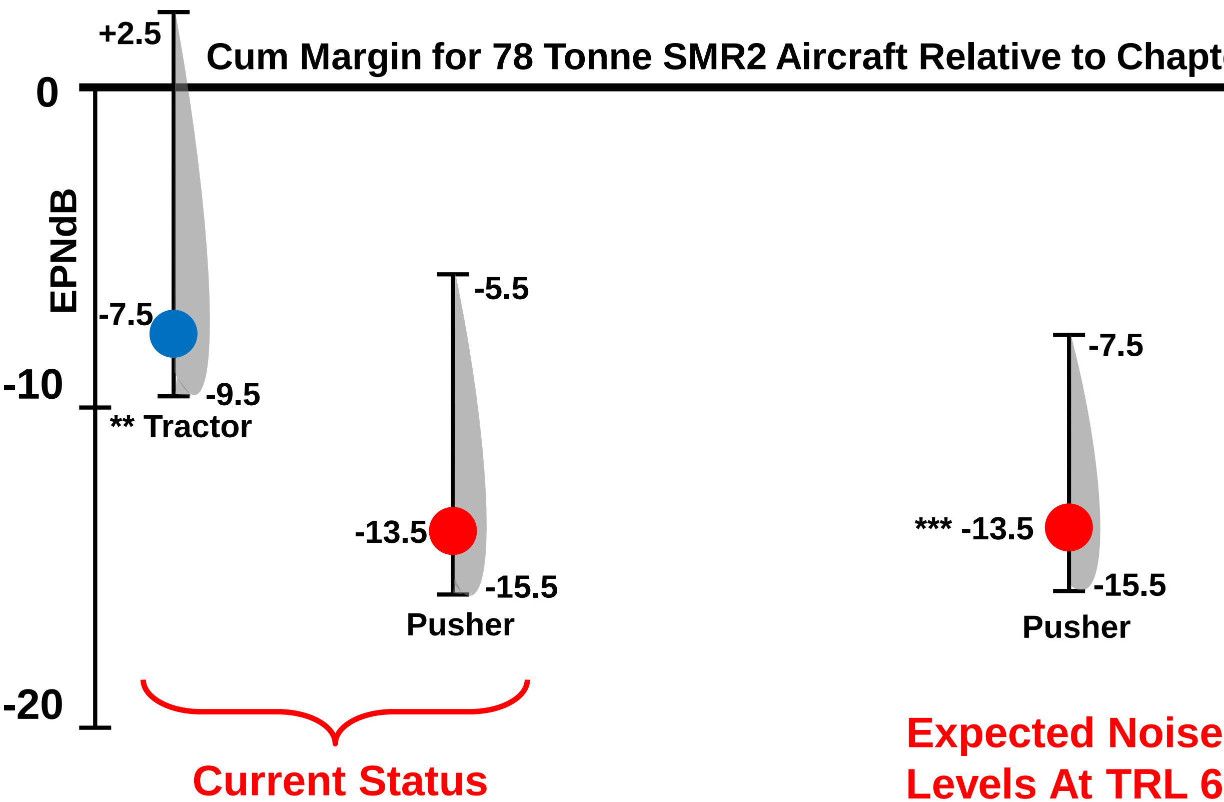
Open Rotor Technology Development & Noise Predictions

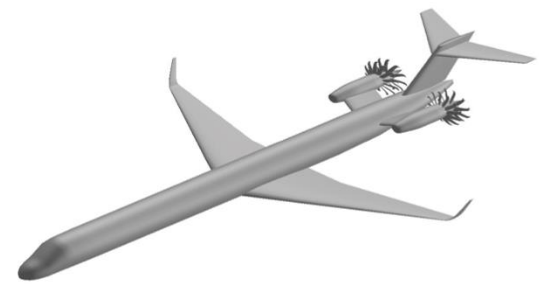
Preliminary Studies & Wind Tunnel Tests → Concept Definition & Flight Demos → Product Development → Entry Into Service

Technology Readiness Level (TRL)

3 — 2 Yrs — 4 — 2 Yrs — 5 — 5 Yrs — 6 — 1 Yr — 7 — 6 Yrs — 8

Cum Margin for 78 Tonne SMR2 Aircraft Relative to Chapter 4 with Estimated Uncertainties



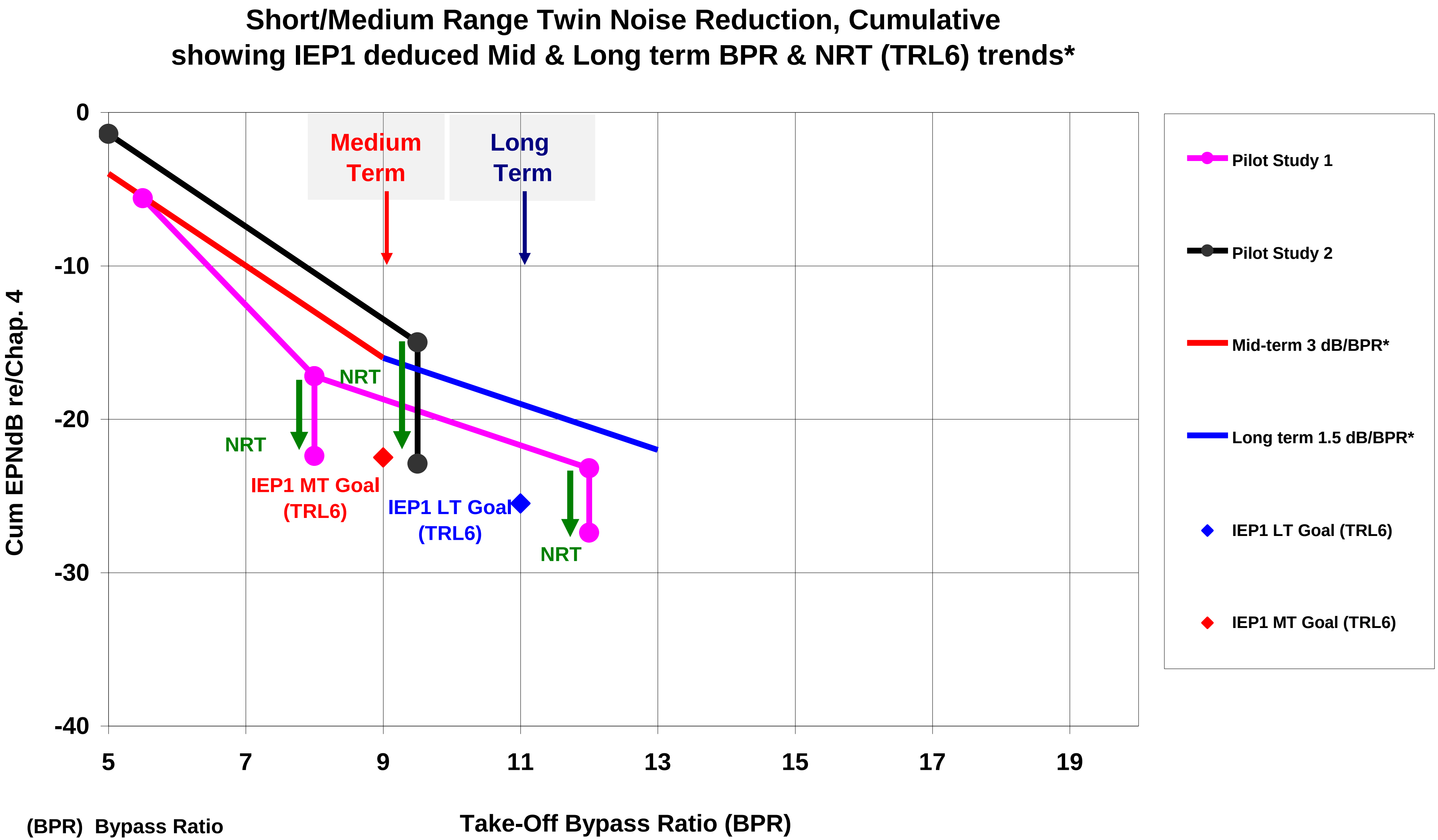


* Notional pusher configuration shown above.

** No known plans for higher TRL development of tractor configurations (wing mounted engines).

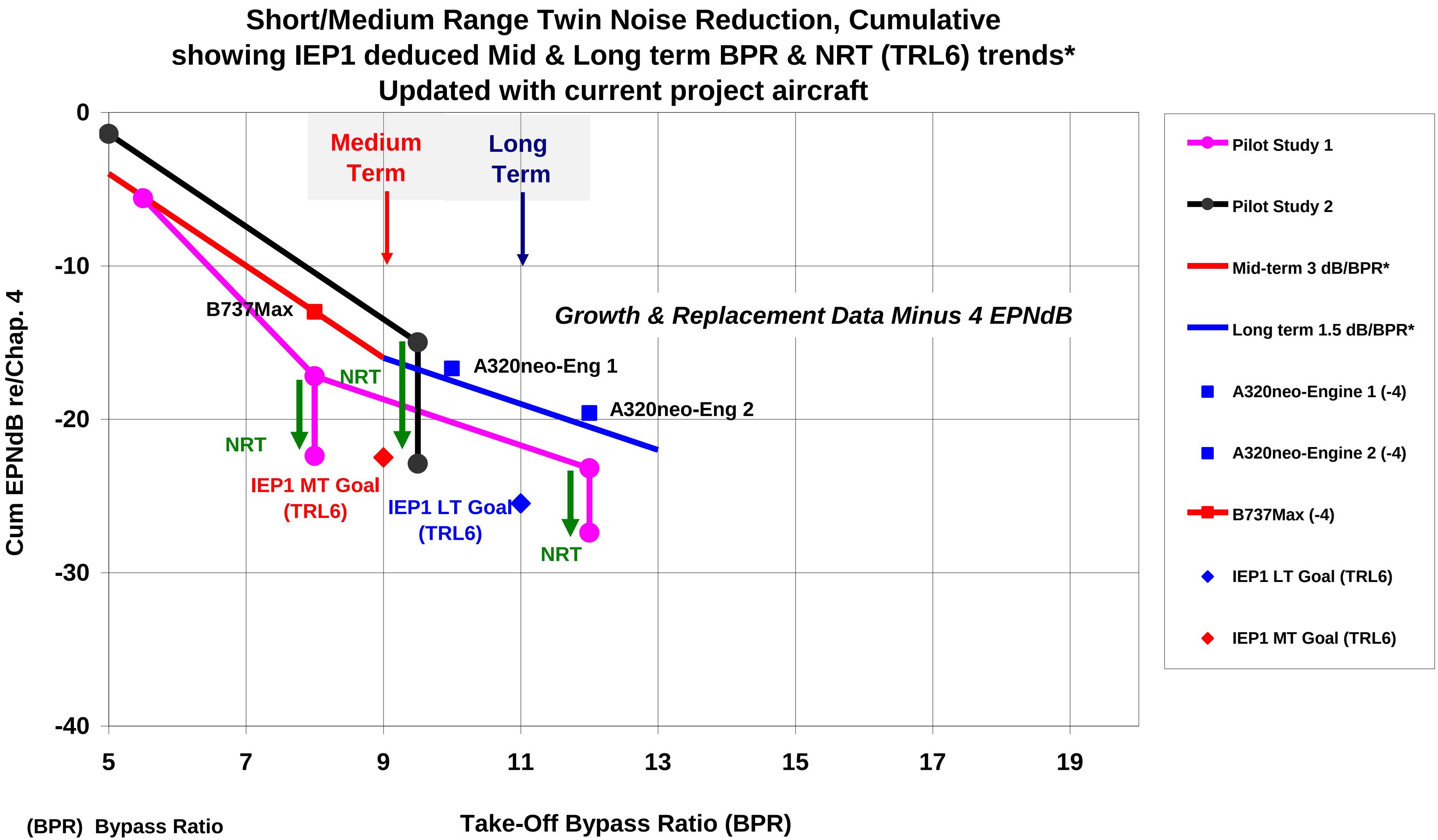
*** Nominal value judged by IEP2 to be the same from TRL4 to TRL6 based on experience from GE Un-Ducted Fan (UDF) flight tests.

Noise Trends with Bypass Ratio – SMR2



(BPR) Bypass Ratio
(NRT) Noise Reduction Technologies
(TRL) Technology Readiness Level

Noise Trends with Bypass Ratio – SMR2



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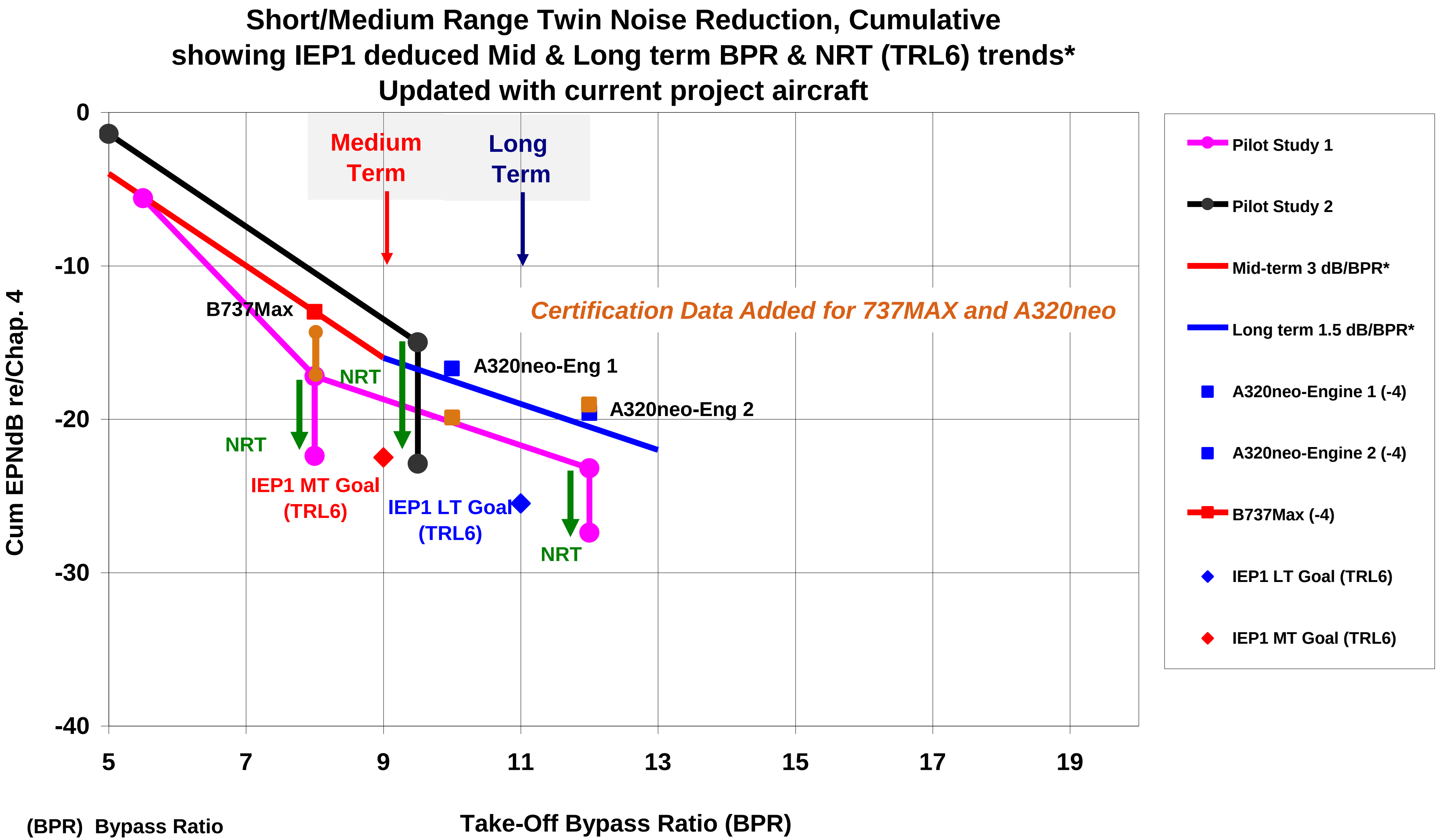
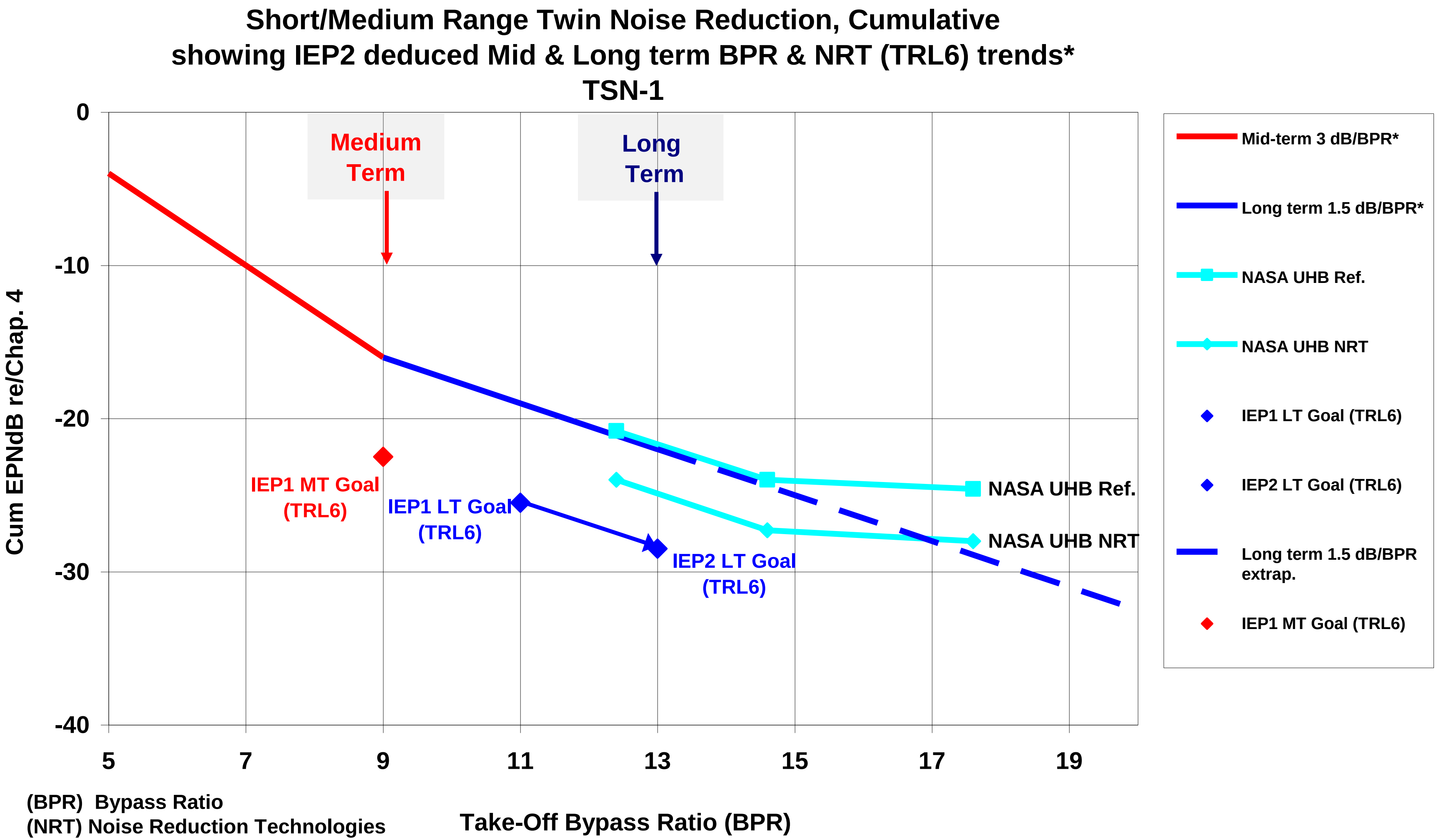
Noise Trends with Bypass Ratio – SMR2



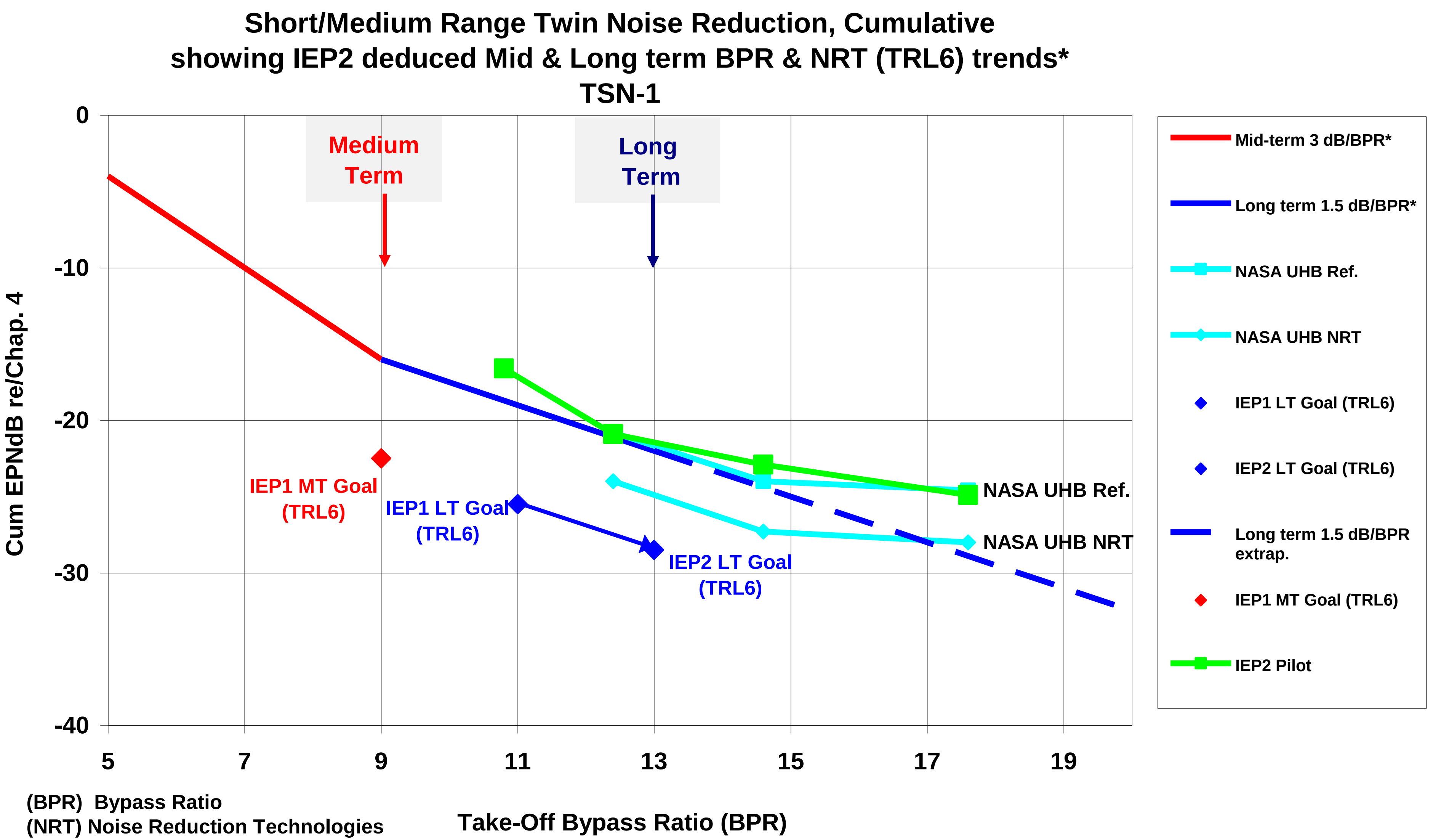
(BPR) Bypass Ratio
(NRT) Noise Reduction Technologies
(TRL) Technology Readiness Level

Noise Trends with Bypass Ratio – SMR2



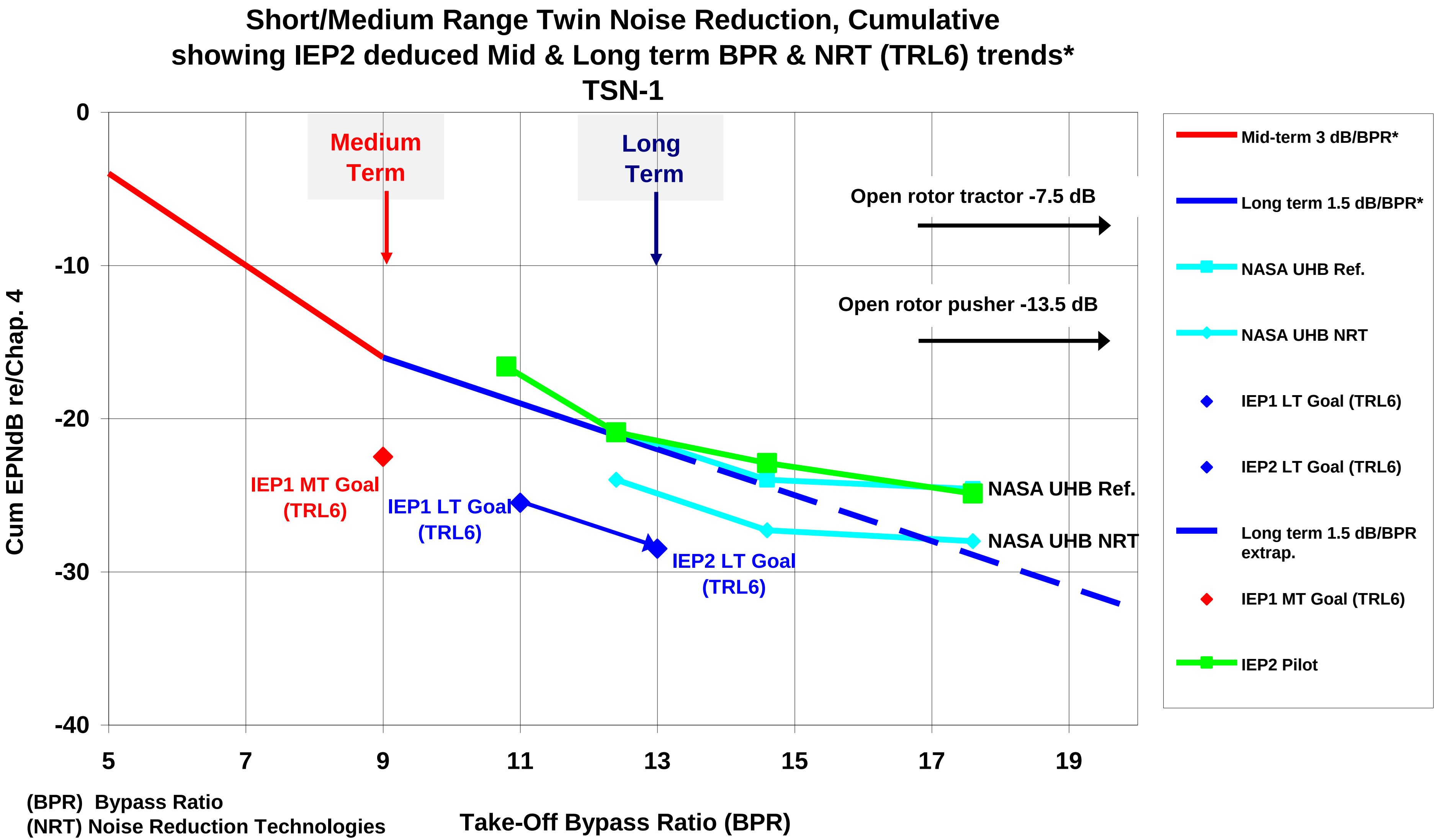
(BPR) Bypass Ratio
(NRT) Noise Reduction Technologies
(TRL) Technology Readiness Level
(TSN) Technology Scenario for Noise
(UHB) Ultra High Bypass ratio

Noise Trends with Bypass Ratio – SMR2



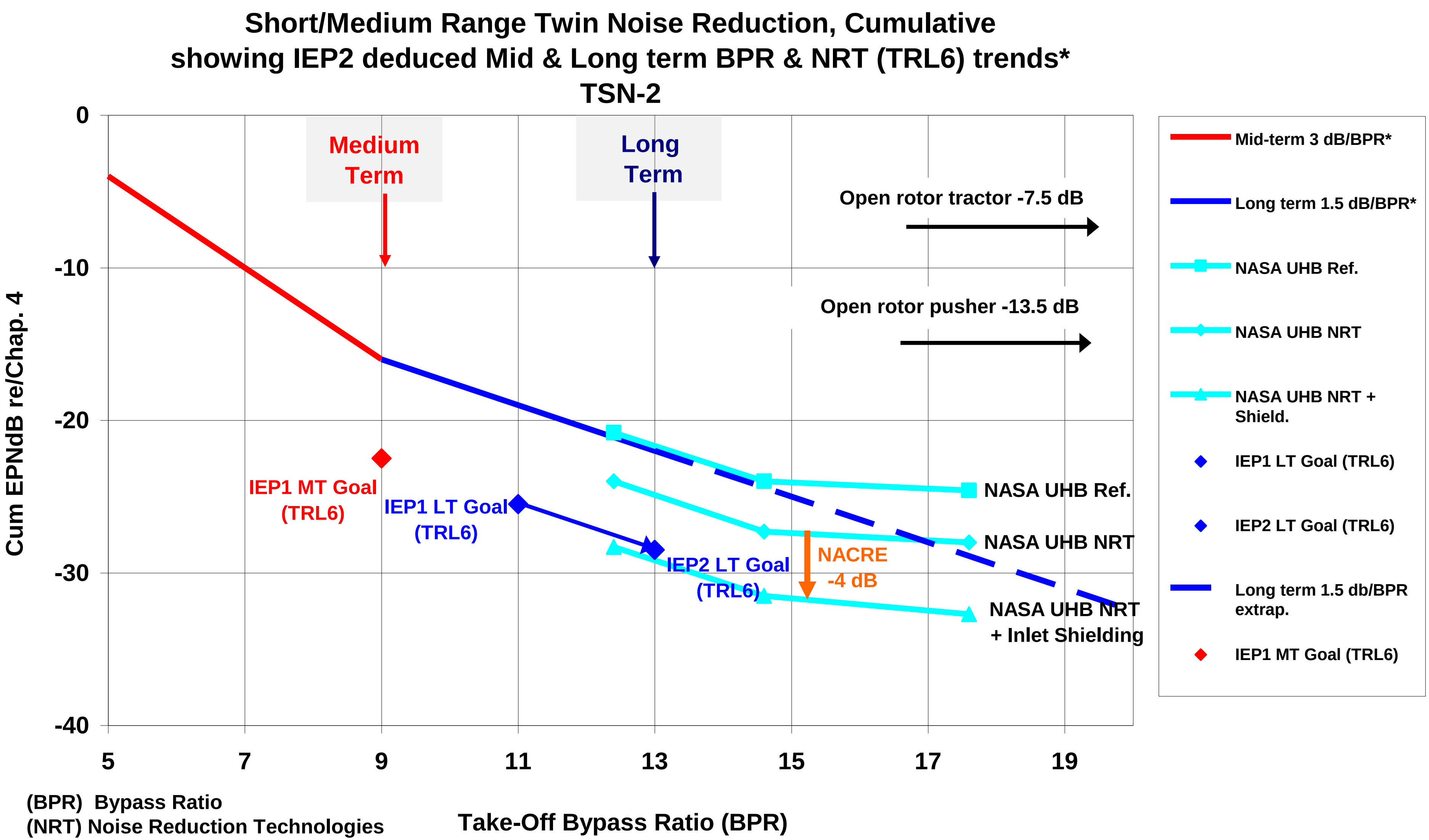
(BPR) Bypass Ratio
(NRT) Noise Reduction Technologies
(TRL) Technology Readiness Level
(TSN) Technology Scenario for Noise
(UHB) Ultra High Bypass ratio

Noise Trends with Bypass Ratio – SMR2



(BPR) Bypass Ratio
(NRT) Noise Reduction Technologies
(TRL) Technology Readiness Level
(TSN) Technology Scenario for Noise
(UHB) Ultra High Bypass ratio
(CROR) Counter-Rotating Open Rotors

Noise Trends with Bypass Ratio – SMR2



(BPR) Bypass Ratio
(NRT) Noise Reduction Technologies
(TRL) Technology Readiness Level
(TSN) Technology Scenario for Noise
(UHB) Ultra High Bypass ratio

Task 3 – Tradeoffs

- Environmental Trade-offs (Noise/NO*x*/CO_2) linked to physical principles are key elements for optimization in design and other major areas (e.g. operations, regulations, research).
- Tradeoffs are very challenging to apprehend, due to complex, "remote and entangled" features and evolving issues:
  - Depends on progress in understanding quantitative trade-offs.
  - Would have required in-depth analyses, especially in little explored territory such as novel configurations. Not compatible with tight schedule.
- IEP used best available information from studies and new data to summarize and assess the effects of tradeoffs. Recent studies have been conducted with simultaneous goals for noise, emissions and fuel burn that included tradeoff assessments.

NASA Short Medium Range Twin (SMR2) Study Results – Fuel Burn vs. Noise

NASA modern airplane:
15% structural weight reduction from composites
5000 psi hydraulic systems
1% drag reduction from drag cleanup and variable trailing edge
Open rotor version has +2100lbs (953 kg) weight penalty

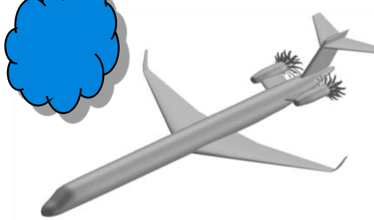
Advanced UHB Turbofan
Fuel burn: 27% *
Noise: 25 dB cum margin to Ch.4 *

NASA modern airplane
162 pax, 3250nm mission
Cruise M= 0.78, 35kft (FL350)
Rear mount Turbofan

N+1 Tech
UHB TF
BPR ~14

Open Rotor (modern blade set)
Fuel burn: 36% *
Noise: 13 dB cum margin to Ch.4 *

N+1 Tech
Open Rotor
BPR >30



Cooperative Study with GE
NASA modern airplane
162 pax, 3250nm mission
Cruise M= 0.78, 35kft (FL350)
Rear mount Open Rotor

1998 technology reference vehicle
162 pax, 3250nm mission

Noise Margin

% Fuel Burn Benefit

* Uncertainty Not Included

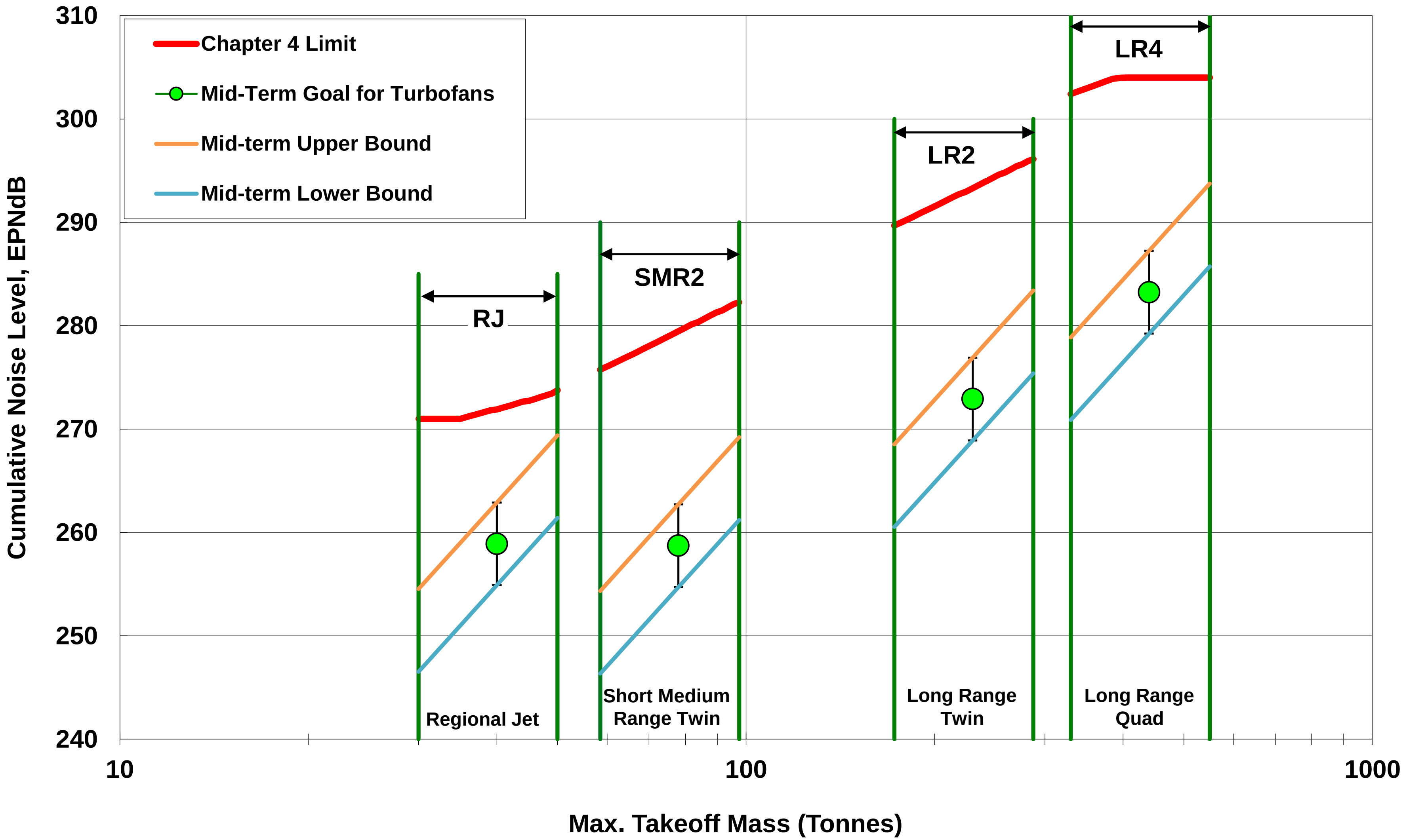
Task 4 - Goals

- Realization Factor
- Updated Noise Goals

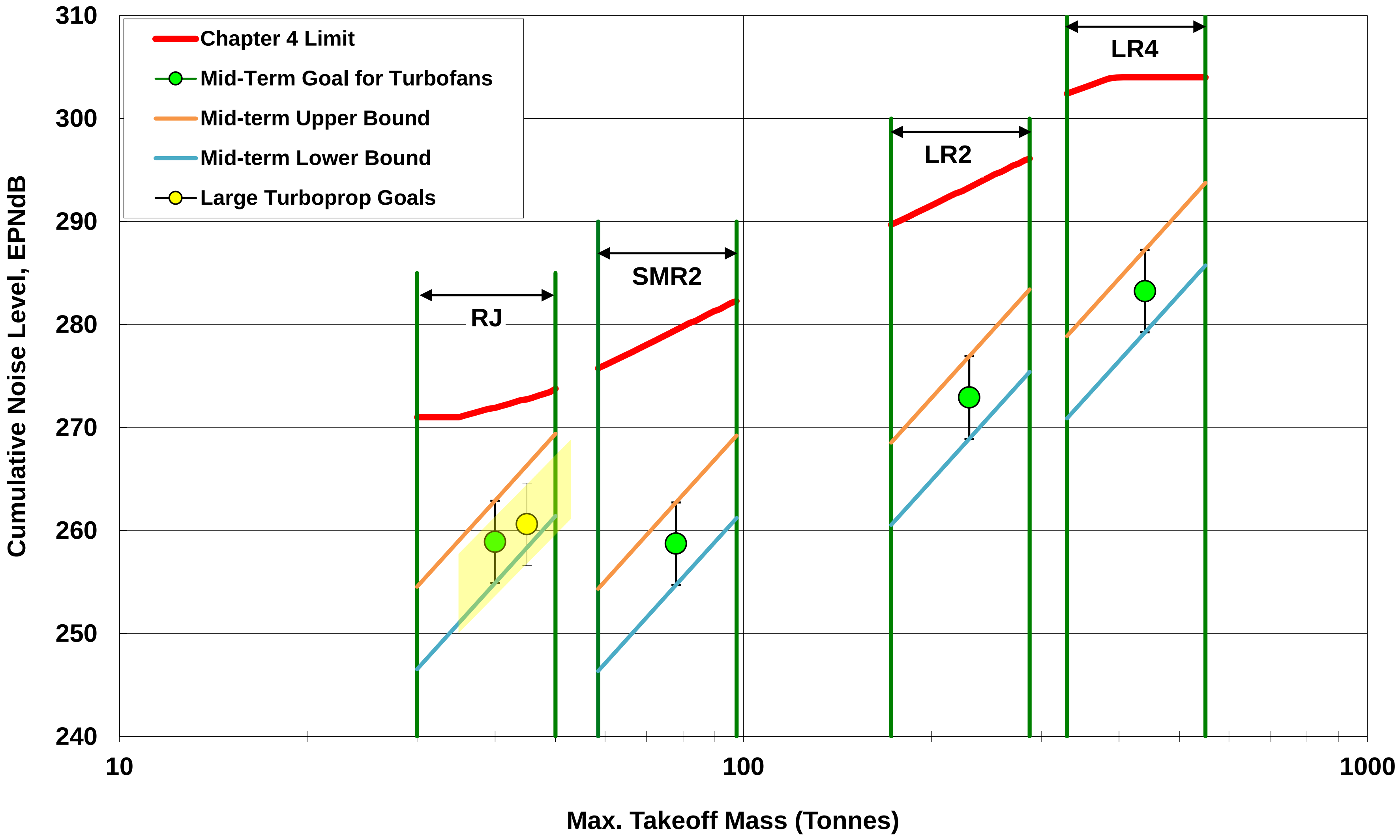
Realization Factor

- The IEP2 has provided recommendations for TRL6 and no Realization Factor (RF) has been used for long term goals.
- Rationale:
  - Current experience is based on turbofan and turboprop powered aircraft that has limited applicability to novel aircraft concepts.
  - IEP2 feels that it is not possible to determine the RF for an Open Rotor aircraft at a TRL8 since there has not been any development for the concept beyond TRL6.
- Mid-term goals are given for TRL 8 using the same RF used by IEP1.

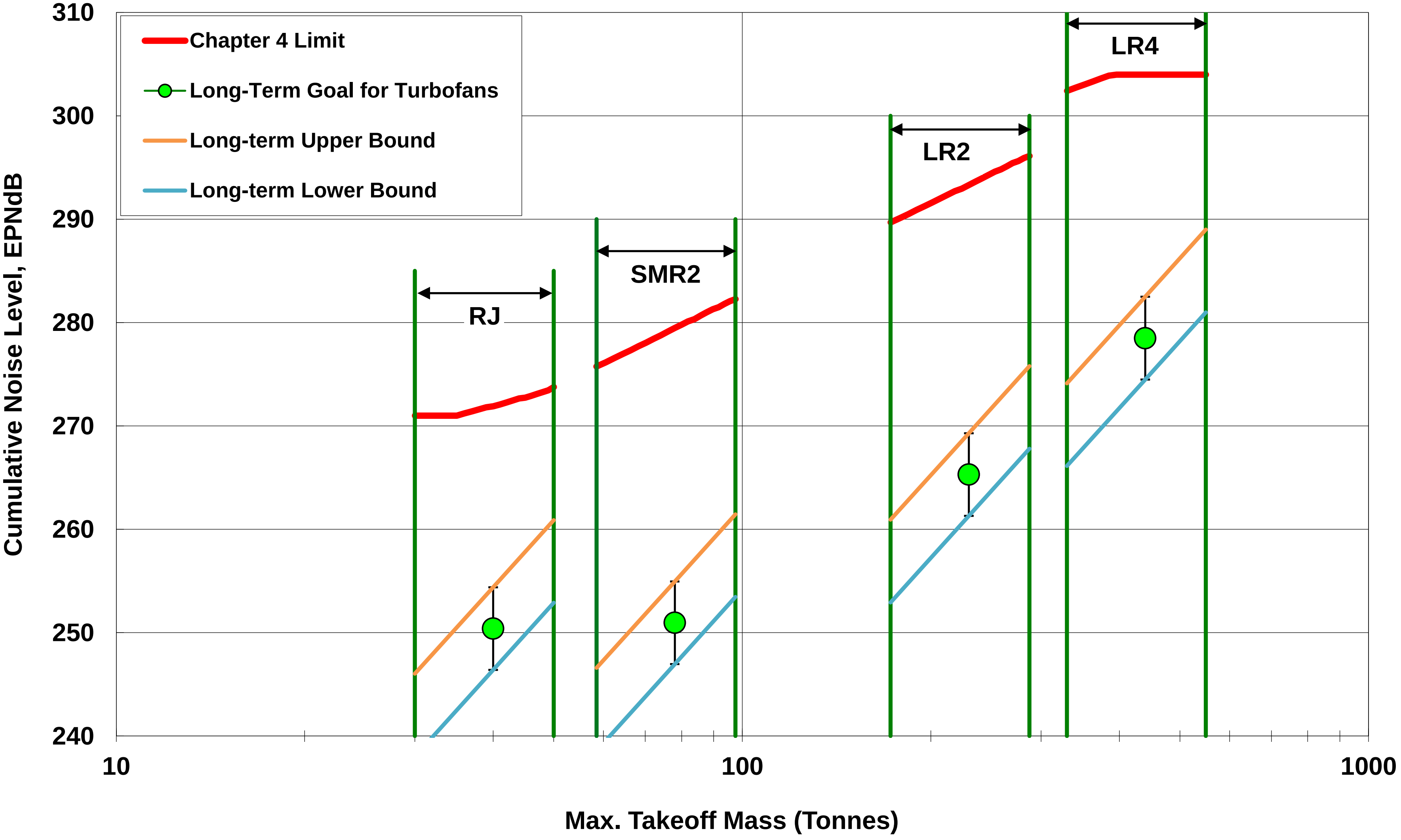
Mid Term (2020) Cumulative Noise Goals at TRL 8



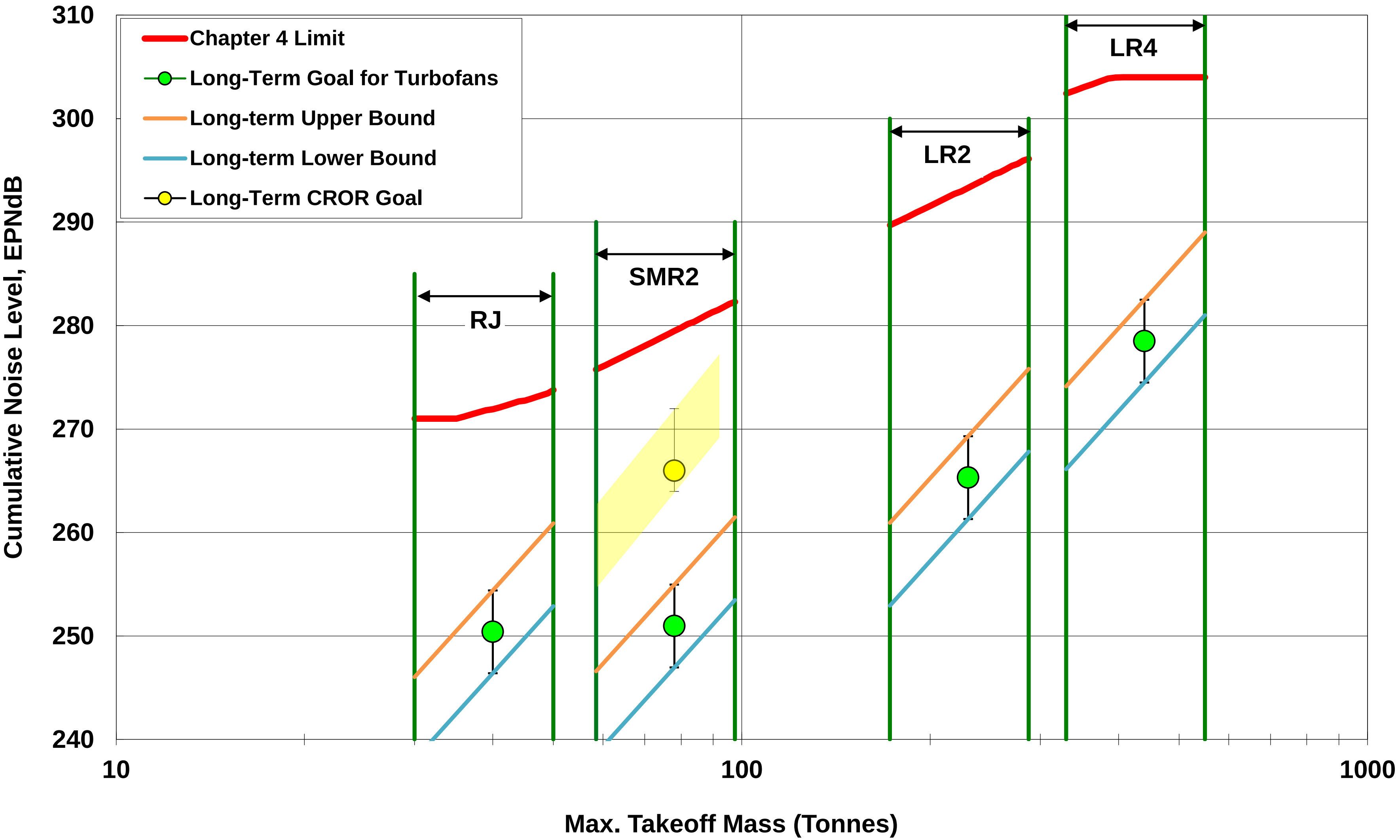
Mid Term (2020) Cumulative Noise Goals at TRL 8
Add Large Turboprops



Long Term (2030) Cumulative Noise Goals at TRL 6
Turbofans Only



Long Term (2030) Cumulative Noise Goals at TRL 6
Add Open Rotor (CROR) for SMR2



Cumulative Noise Margin Goals Relative to Chapter 4, Mid-Term (2020)

Mid-term turbofan goals have not been changed from IEP1 review. Goals have been added for large turboprops. Also, the uncertainty values for noise estimates have been rounded to ±4 EPNdB.

Aircraft Category	BPR Goal	NR TRL6	NR TRL8	Cum Ref	Cum Goal TRL6	Cum Goal TRL8
Regional Jet (RJ)						
40 tonnes (nominal)	7±1	10	9	4	14	13±4
50 tonnes (max)	7±1	10	9	-0.5	9.5	8.5±4
Large Turboprops						
45 tonnes (nominal)	-	9.5	9	3	12.5	12±4
53 tonnes (max)	-	9.5	9	0.5	10	9.5±4
Short Medium Range Twin (SMR2)						
Turbofans: 78 tonnes (nominal)	9±1	17.5	16	5	22.5	21±4
98 tonnes (max)	9±1	17.5	16	1.5	19	17.5±4
CROR: 78 tonnes (nominal)	-	-	-	-	-	-
91 tonnes (max)	-	-	-	-	-	-
Long Range Twin (LR2)						
230 tonnes (nominal)	10±1	16	14.5	6	22	20.5±4
290 tonnes (max)	10±1	16	14.5	2.5	18.5	17±4
Long Range Quad (LR4)						
440 tonnes (nominal)	9±1	17.5	16	5	22.5	21±4
550 tonnes (max)	9±1	17.5	16	-1.5	16	14.5±4

Cumulative Noise Margin Goals Relative to Chapter 4, Long-Term (2030)

Long-term goals have only been updated for SMR2 and LR2. 3 dB increase from the IEP1 review for turbofans is due to BPR increase from 11 to 13. Goals have been added for SMR2 aft mounted CROR.

Aircraft Category	BPR Goal	NR TRL6	NR TRL8	Cum Ref	Cum Goal TRL6	Cum Goal TRL8
Regional Jet (RJ)						
40 tonnes (nominal)	9±1	17.5	-	4	21.5±4	-
50 tonnes (max)	9±1	17.5	-	-0.5	17±4	-
Large Turboprops						
45 tonnes (nominal)	-	-	-	-	-	-
53 tonnes (max)	-	-	-	-	-	-
Short Medium Range Twin (SMR2)						
<u>Turbofans</u>: 78 tonnes (nominal)	13±1	25	-	5	30±4	-
98 tonnes (max)	13±1	25	-	1.5	26.5±4	-
<u>CROR</u>: 78 tonnes (nominal)	-	8.5	-	5	* 13.5+2/-6	-
91 tonnes (max)	-	8.5	-	2	** 10.5+2/-6	-
Long Range Twin (LR2)						
230 tonnes (nominal)	13±1	22	-	6	28±4	-
290 tonnes (max)	13±1	22	-	2.5	24.5±4	-
Long Range Quad (LR4)						
440 tonnes (nominal)	11±1	22	-	5	27±4	-
550 tonnes (max)	11±1	22	-	-1.5	20.5±4	-

* CROR cumulative margin with uncertainties range from 7.5 to 15.5 EPNdB for 78 tonne nominal weight aircraft.

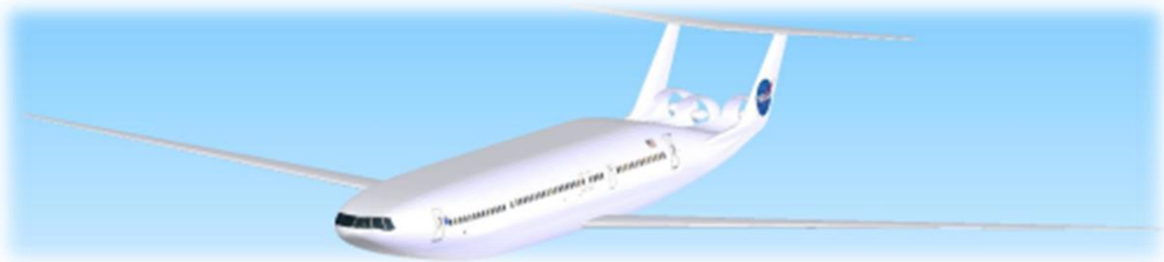
** CROR cumulative margin with uncertainties range from 4.5 to 12.5 EPNdB for 91 tonne maximum weight aircraft .

Conclusions (1/4)

- Reference aircraft and noise levels from IEP1 can be used as reference for IEP2 for Mid-Term (2020) and Long-Term (2030) goals.

- Novel aircraft concept studies are available that have considered environmental efficiencies and economic tradeoffs during conceptual design, and offer a balanced approach to reducing noise, emissions and fuel burn.

- IEP2 expects TSN-1 to prevail over the more aggressive TSN-2 (technology scenarios for noise). TSN-2 is feasible with increased resource investments and could provide additional noise reduction by 2030. The MIT “Double Bubble D8” concept aircraft is a good example.



Conclusions (2/4)

- Novel aircraft concepts may enable steeper approach glide slopes and significant noise reduction.
- Noise reduction technologies have been updated from the IEP1 review and were applied to novel aircraft.
- The Realization Factor (RF) used by IEP1 cannot be applied to novel aircraft concepts that have not been developed and tested beyond TRL6.
- IEP2 pilot studies indicate alternative noise correlations for turbofans are possible based on specific thrust and other overall aircraft parameters. This approach helps predict aircraft noise levels with higher BPR engines where previous correlations are less reliable.
- Novel aircraft can be developed by 2030 in SMR2/LR2 categories using Ultra High Bypass (UHB) engines. Examples of engines include counter-rotating open rotors (CROR) and geared turbofans (GTF).

Conclusions (3/4)

- Wing mounted (tractor) Open Rotors are expected to be about 6 EPNdB cum louder than aft mounted pusher configurations.
- A skewed uncertainty distribution is recommended for CROR.
- En route noise from CROR aircraft with modern technologies cruising at 35,000 feet is expected to be significantly quieter than Un-Ducted Fan (UDF) flight tests from the 1980's.
  - i) Projections using TRL4 wind tunnel data predict ground noise levels to be 13 to 20 dBA quieter.
  - ii) Comparisons with 2009 background noise measurements in Europe show the CROR flyover noise levels would be near the upper band of the turbofan noise levels.
  - iii) Ongoing research in Europe on Open Rotor en route noise not yet available.

Conclusions (4/4)

Noise Goals for Short-Medium Range Twins and Large Turboprops

- SMR2 CROR (pusher): TRL6 long-term cum noise goal under Chapter 4:
  - **13.5 +2/-6 EPNdB (7.5 to 15.5) for nominal weight, 78 tonne aircraft**
  - **10.5 +2/-6 EPNdB (4.5 to 12.5) for maximum weight, 91 tonne aircraft**
- SMR2 UHB Turbofans:TRL6 long-term cum noise goal under Chapter 4:
  - **30.0 ±4 EPNdB (26 to 34) for nominal weight, 78 tonne aircraft**
  - **26.5 ±4 EPNdB (22.5 to 30.5) for maximum weight, 98 tonne aircraft**
- Large Turboprops: TRL8 mid-term cum noise goal under Chapter 4:
  - **12.0 ±4 EPNdB (8 to 16) for nominal weight, 45 tonne aircraft**
  - **9.5 ±4 EPNdB (5.5 to 13.5) for maximum weight, 53 tonne aircraft**

2nd CAEP Noise Technology Independent Experts Goals Review

Final Report
Noise Technology Independent Expert Panel (IEP2)
Working Group 1 (Noise Technical)
CAEP/9-WP/16
November 30, 2012

Backup Charts

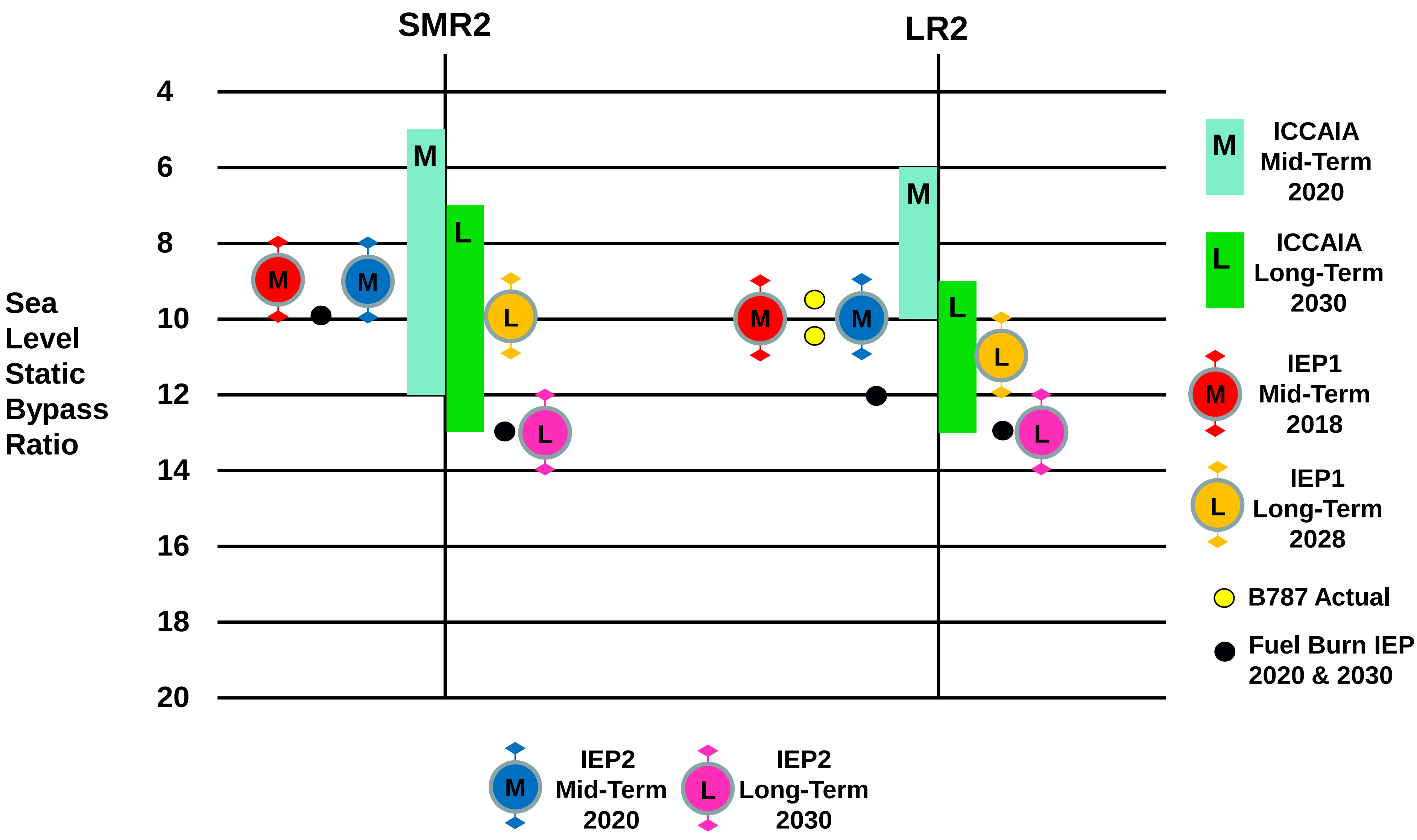
Reference Aircraft

Aircraft Category	Weight (MTOM), tonne	Cum Level relative to Chapter 4
Regional Jet (RJ)	40	-4 EPNdB
Small-Medium Range Twin (SMR2)	78	-5 EPNdB
Long Range Twin (LR2)	230	-6 EPNdB
Long Range Quad (LR4)	440	-5 EPNdB

Same reference levels used by IEP1, Large Turboprops and Open Rotors (CROR) were studied in separate categories.

Studies

Bypass Ratio Range for Technology Scenarios

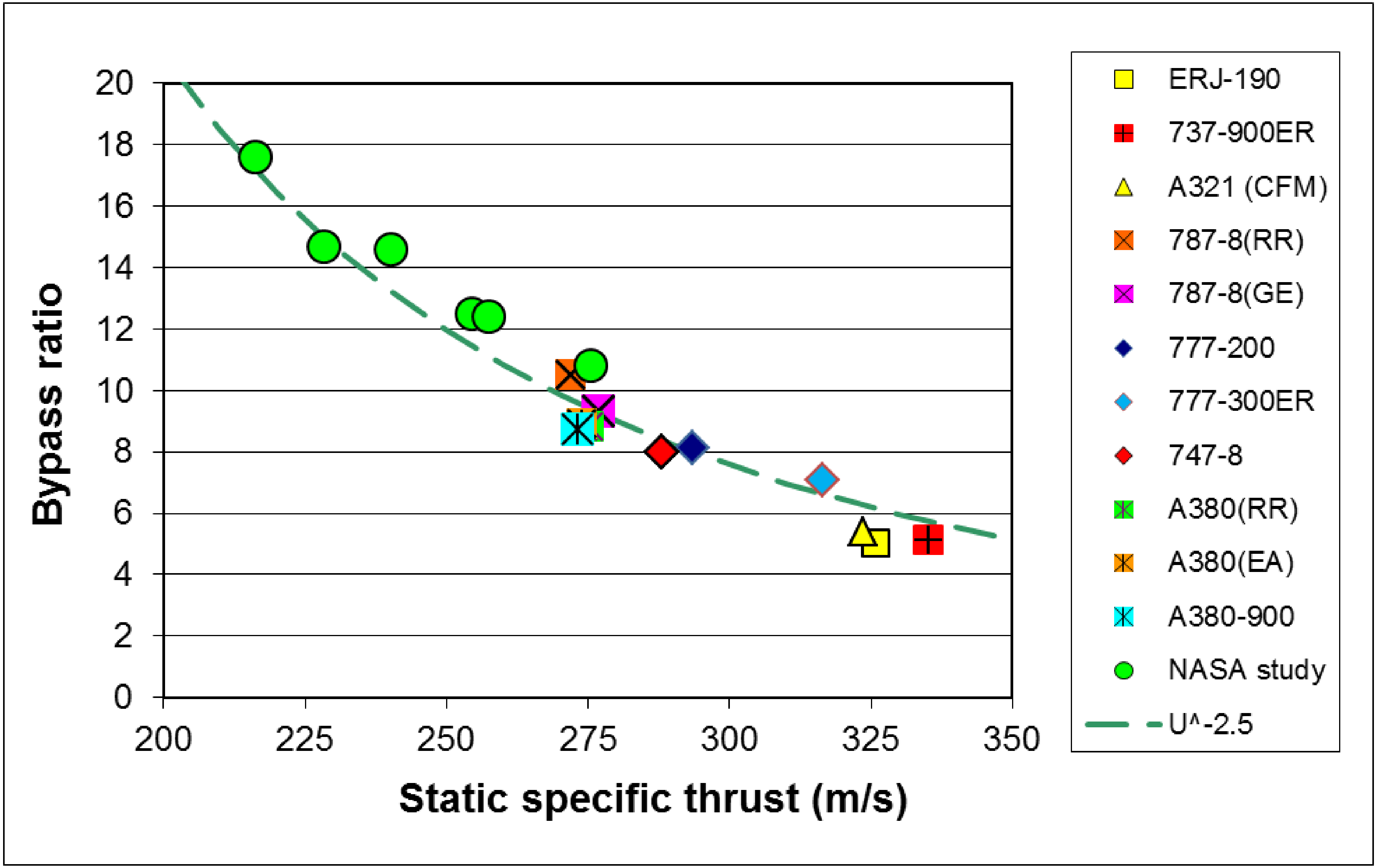


Most Likely Future Target Values

IEP2 Pilot Study for Turbofans

- Bypass ratio is a convenient parameter for correlating engine noise.
- Engine noise depends on many parameters.
  - Jet speed is the most important.
  - Fan tip speed and pressure ratio, liners, blade counts, rotor-stator separation, rotor blade shape, etc. are other parameters.
- Bypass ratios and jet speeds are correlated, but bypass ratios have increased in recent years substantially without a corresponding large decrease of jet speed.
- Since jet speed and fan pressure ratio are important parameters for jet and fan noise, it was proposed to support simple bypass ratio correlations with more detailed studies that correlate with more relevant parameters.
- Predictions using specific thrust as a correlation parameter were used to estimate noise levels for aircraft with higher BPR across different aircraft categories.

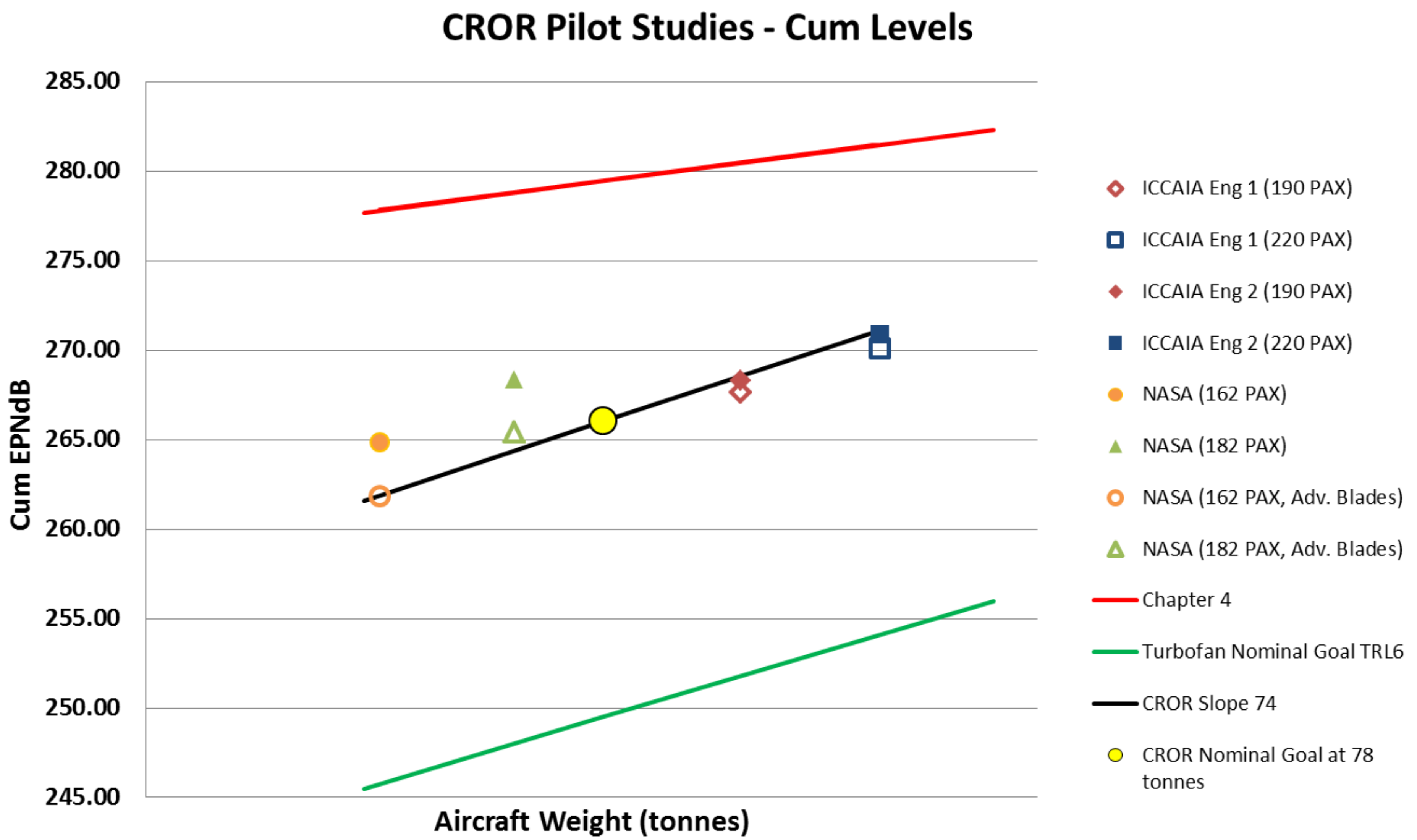
Bypass Ratio vs. Specific Thrust



Open Rotor Studies

- Noise estimates for counter rotating open rotors (CROR) were determined using information from ICCAIA and NASA/GE.
- Data from TRL4 model scale wind tunnel tests were used with aircraft systems analyses to predict noise and fuel burn.
- ICCAIA provided estimates for heavier aircraft within the SMR2 category, where NASA/GE provided estimates for lighter aircraft.
- The IEP2 estimates that cumulative noise levels will vary with weight following 74*log(MTOW).
- IEP2 recommends a nominal TRL6 noise goal for pusher Short Medium Range Twin (SMR2) CROR of 13.5 EPNdB cum under Chapter 4, with a +2/-6 EPNdB cum uncertainty.
- For a maximum weight of 91 tonnes, the margin is estimated to be 10.5 EPNdB cum under Chapter 4, with a +2/-6 EPNdB cum uncertainty.

Predicted Open Rotor Cumulative Noise Levels



CROR Tractor versus Pusher

- IEP2 evaluated CROR installation effects for wing mounted tractor versus an aft mounted pusher configuration.
- Study used information from IER2 for angle of attack variations, the NASA CROR study, and experimental data for higher angles of attack.
- Aft mounted engines will have lower angle of attack (2 to 4 degrees) over wing mounted engines which depending on location, may vary from 8 to 12 degrees angle of attack.
- Noise levels were estimated for SMR2 starting with the aft mounted results, subtracting the pylon penalty, and adding the expected increase in noise from higher angles of attack.

CROR Tractor versus Pusher

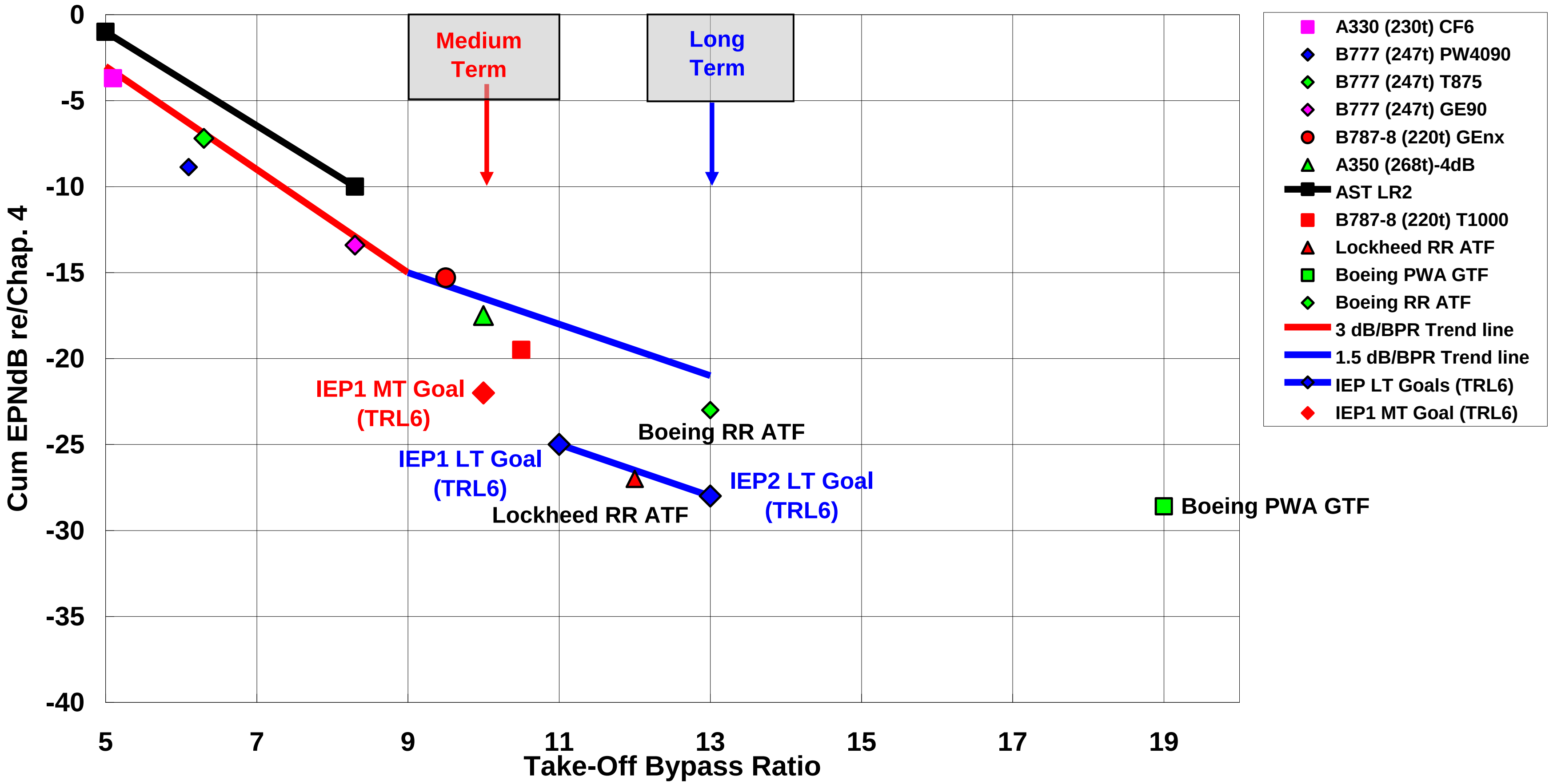
	Approach		Lateral		Flyover		Cumulative	
Angle of Attack	10	12	8	10	8	10	Low	High
Isolated	88.8	88.8	88.2	88.2	80.1	80.1	257.1	257.1
AoA Effects	3.3	4.0	3.4	4.3	3.4	4.3	10.2	12.6
Flight Mach Effects	0.1	0.1	1.2	1.2	1.3	1.3	2.6	2.6
Overall	92.2	92.9	92.8	93.7	84.8	85.7	269.9	272.3
Stage 3 Rule**	100.3	100.3	96.5	96.5	91	91	287.8	287.8
Stage 3 Margin	-8.1	-7.4	-3.7	-2.8	-6.2	-5.3	-17.9	-15.5
Stage 4 Margin							-7.9	-5.5

Aft Mounted CROR was 13.1 dB Under Chapter 4

Wing mounted CROR's (about 5.5 to 7.9 EPNdB cum margin relative to Chapter 4) are expected to be louder than aft mounted CROR's due to higher inflow angle of attack caused by the upwash of the wing. The IEP2 Estimates 6 EPNdB cum difference between pusher and tractor CROR.

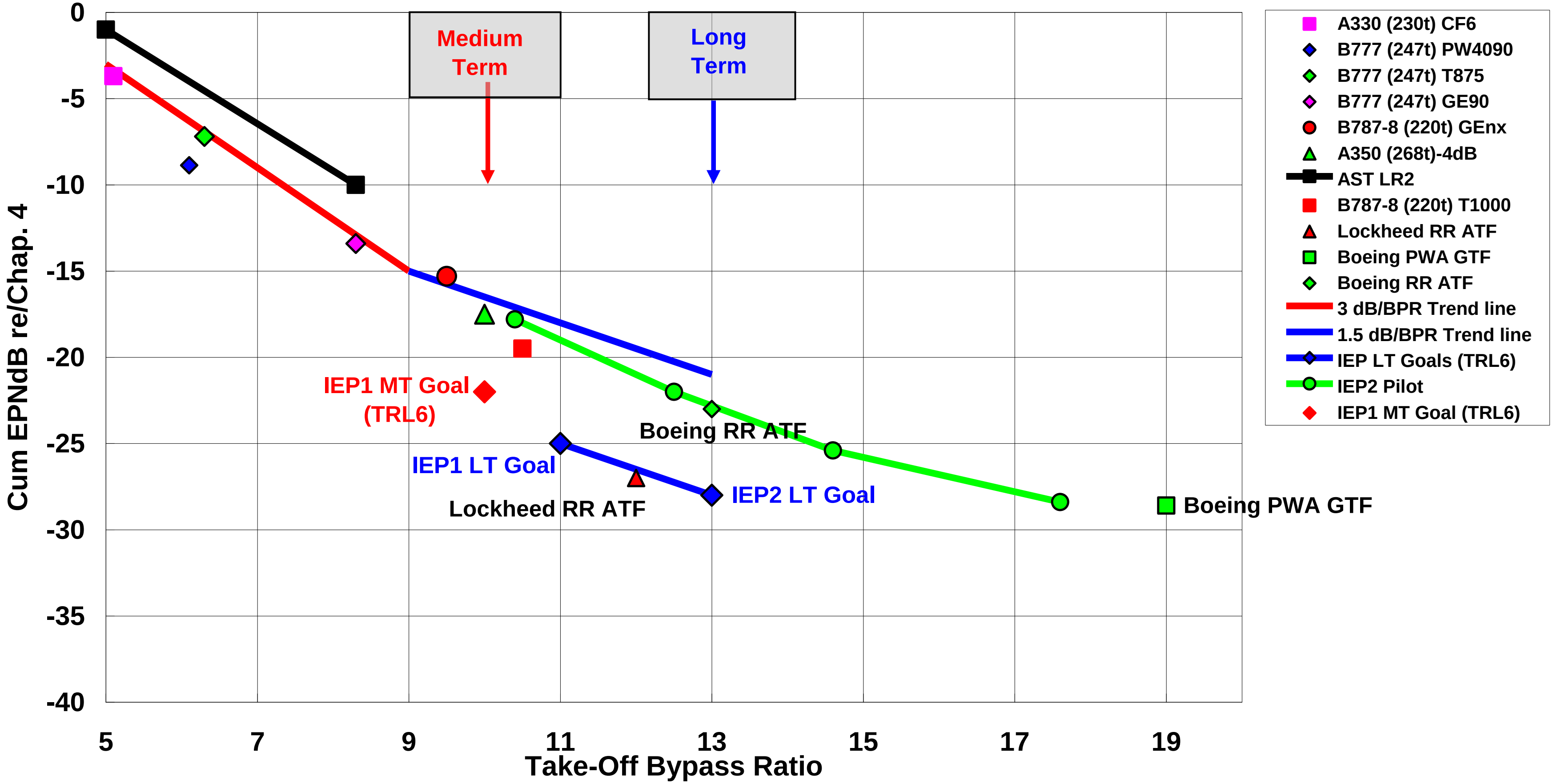
Noise Trends with BPR for LR2

Long Range Twin Noise Data, Cumulative compared with IEP deduced BPR trends TSN-1



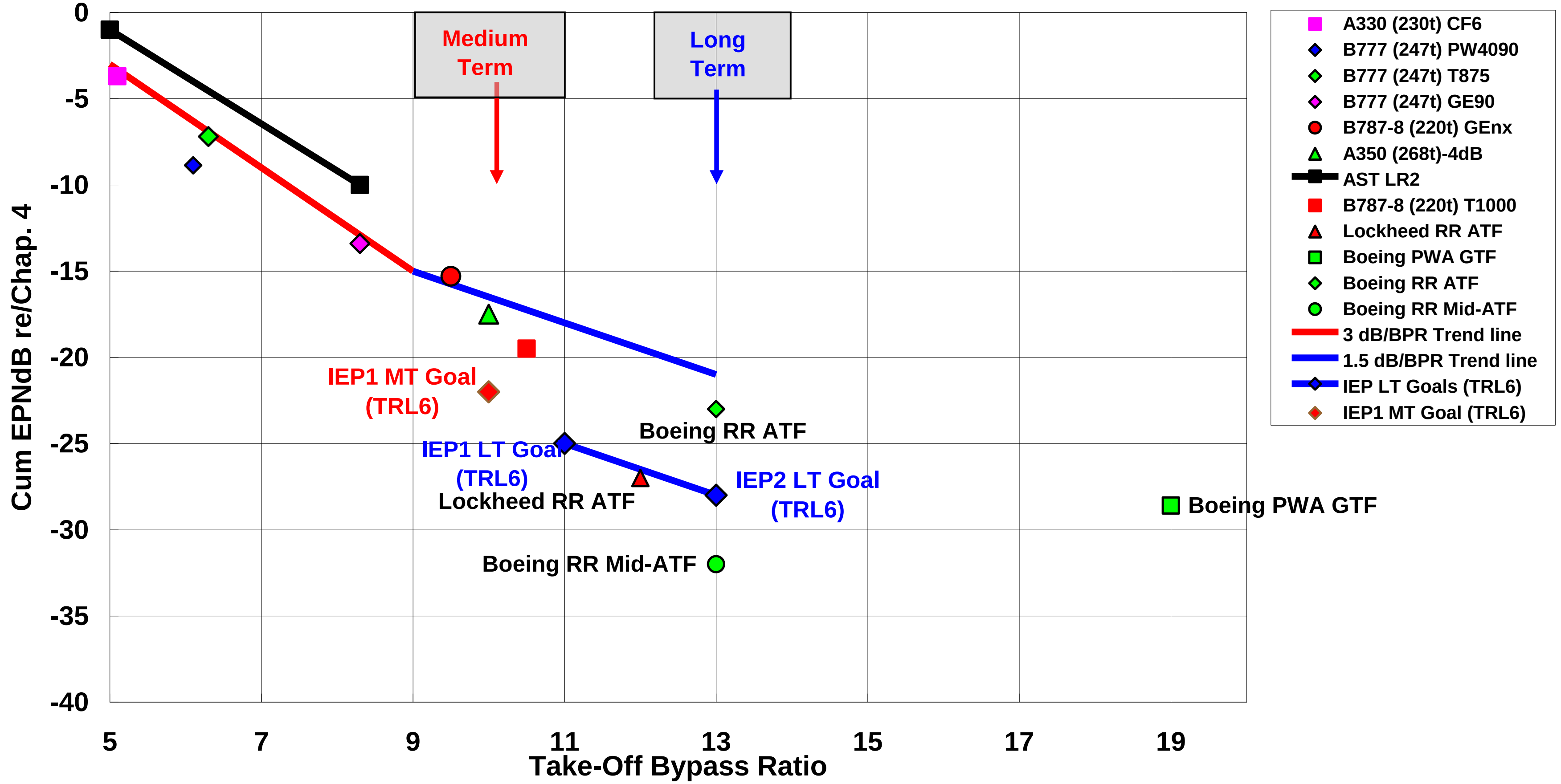
(RR) Rolls-Royce
(ATF) Advanced Turbofan
(PWA) Pratt & Whitney
(GTF) Geared Turbofan
(AST) Advanced Subsonic Technology (from 1990's)

Long Range Twin Noise Data, Cumulative compared with IEP deduced BPR trends TSN-1



(RR) Rolls-Royce
(ATF) Advanced Turbofan
(PWA) Pratt & Whitney
(GTF) Geared Turbofan
(AST) Advanced Subsonic Technology (from 1990's)

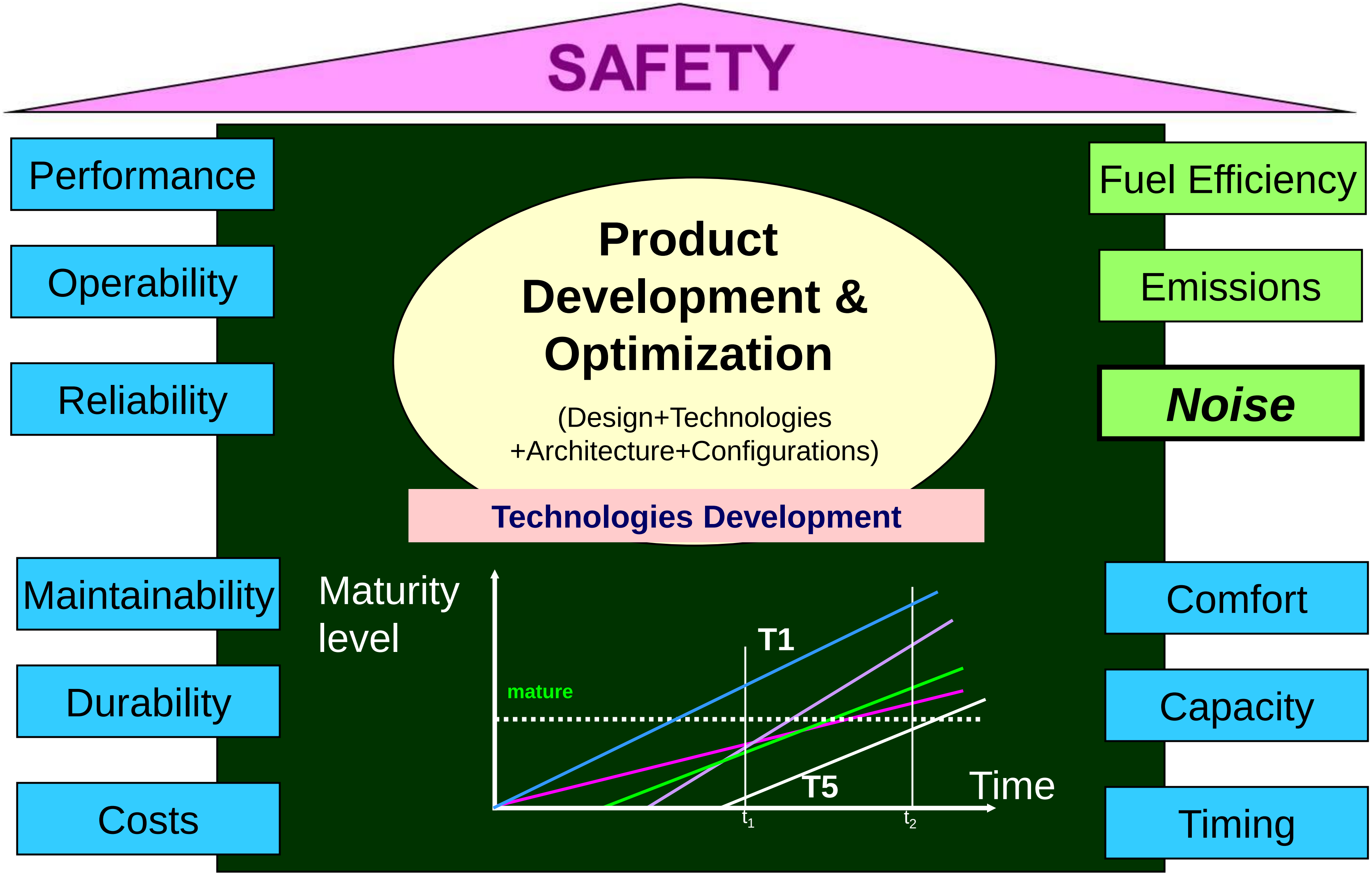
Long Range Twin Noise Data, Cumulative compared with IEP deduced BPR trends TSN-2



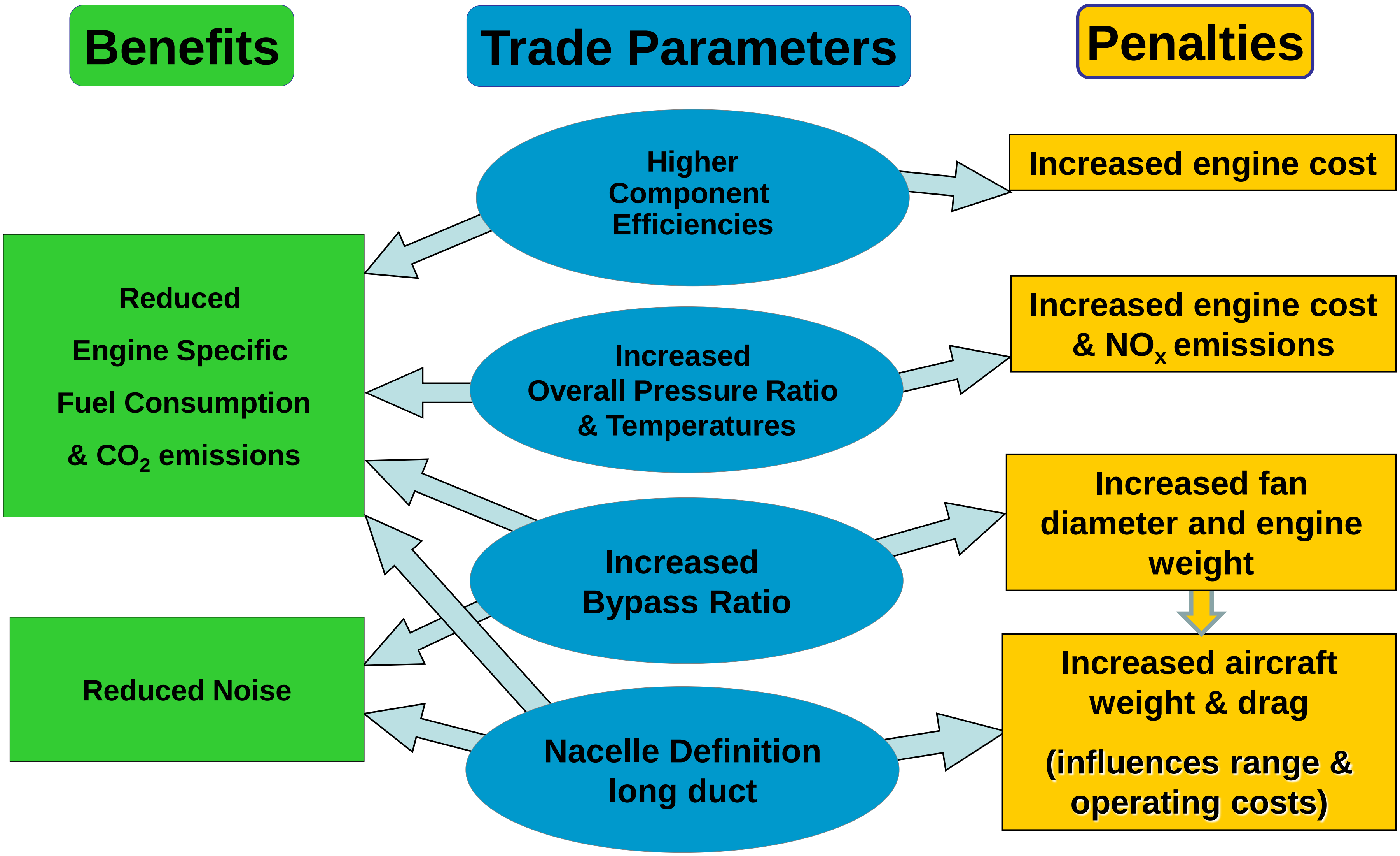
(RR) Rolls-Royce
(ATF) Advanced Turbofan
(PWA) Pratt & Whitney
(GTF) Geared Turbofan
(AST) Advanced Subsonic Technology (from 1990's)

Tradeoffs

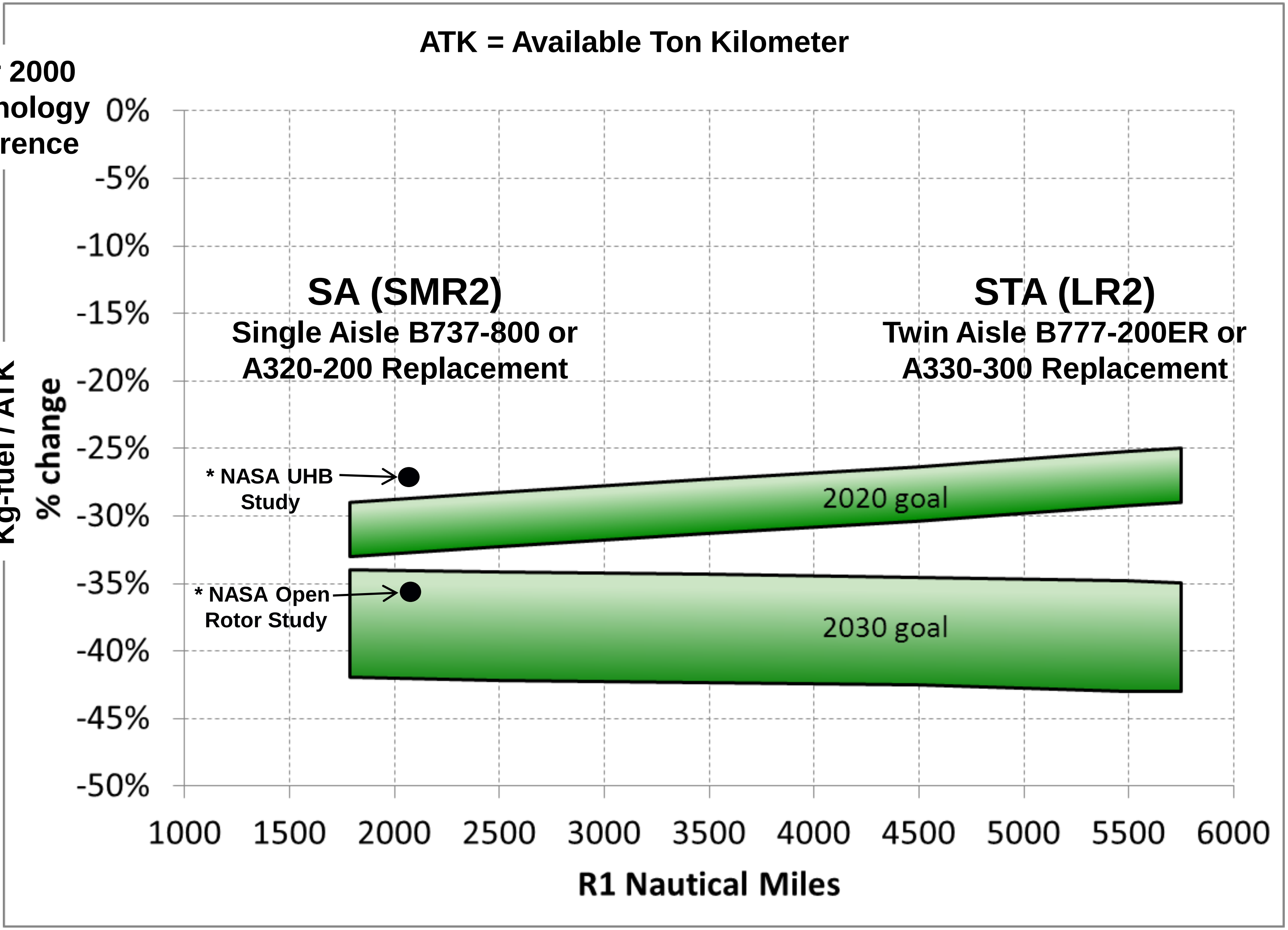
Overall TradeOffs and Optimization



Propulsion System/Aircraft Environmental Tradeoffs



Fuel Burn IEP Results - Goals



* The NASA studies were focused on advanced propulsion and had limited airframe technologies. Additional airframe technologies would provide additional fuel burn reduction. Results are for a R1 mission design.

En Route Noise

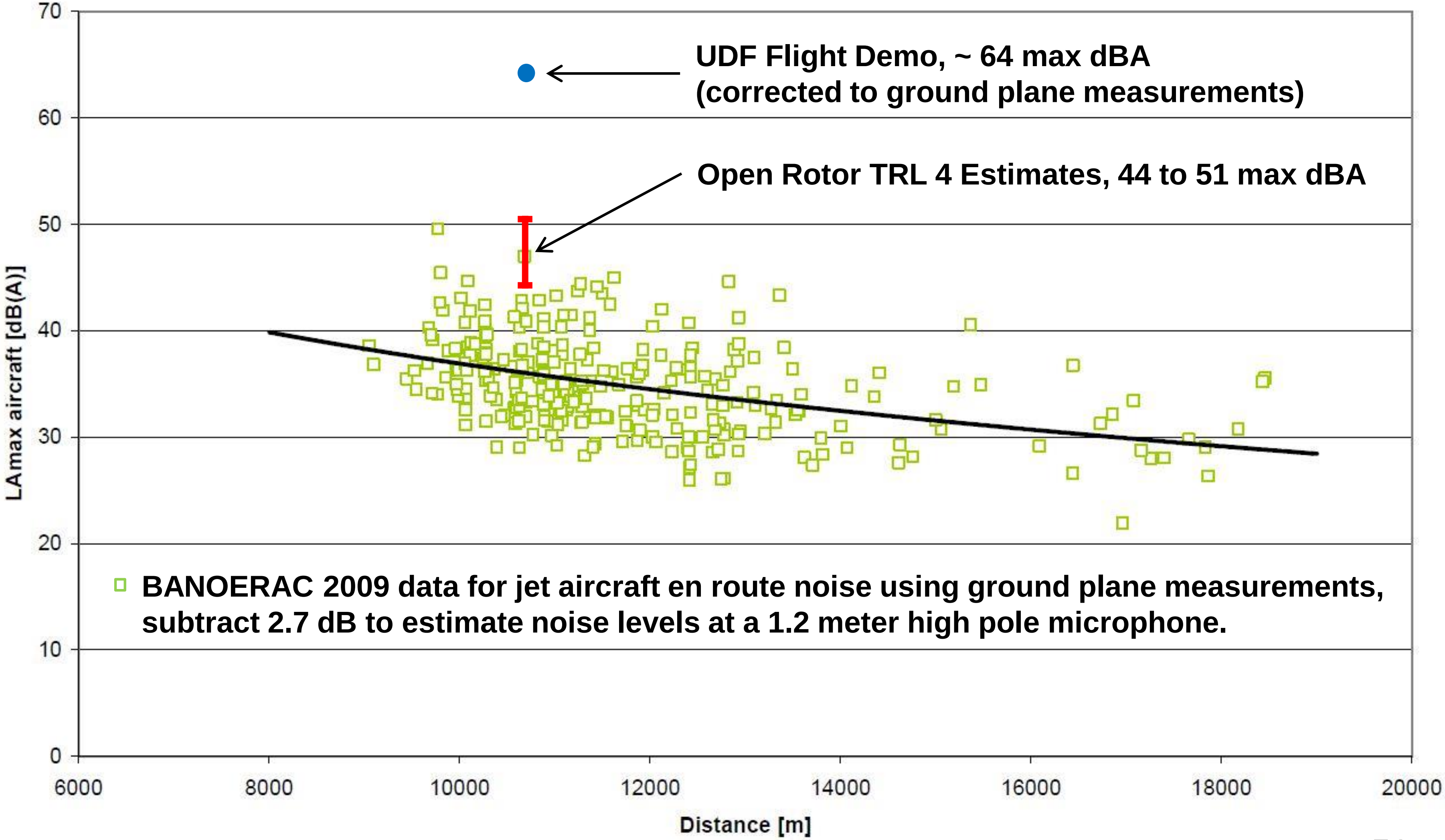
CROR En Route Noise

- En route noise for newer blade designs has been evaluated using wind tunnel data for cruise simulations.
- Cooperative work between NASA and GE for IEP2.

- Unsteady surface pressures from near field measurements have been scaled and propagated to the ground from 35,000 feet using atmospheric attenuation models.
- Only high altitude cruise estimates are possible at this time since measurements are not available for climb conditions. Recommend experimental program to acquire climb data.
- Results show significant noise reduction is expected compared to previous Un-Ducted Fan (UDF) flight demonstration tests. Estimates at TRL4 are 13 to 20 dBA quieter than UDF flight demonstrations from late 1980’s.

CROR En Route Noise Estimates

Open Rotor ground noise from 35,000 ft. cruise is estimated to be near the upper portion of data scatter from current jet powered aircraft



En Route Noise Summary & References

- Although there have been significant improvements in noise reduction using current generation designs, en route noise needs to be continuously monitored and updated.
- More definitive open rotor en route noise data is expected to be available from Europe and should be used to verify cruise and climb noise estimates. In the short term, data is expected from a 4-engine single rotor blade aircraft test and in the longer term from a more representative counter-rotating blade flying test bed demonstrator.
- Information about previous Un-Ducted Fan (UDF) flight tests and background noise data can be found in the following references:

Harris, R.W. and Cuthbertson, R.D., "UDF/727 Flight Test Program," AIAA-87-1733, July 1987.

Donelson, J.E., Lewerenz, W.T., and Durbin, R.T., "UHB Technology Validation – The Final Step," AIAA-88-2807, July 1988.

Hager, R.D. and Vrabel, D, "Advanced Turboprop Project," NASA SP-495, 1988.

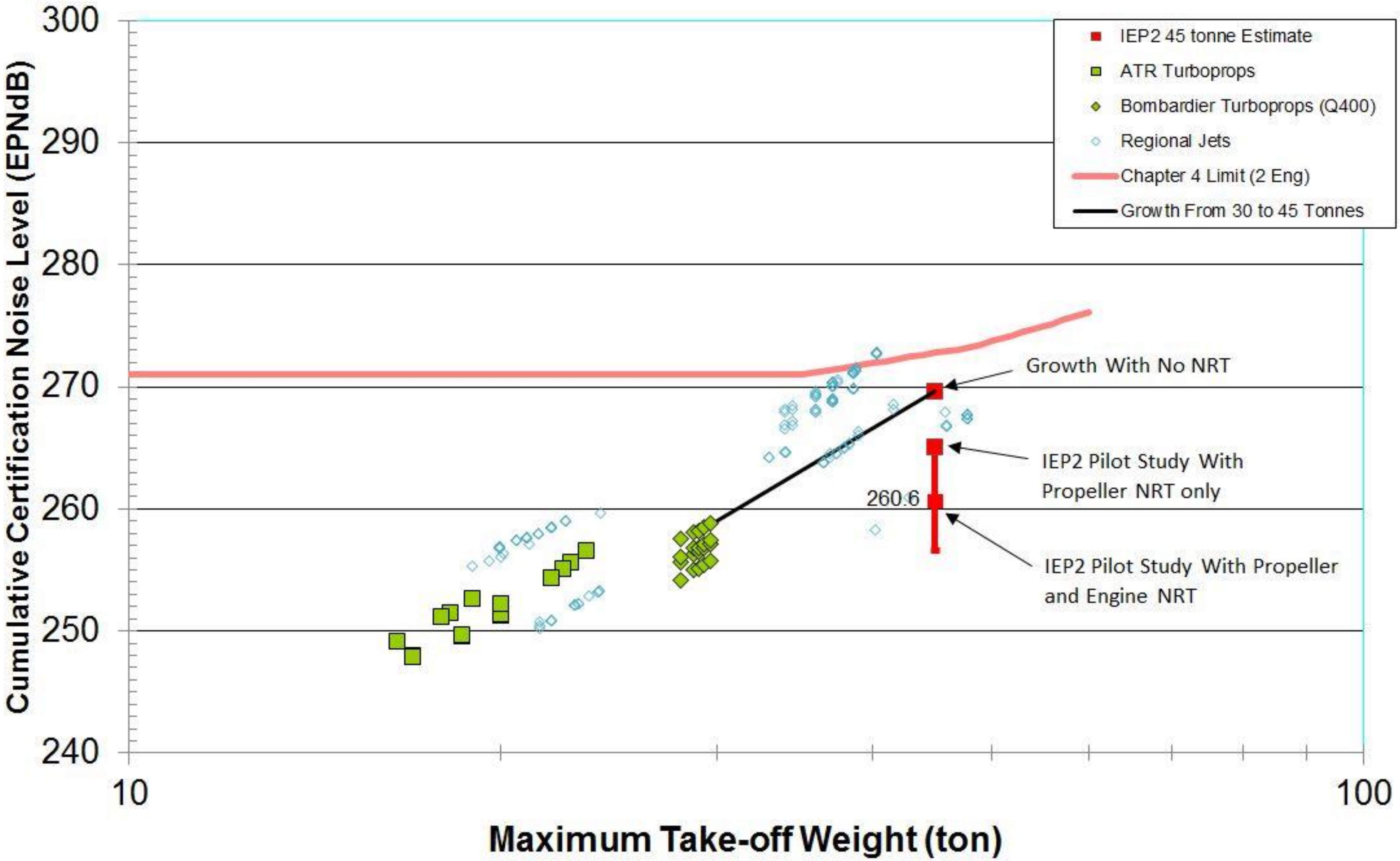
"Background Noise level and noise levels from En Route AirCraft (BANOERAC)," European Aviation Safety Agency, EASA.2008/OP14, October 2009.

Large Turboprop Study

Large Turboprop Study

- There is interest in developing larger turboprops for fuel efficiency.
- The IEP2 worked with ICCAIA to estimate noise levels using a Bombardier Q400 as a baseline (EIS 2001, 72-79 PAX, 30 tonne).
- New aircraft applications were studied for nominal 45 tonne MTOW, with a variant range of 35 to 53 tonnes.
- ICCAIA and the IEP2 agree that noise reduction technologies that can be applied by Mid Term (2020) at TRL8 include:
    - Increasing the number of propeller blades from 6 to 8.
    - Decreasing the propeller speed by 5%.
    - Improving the engine inlet/compressor design.
- The propeller noise can be decreased by 4.5 EPNdB cum (3 dB from increased blade count + 1.5 dB from reduced tip speed), and the engine noise can be decreased by 4.5 EPNdB cum.

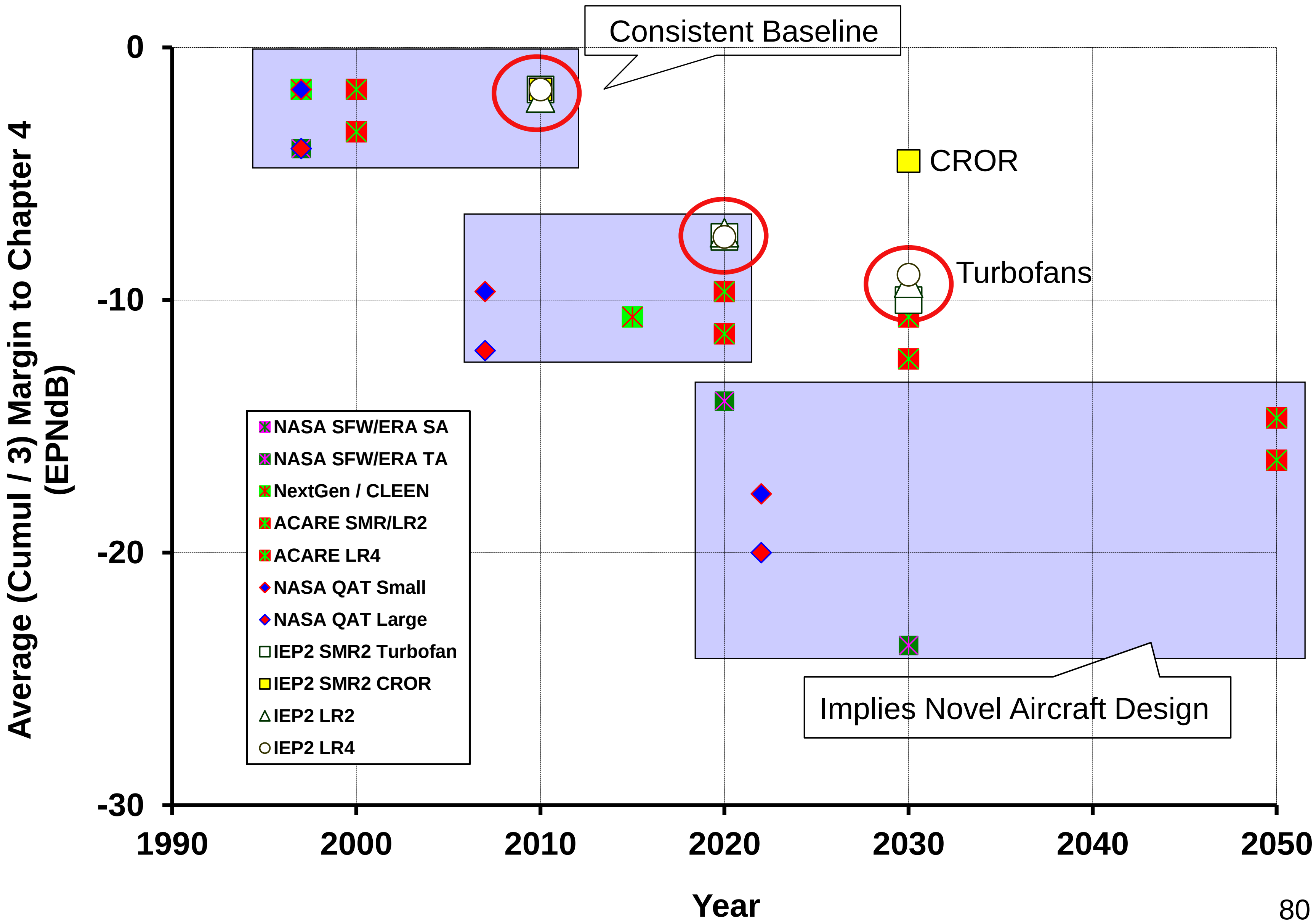
Large Turboprop Study Results



Large Turboprop Study

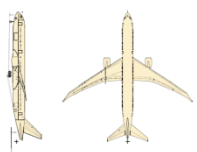
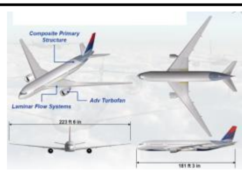
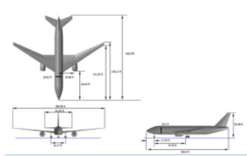
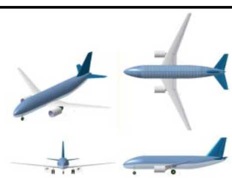
- The IEP2 estimates that cumulative noise levels will vary with weight following 60*log(MTOW).
- IEP2 recommends a nominal TRL8 mid-term noise goal for large turboprops (~45 tonnes) of 12.0 EPNdB cum under Chapter 4, with a ±4 EPNdB cum uncertainty.
- For a maximum weight of 53 tonnes, the margin is estimated to be 9.5 EPNdB cum under Chapter 4, with a ±4 EPNdB cum uncertainty.

Comparison with Research Program Goals (TRL6)

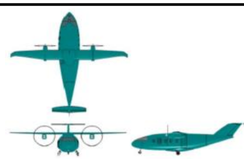
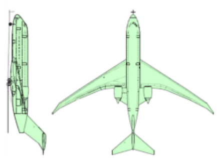
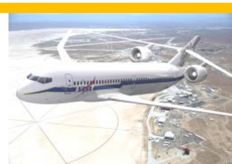


Novel Aircraft and Engines

Novel Aircraft and Engine Concepts

Aircraft Concept	**Picture**	**Mission**	**Reference**	**Fuel Burn** (% below reference)	**Noise** (cum EPNdB under Chapter 4	**NOx** (% under CAEP/6)
Conventional Tube & Wing				**Reported Benefits**		
NASA N+1 UHB Turbofan		162 pax 3250 nm M=0.78 35,000’	B737-800	27	21 to 33	-
NASA ERA Boeing 2025		224 pax 8000 nm M=0.85 35,000’	B767 (1998 Technologies)	RR ATF: 45.7 P&W GTF: 46.6	23 28.6	72 76
NASA ERA Lockheed Martin 2025		224 pax 8000 nm M=0.85 47,000’	1998 Technologies with Scaled Trent 800	>50	27 to 34.9	68
NASA ERA Northrop Grumman 2025		224 pax 8000 nm M=0.85 39,000’	1998 Technologies with Scaled Trent 800	37.8	23.6	72
NASA SFW Northrop Grumman 2035		120 pax 1600 nm M=0.75 45,000’	B737-500 variant	64	70	75

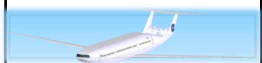
Novel Aircraft and Engine Concepts

Aircraft Concept	Picture	Mission	Reference	**Fuel Burn** (% below reference)	**Noise** (cum EPNdB under Chapter 4	**NOx** (% under CAEP/6)
NASA SFW General Electric 2035		20 pax 800 nm M=0.55 39,000’	B20/GE4600B	68.9	75	77
Novel Tube & Wing				**Reported Benefits**		
NASA ERA Boeing 2025		224 pax 8000 nm M=0.85 35,000’	B767 (1998 Technologies)	42.5	32	72
NACRE Proactive Green		Not Available	Single Aisle	-	4 below unshielded configurations	-
NASA ERA Lockheed Martin Box Wing		224 pax 8000 nm M=0.85 39,000’	1998 Technologies with Scaled Trent 800	>50	33 to 39	>85
NASA SFW MIT D8.1 Double Bubble		180 pax 3000 nm M=0.72 43,300’	B737-800	49	43	53

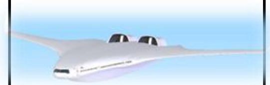
Selected for interviews by IEP2 to investigate feasibility for long-term 2030 EIS (entry into service), but deemed not likely.

Estimated by IEP2 to be feasible for long-term 2030 EIS based on interviews, but no current plans for product launch.

Novel Aircraft and Engine Concepts

Aircraft Concept	Picture	Mission	Reference	Fuel Burn (% below reference)	Noise (cum EPNdB under Chapter 4	NOx (% under CAEP/6)
NASA SFW MIT D8.5 Double Bubble		180 pax 3000 nm M=0.74 46,400’	B737-800	70.8	60	87.3
NASA SFW Boeing Sugar High Strut Braced Wing		154 pax 3500 nm M=0.70 42,100’	B737 (2008 Technologies)	38.9	22	72
NASA SFW Boeing Sugar Volt Strut Braced Electric		154 pax 3500 nm M=0.70 42,000’	B737 (2008 Technologies)	63.4	>22	79
Tail-Less Aircraft				**Reported Benefits**		
NASA ERA Boeing Blended Wing Body		224 pax 8000 nm M=0.85 39,000’	B767	53.7	42	74
NASA SFW Boeing Sugar Ray Hybrid Wing Body		154 pax 3500 nm M=0.70 40,800’	B737 (2008 Technologies)	43.3	37	72

Novel Aircraft and Engine Concepts

Aircraft Concept	**Picture**	**Mission**	**Reference**	**Fuel Burn** (% below reference)	**Noise** (cum EPNdB under Chapter 4	**NOx** (% under CAEP/6)
NASA SFW MIT H3.2 Hybrid Wing Body		354 pax 7600 nm M=0.80 41,000’	B777-200LR	54	46	81
Cambridge/ MIT Silent Aircraft		215 pax 5000 nm M=0.80 45,000’	B777	25	62 dBA outside airport perimeter	-
NASA ERA Northrop Grumman Flying Wing		224 pax 8000 nm M=0.85 52,000’	1998 Technologies	41.5	74.7	88
Novel Engines (excluding UHB turbofans and CROR)						
European Commission VITAL Ducted CR Turbofans		Not Available	Equivalent Pressure Ratio Single Stage Fan	CRTF2a CRTF2b	Counter-Rotating blades with reduced tip speeds	-

Conventional Tube & Wing Aircraft

NASA N+1: UHB Turbofan Tube and Wing

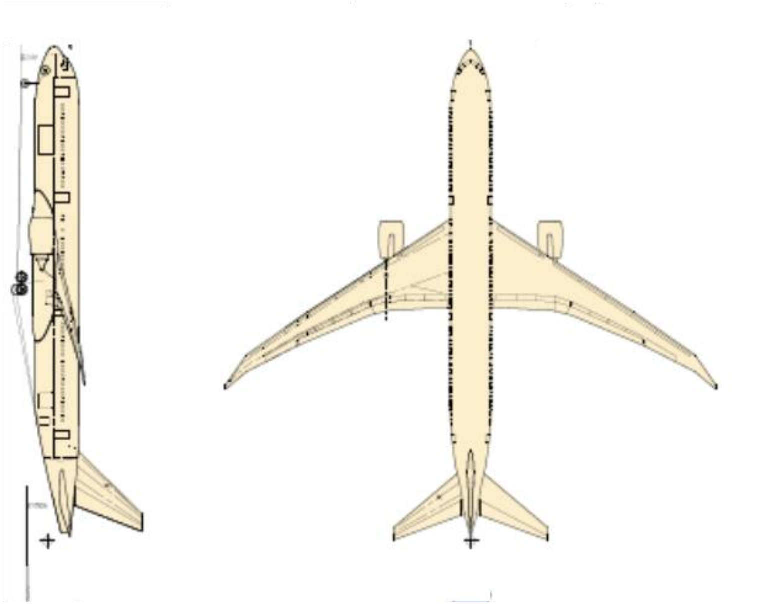
- 162 PAX, 3250 nm, M=0.78 at 35,000’
- Reference aircraft Boeing 737-800, CFM56-7B2 engines
- 27% fuel burn reduction
- Noise reduction:

  21 to 25 EPNdB cum with current technologies

  24 to 28 EPNdB cum with aft fan and airframe technologies

  28 to 33 EPNdB cum suppressing all inlet noise except jet.

NASA ERA: Boeing 2025 Tube and Wing

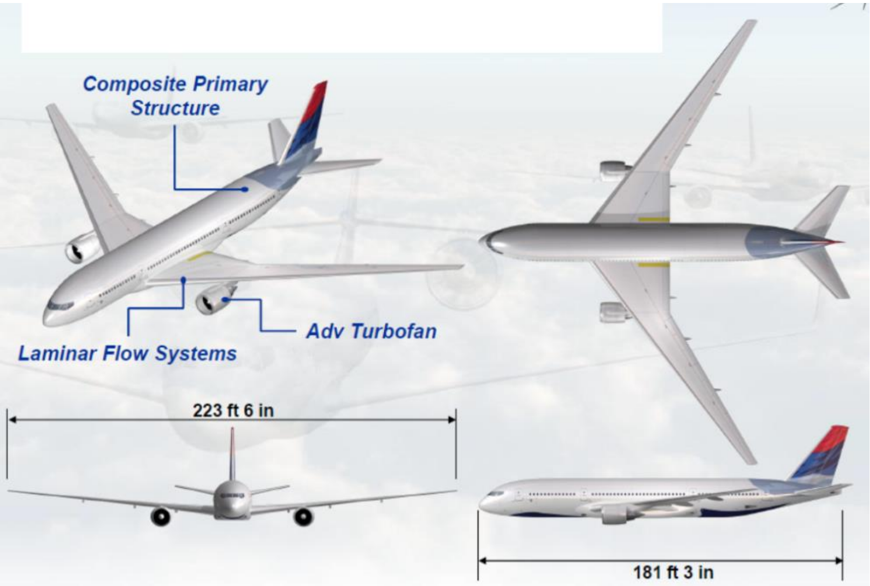


- 224 PAX, 8000 nm, M=0.85 at 35,000'
- Reference aircraft Boeing 767 with 1998 technologies, Scaled PW4090 and Trent 800 family
- Rolls-Royce Advanced 3-Spool Turbofans:

  45.7% fuel burn reduction, 23 EPNdB cum below Chapter 4, 72% LTO NOx reduction (CAEP/6)
- P&W GTF:

  46.6% fuel burn reduction, 28.6 EPNdB cum below Chapter 4, 76% LTO NOx reduction (CAEP/6)

NASA ERA: Lockheed Martin 2025 Tube and Wing



- 224 PAX, 8000 nm, M=0.85 at 47,000'
- Reference aircraft: 1998 technologies with scaled Trent 800
- Advanced Rolls-Royce 3-spool turbofans and advanced airframe:

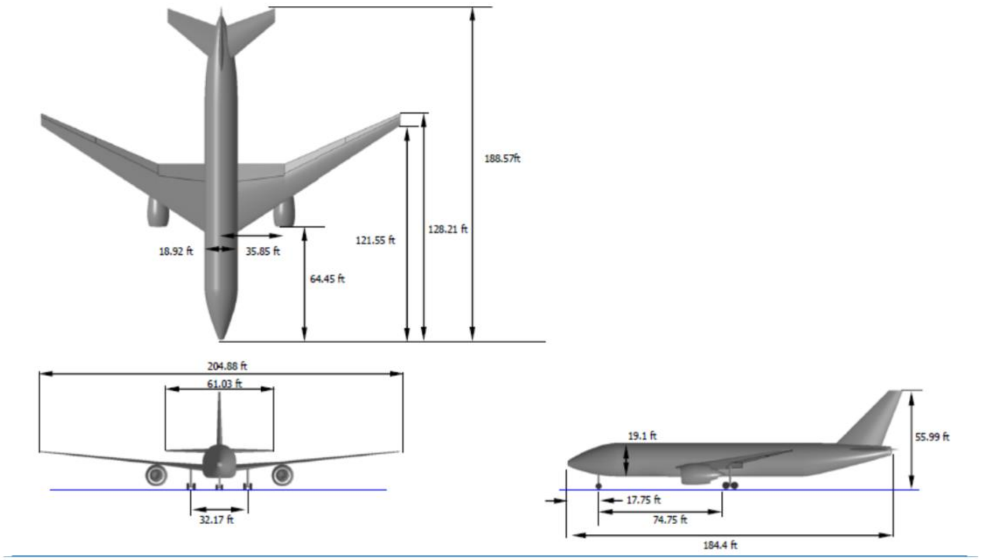
  >50% fuel burn reduction

  27 EPNdB cum below Chapter 4 with 3 degree approach glide slope

  34.9 EPNdB cum below Chapter 4 with 6 degree approach glide slope

  68% LTO NOx reduction below CAEP/6

NASA ERA: Northrop Grumman 2025 Tube and Wing



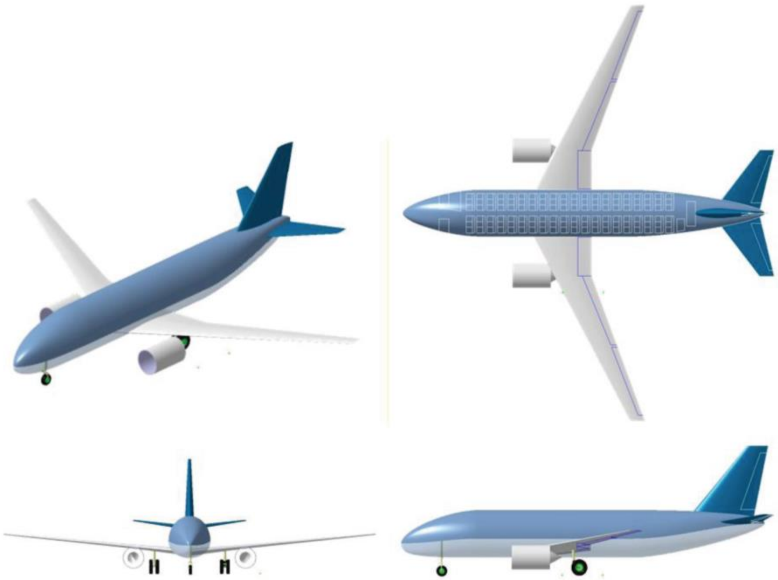
- 224 PAX, 8000 nm, M=0.85 at 39,000’
- Reference aircraft: 1998 technologies with scaled Trent 800
- Advanced Rolls-Royce 3-spool turbofans and advanced airframe:

  37.8% fuel burn reduction

  23.6 EPNdB cum below Chapter 4

  72% LTO NOx reduction below CAEP/6

NASA SFW: Northrop Grumman 2035 Tube and Wing



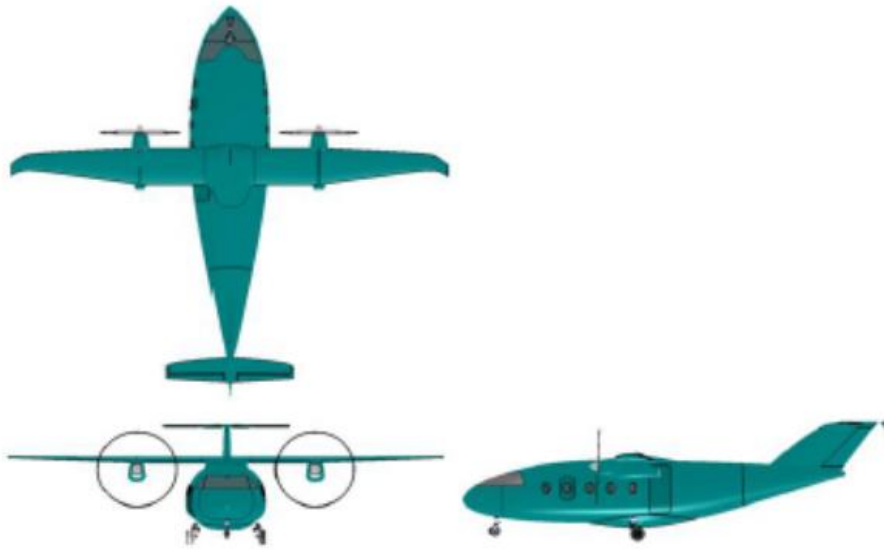
- 120 PAX, 1600 nm, M=0.75 at 45,000’
- Reference aircraft: variant of Boeing 737-500
- Advanced Rolls-Royce 3-spool UHB turbofans and advanced airframe:

  64% fuel burn reduction

  70 EPNdB cum below Chapter 4

  75% LTO NOx reduction below CAEP/6

NASA SFW: General Electric 2035 Tube and Wing



- 20 PAX, 800 nm, M=0.55 at 39,000’
- Reference aircraft: B20/GE4600B, exploits community airports increasing point-to-point travel
- Advanced turboprops:

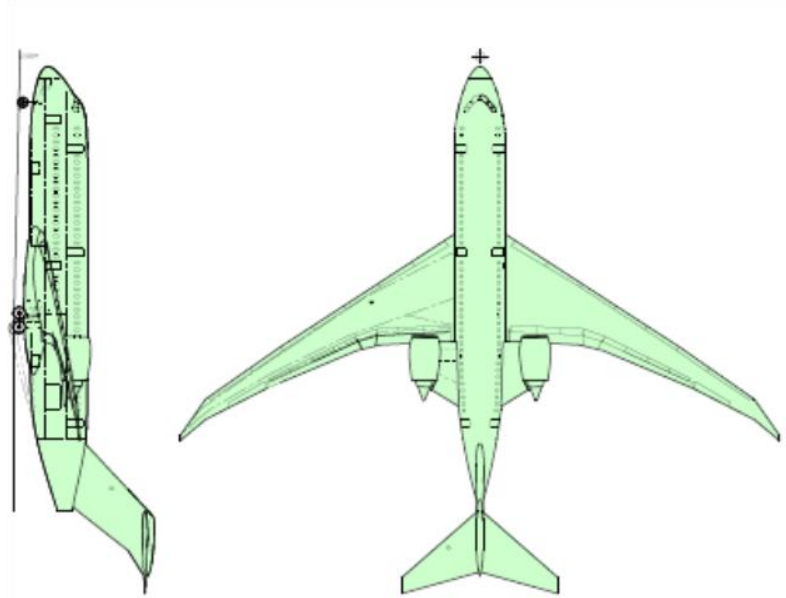
  68.9% fuel burn reduction

  75 EPNdB cum below Chapter 4

  77% LTO NOx reduction below CAEP/6

Novel Tube & Wing Aircraft

NASA ERA: Boeing 2025 Advanced Tube and Wing



- 224 PAX, 8000 nm, M=0.85 at 35,000'
- Reference aircraft Boeing 767 with 1998 technologies, Scaled PW4090 and Trent 800 family
- Mid-Mounted Rolls-Royce Advanced 3-Spool Turbofans:

  42.5% fuel burn reduction, 32 EPNdB cum below Chapter 4, 72% LTO NOx reduction (CAEP/6)
- 9 EPNdB cum benefit due to engine shielding, 3.2% fuel burn penalty

NACRE: Proactive Green Concepts

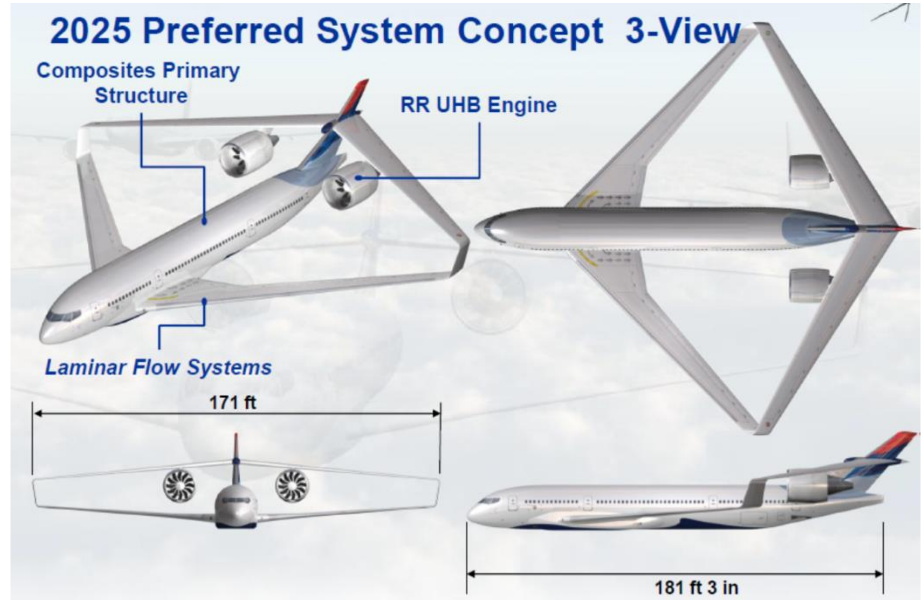
- Noise, fuel burn and emissions estimates not available
- Primarily focused on shielding benefits from engine placement
- Two concepts:

  Pro-Green 1 – Twin rear-mounted contra-fan with BPR 8 engines

  Pro-Green 2 – Twin rear-mounted contra-rotating open rotor engines

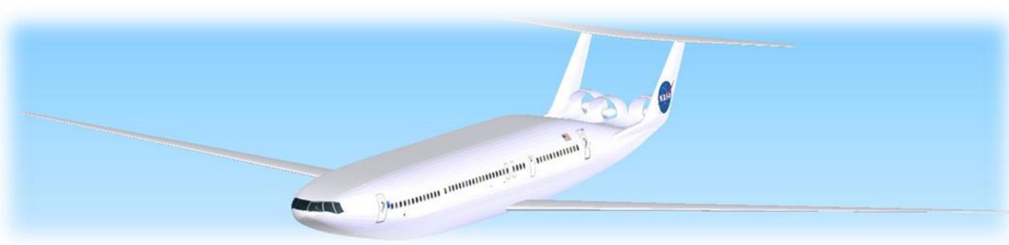
- Shielding provides ~4EPNdB cum benefit relative to unshielded configurations based on computations and wind tunnel tests for Pro-Green 1 concept.
- Unlikely to enter into service before 2030

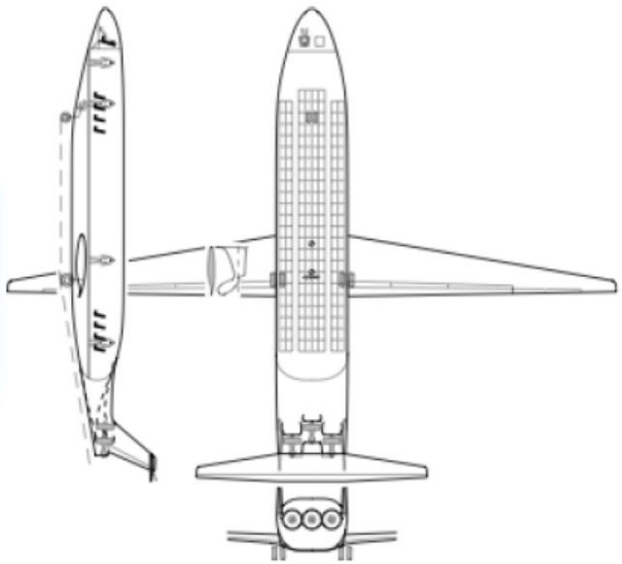
NASA ERA: Lockheed Martin Box Wing



- 224 PAX, 8000 nm, M=0.85 at 39,000'
- Reference aircraft: 1998 technologies with scaled Trent 800
- Rolls-Royce 3-spool UHB turbofans and box wing:
  - >50% fuel burn reduction
  - 33 to 39 EPNdB cum below Chapter 4, 6 degree glide slope on approach
  - >85% LTO NOx reduction below CAEP/6

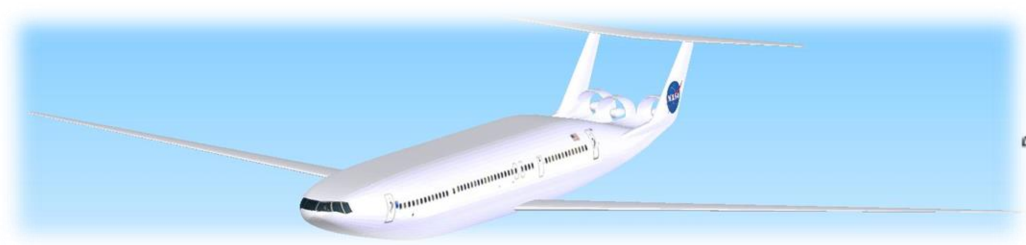
NASA SFW: MIT D8.1 Double Bubble Lifting Body

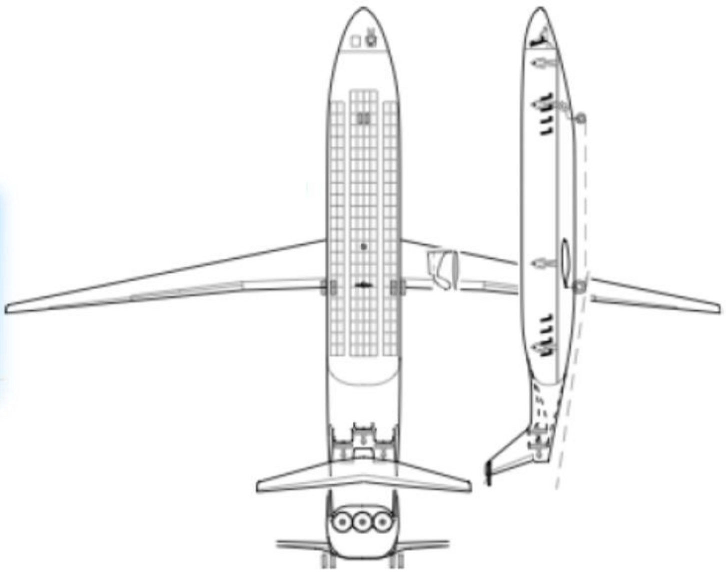




- 180 PAX, 3000 nm, M=0.72 at 43,300’
- Reference aircraft: B737-800
- BPR 6 turbofans and lifting body:
    - 49% fuel burn reduction
    - 43 EPNdB cum below Chapter 4
    - 53% LTO NOx reduction below CAEP/6

NASA SFW: MIT D8.5 Double Bubble Lifting Body





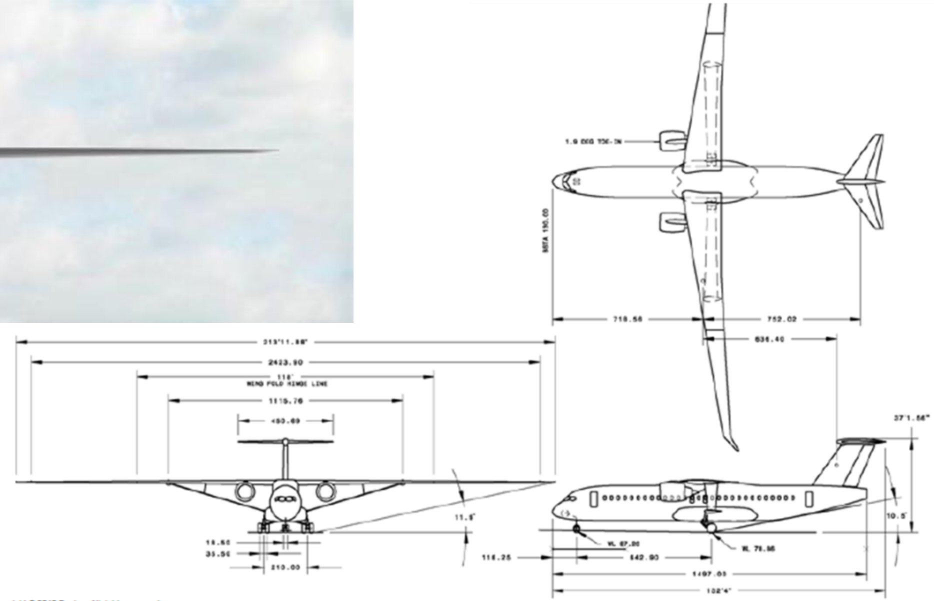
- 180 PAX, 3000 nm, M=0.74 at 46,400’
- Reference aircraft: B737-800
- BPR 20, OPR 50 turbofans and lifting body:

  70.8% fuel burn reduction

  60 EPNdB cum below Chapter 4, 4 degree glide slope on approach, runway displacement threshold.

  87.3% LTO NOx reduction below CAEP/6

NASA SFW: Boeing Sugar High Strut Braced



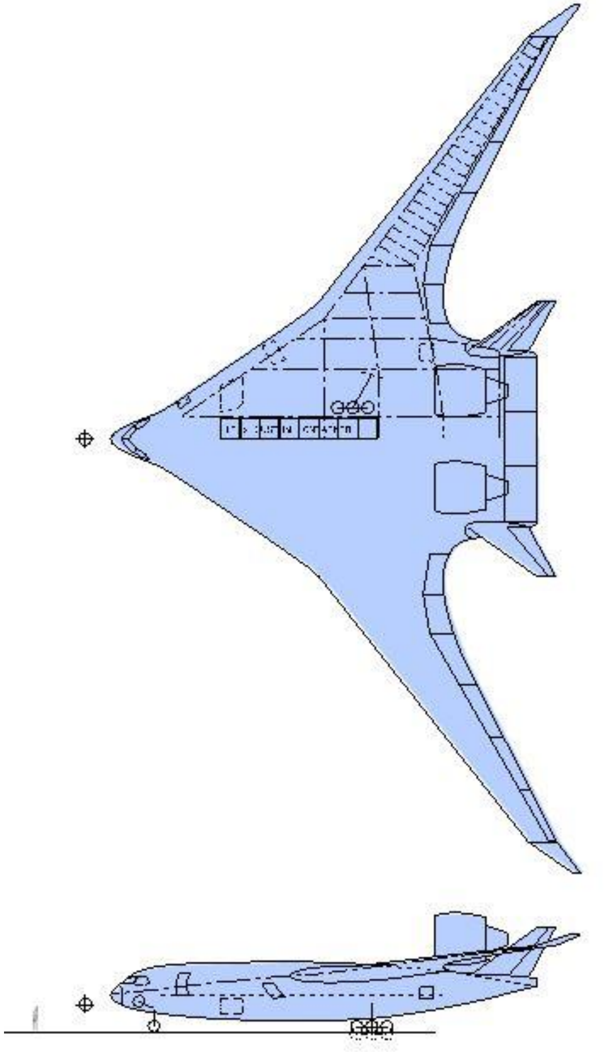
- 154 PAX, 3500 nm, M=0.70 at 42,100’
- Reference aircraft: B737 with 2008 technologies
- BPR 13, OPR 59 turbofans and strut braced wing & T-tail:
  - 38.9% fuel burn reduction
  - 22 EPNdB cum below Chapter 4
  - 72% LTO NOx reduction below CAEP/6

NASA SFW: Boeing Sugar Volt Strut Braced Electric

- 154 PAX, 3500 nm, M=0.70 at 42,000’
- Reference aircraft: B737 with 2008 technologies
- Hybrid turbine/electric propulsion system and strut braced wing & T-tail:
  - 63.4% fuel burn reduction
  - >22 EPNdB cum below Chapter 4
  - 79% LTO NOx reduction below CAEP/6

Tail-Less Aircraft Concepts

NASA ERA: Boeing Blended Wing Body



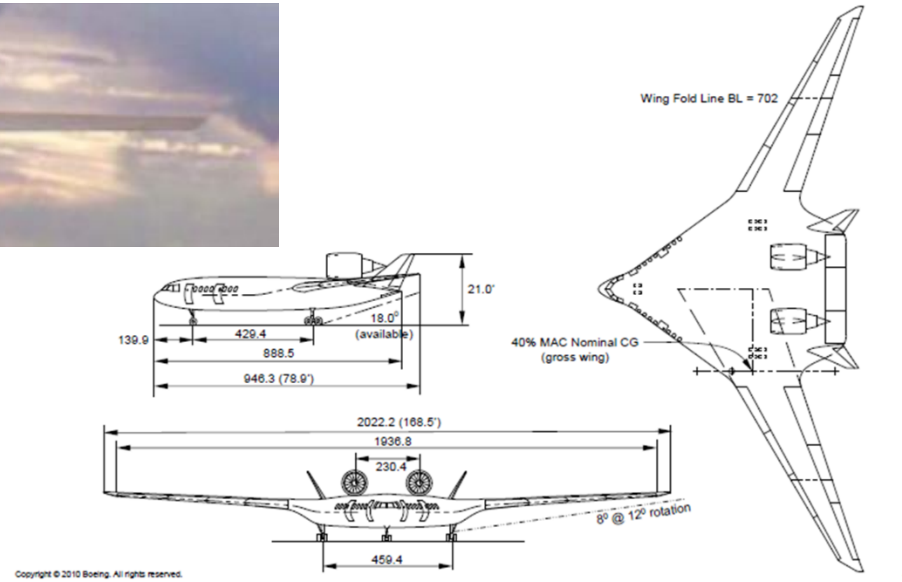
- 224 PAX, 8000 nm, M=0.85 at 39,000’
- Reference aircraft: B767
- UHB geared turbofan engines mounted above a blended wing body:

    53.7% fuel burn reduction

    42 EPNdB cum below Chapter 4

    74% LTO NOx reduction below CAEP/6

NASA SFW: Boeing Sugar Ray Hybrid Wing Body



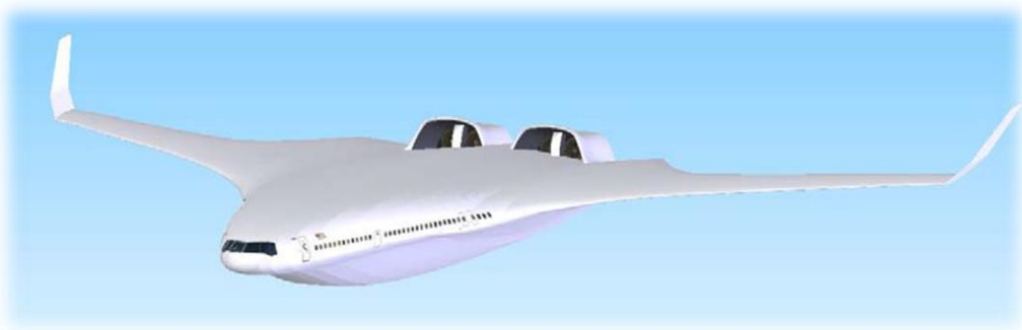
- 154 PAX, 3500 nm, M=0.70 at 40,800'
- Reference aircraft: B737 with 2008 technologies
- High BPR turbofans mounted above wing:

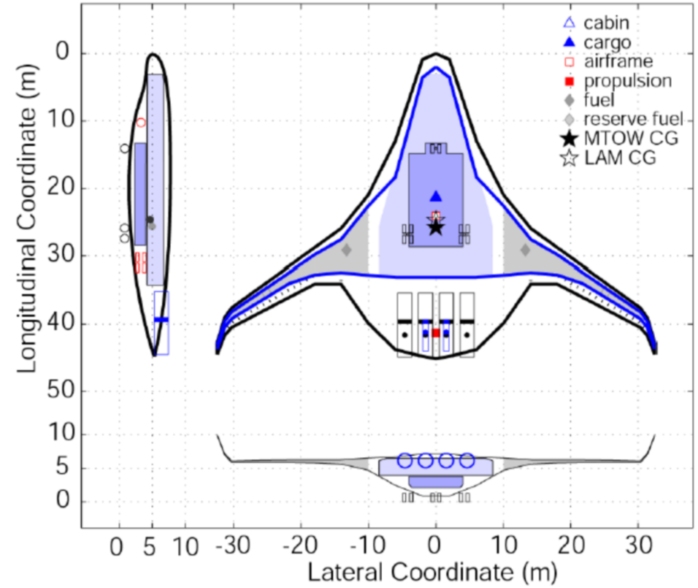
    43.3% fuel burn reduction

    37 EPNdB cum below Chapter 4

    72% LTO NOx reduction below CAEP/6

NASA SFW: MIT H3.2 Hybrid Wing Body





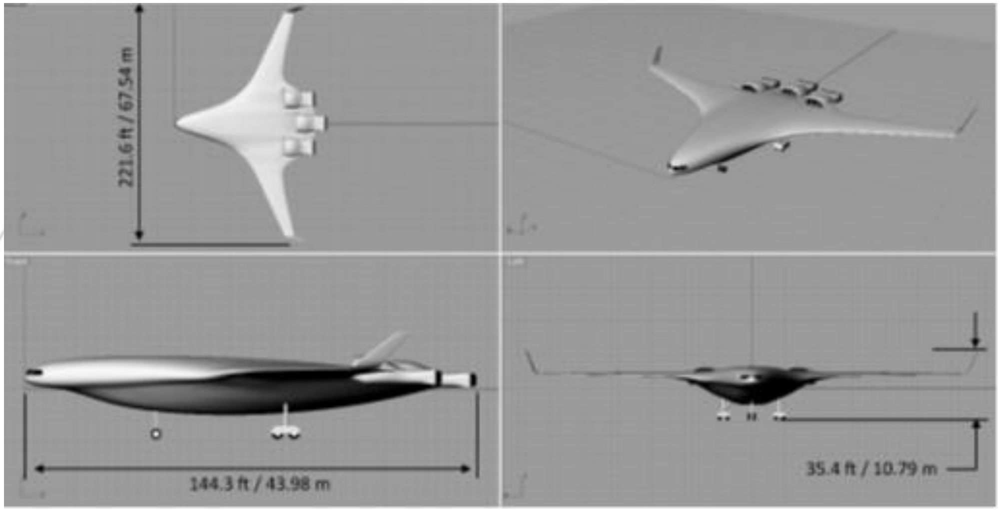
- 354 PAX, 7600 nm, M=0.80 at 41,000'
- Reference aircraft: B777-200LR
- BPR 20, OPR 50 turbofans and hybrid wing body:

54% fuel burn reduction

46 EPNdB cum below Chapter 4, 4 degree glide slope on approach, runway displacement threshold.

81% LTO NOx reduction below CAEP/6

Cambridge/MIT: Silent Aircraft Initiative



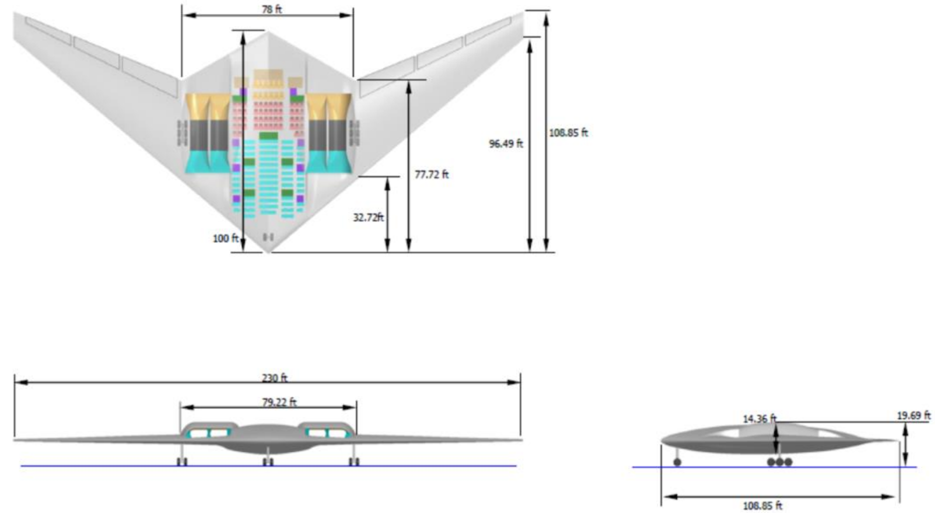
- 215 PAX, 5000 nm, M=0.80 at 45,000’
- Reference aircraft: B777
- Three BLI engines, each geared to three propulsors with low-noise airframe:

  25% fuel burn reduction

  62 dBA outside airport perimeter

  LTO NOx reduction not available

NASA ERA: Northrop Grumman Flying Wing



- 224 PAX, 8000 nm, M=0.85 at 52,000’
- Reference aircraft: 1998 technologies with scaled Trent 800
- Embedded high BPR engines and flying wing:

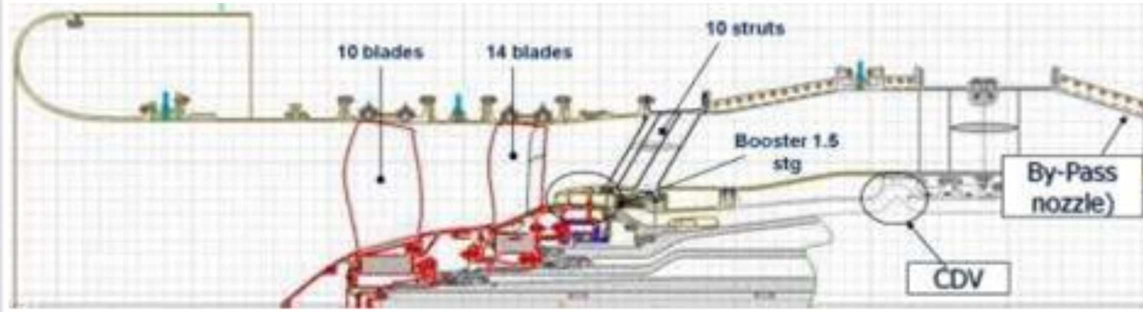
    41.5% fuel burn reduction

    74.7 EPNdB cum below Chapter 4

    88% LTO NOx reduction below CAEP/6

Novel Engine Concepts

European Commission: VITAL Ducted CR Turbofans



- Objective is to reduce noise, emissions and fuel burn.
- Reference engine: CRTF1 (Counter-Rotating Turbofan) matching equivalent conventional single stage fan pressure ratio. CRTF has reduced tip speeds to lower noise.
- Advanced engines:

  CRTF2a – thickened blades simulating composites materials.

  CRTF2b – thickened blades with blisk construction