System and Fleet level Environmental Assessments for N+2 Technologies

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Outline

- Vehicle Goals for N+1, N+2, and N+3
- Support of NASA & FAA System Assessment
- Technology Assessments
- Vehicle Assessment
  – Framework for assessment
  – Vehicle classes considered
  – Role of surrogate models
  – Decision support dashboard development
- Uncertainty Assessments
- Fleet Level Assessments
- Concluding Remarks

Assessment Goals and GT Involvement

Generational Assessment

CORNERS OF THE TRADE SPACE	N+1 = 2015*** Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020*** Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

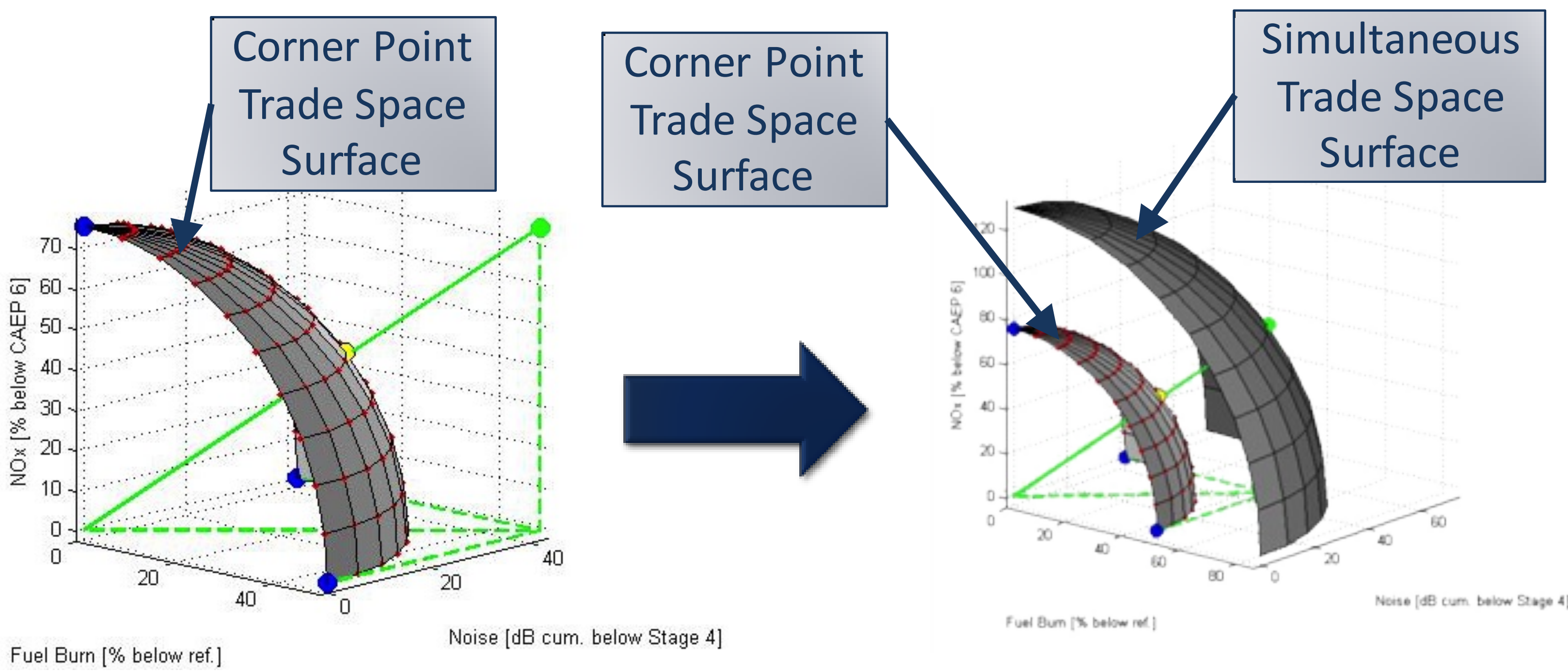
Approach for N+1, N+2, & N+3 Timeframe Technologies

- Develop vehicle concepts envisioned for integration into the fleet by N+1, N+2, and N+3 timeframes
- ***SIMULTANEOUS*** reduction of noise, NOx, and fuel burn at vehicle level
- *Accelerate* maturation of technologies envisioned for advanced vehicle concepts
- Advance TRL and IRL for *innovative* technology-based solutions to 5 or 6 by required timeframe

Assessment Goals for ERA: Simultaneous Achievement of Environmental Metrics

- Simultaneous achievement of multiple goals increases technology challenge
- Interdependency and trade-offs exist between metrics

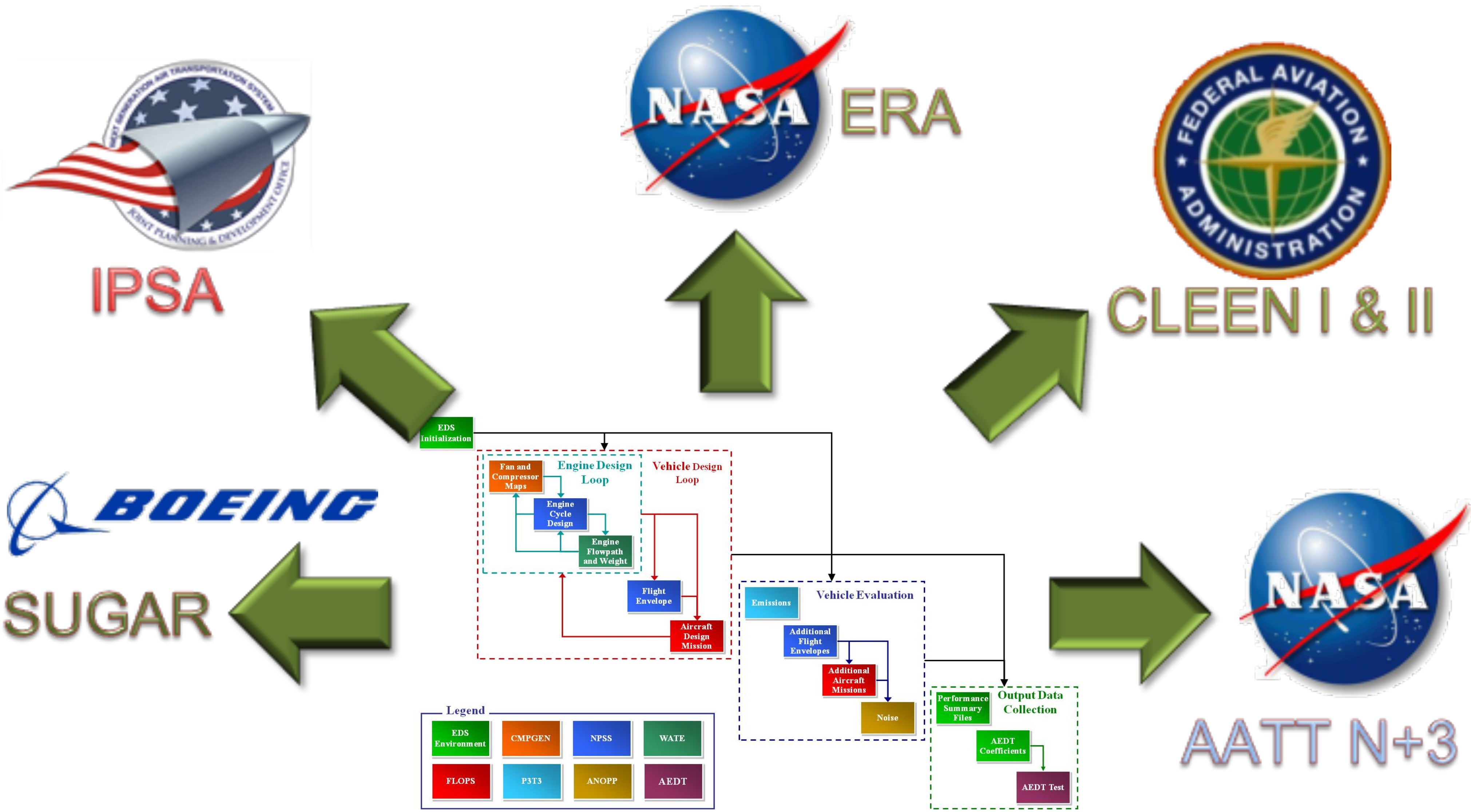
Notional Goal Trade Surfaces



Vehicle and Fleet Technology Assessment

- GT-ASDL was tasked to perform systems assessments
  - For various classes of vehicles
  - For both conventional and unconventional configurations
  - Incorporating N+1, N+2, and N+3 technology portfolios
- Served as independent system assessment team for NASA and FAA and worked cooperatively with various organizations, e.g.:
  - NASA System Analysis Branch: ERA and AATT project teams at LaRC and GRC
  - FAA Office of Environment and Energy: CLEEN I/II program, VOLPE, etc.
- Employed a bottom-up technology assessment methodology
- The examples shown in this presentation are from the NASA work performed for ERA, but a similar process was followed for the FAA assessments as well as the NASA N+3 assessments
- The approach followed was developed over a period of years in collaboration and with support from the FAA/AEE and NASA and allows for generational assessments across N+1, N+2 and N+3 based on common tools, assumptions and modeling philosophy

Generational Assessment Overview

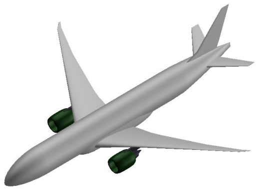


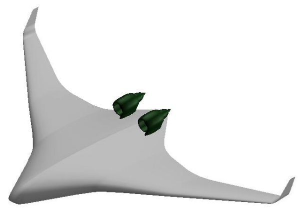
N+2 Vehicle Architectures and Modeling

N+2 Architecture Concepts

Airframe Concepts

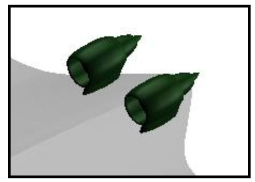
Tube & Wing (T&W)





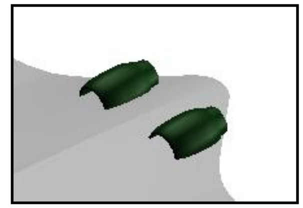
Hybrid Wing Body (HWB)

Propulsion Airframe Integration (PAI)



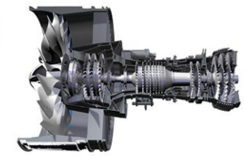
Podded Engines

Embedded Engines



Engine Concepts

Advanced Direct Drive (ADD)



Geared Turbofan (GTF)

Open Rotor

ERA1 Solicitation Winning Designs

Lockheed Martin

Northrop Grumman

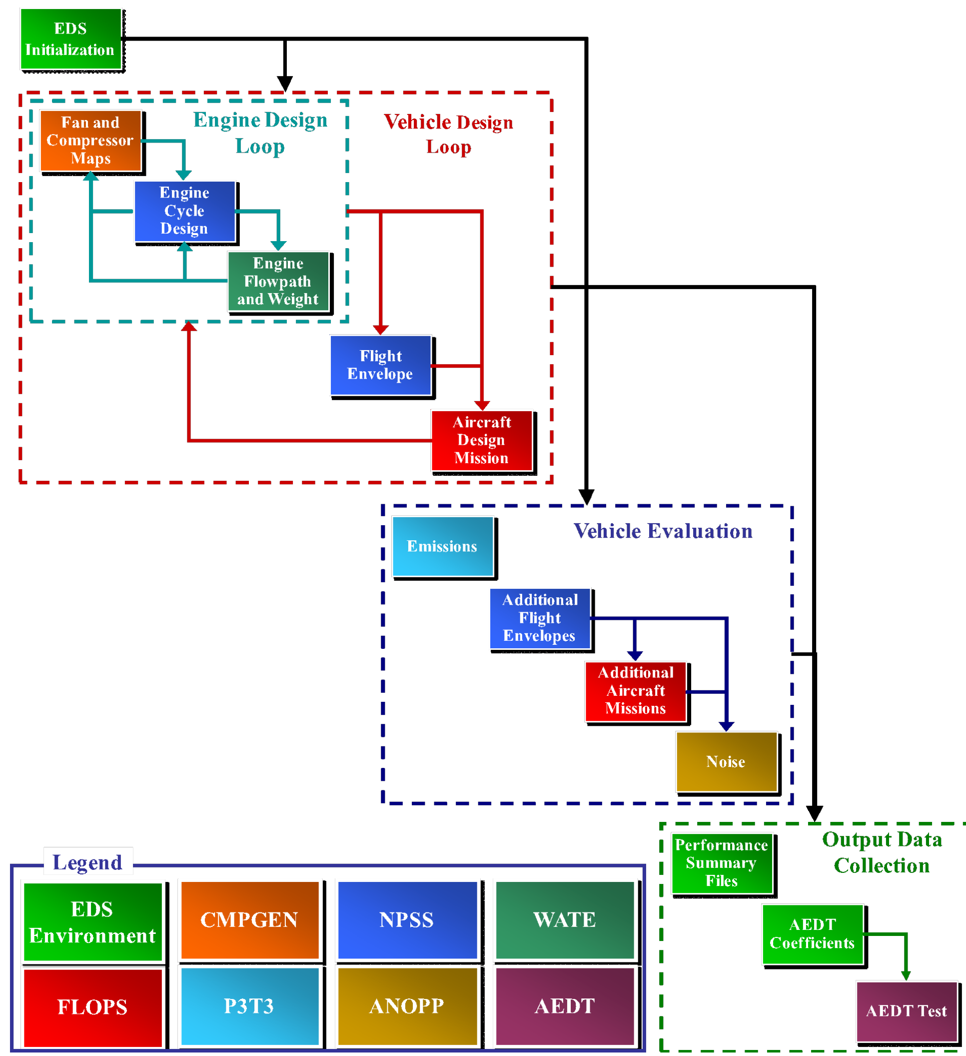
Boeing

… and many others

Image from Mark Mangelsdorf Feb. 2010 ERA bidders conference presentation

Vehicle Modeling Environment

- Environmental Design Space (EDS)
  - An M&S environment developed with support by the FAA/AEE to model existing aircraft as well as advanced technologies and concepts
- EDS integrates continuously updated NASA design tools with industry vetted design logic to provide a parametric aircraft design capability
  - Consistent engine to airframe match
  - Creates output links to connect with fleet assessment tools
  - Takes advantage of years of development and validation by NASA
- EDS provides integrated analysis capability to estimate:
  - Source noise
  - Exhaust emissions
  - Engine and vehicle performance



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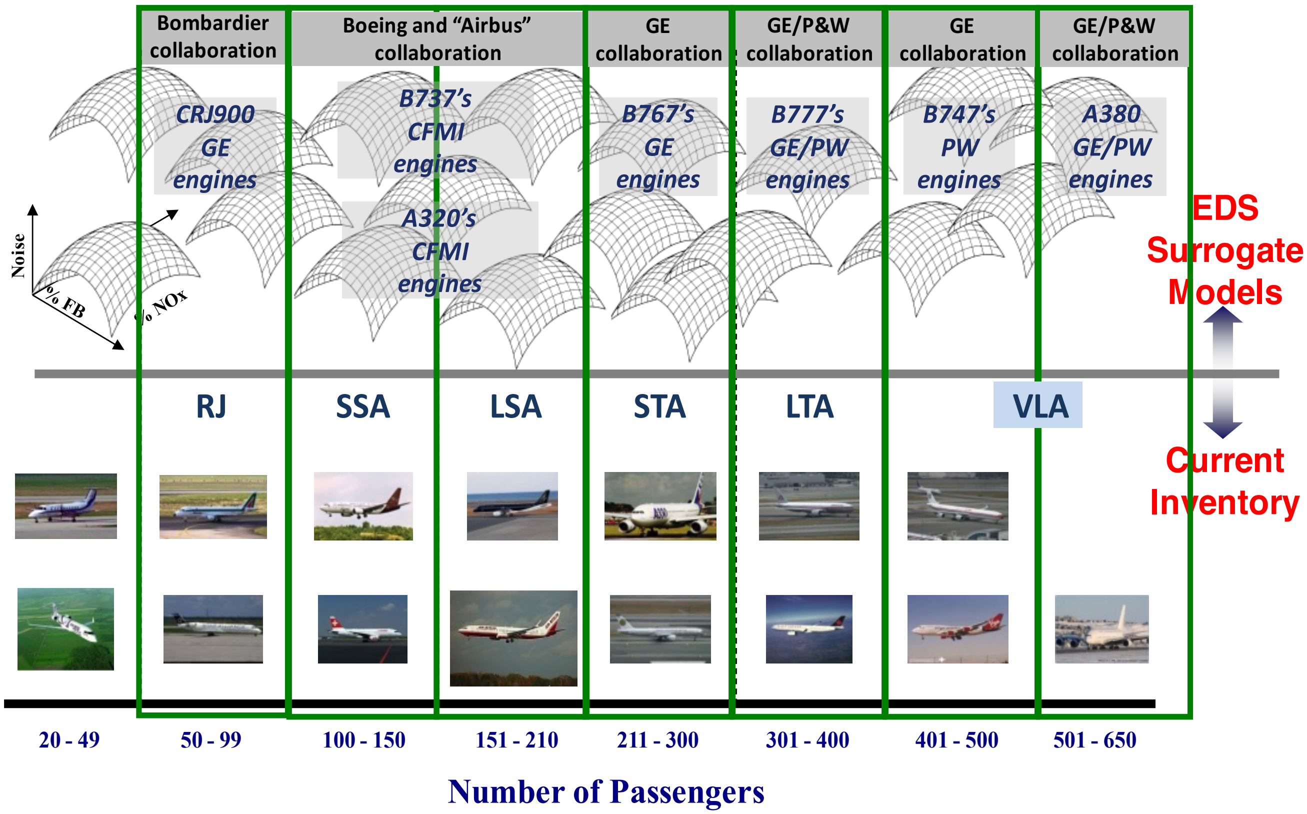
EDS Vehicle Calibration

- EDS vehicle models have been developed, calibrated, and validated to existing vehicle in the fleet. Rigorous vetting process with industry SMEs

- EDS captures existing aircraft models from Regional Jets, RJs through Very Large Aircraft, VLA aircraft

- Existing aircraft models serve as departure point for modeling new technology engines and aircraft



Vehicle Concepts Modeled

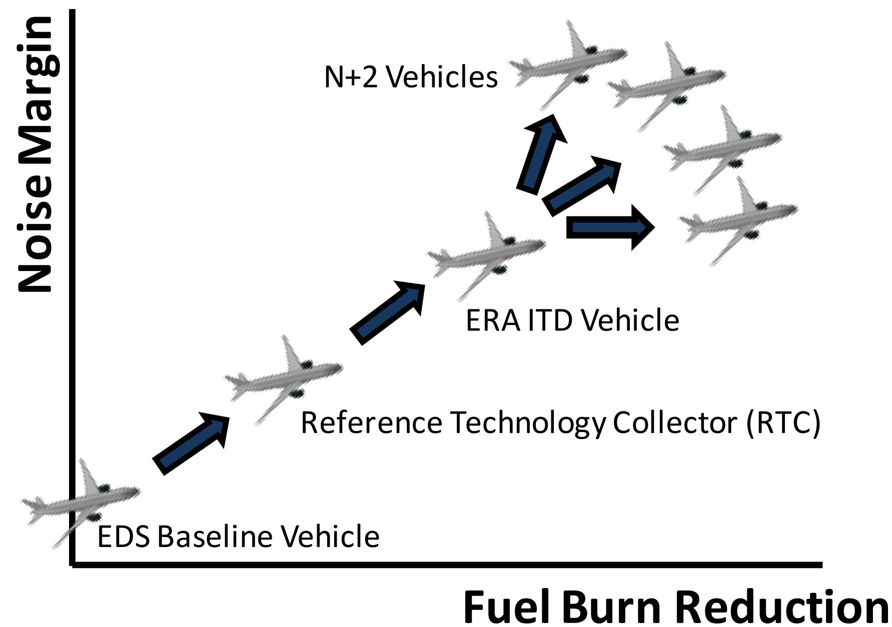
- Varying size classes from regional jet (i.e. CRJ 900) to very large aircraft (i.e. B747-400)
- Vehicle configurations consist of conventional (i.e. tube & wing) and unconventional concepts
- Vehicle concepts originated from NASA and/or FAA and public domain research or from industry led studies funded by NASA

The Subsonic Ultra Green Aircraft Research, or SUGAR, Volt design concept.
Image credit: NASA/The Boeing Company

N+2 Technology Assessment

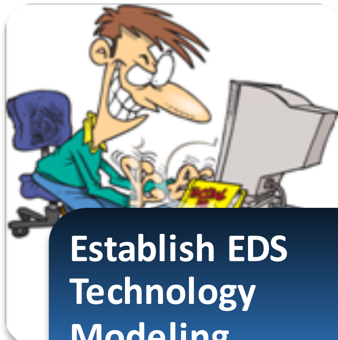
Technology Portfolio Selection

- For NASA's ERA program three different technology portfolios evaluated:
  - Reference Technology Collectors (RTCs); 2010 State of the art concepts
  - ERA Integrated Technology Demonstrator (ITD) technologies
  - N+2 Technologies
- Technology portfolios build off previous technologies while correcting for compatibility and scaling issues
- Conducted several technology review sessions with NASA Subject Matter Experts (SMEs) to:
  - Review technology modeling methods and assumptions
  - Estimate technology impacts based on testing/literature/high fidelity simulation



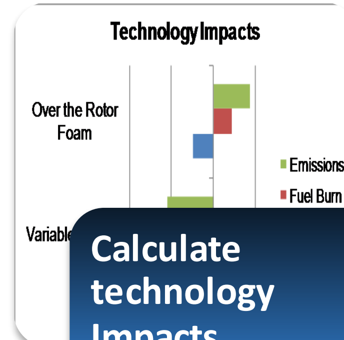
Vehicle Technology Modeling Process

Research Technology
- Conduct Literature Review
- Identify Interdependencies
- Elicit SMEs



Establish EDS Technology Modeling Methodology
- Identify how technology works
- Establish modeling routine
- Implement in EDS

Verify EDS Technology Model
- Conduct reviews to ensure technology is modeled correctly



Calculate technology Impacts
- Install technology on the aircraft and engine to determine effect on fuel burn, noise, and emissions

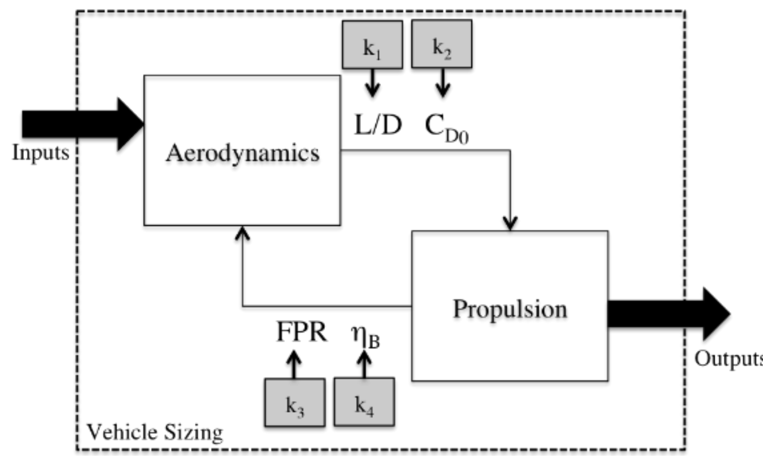
- **N+1, N+2 and N+3 technology portfolios originated from NASA and/or FAA**
- **More than 80 specific technologies assessed for multiple portfolios**
- Series of workshops held at Georgia Tech with NASA SMEs to determine the proper way to model all technologies
- Technology report was created to make the technology modeling as transparent as possible

Vehicle Technology Modeling Enabler

k-factor Approach

- Quantitative forecasting requires quantitative representation of technologies
- Technologies, or potential impacts of technologies, can be defined as delta's with respect to a current system baseline
- ``k-factors'' directly modify computed metrics during the analysis process, which in turn simulate technology benefits and penalties

$$Range = \frac{V}{k_{TSFC} TSFC} \frac{k_{C_L}}{k_{C_D}} \frac{C_L}{C_D} \ln \frac{k_{W_0}}{k_{W_1}} \frac{W_0}{W_1}$$

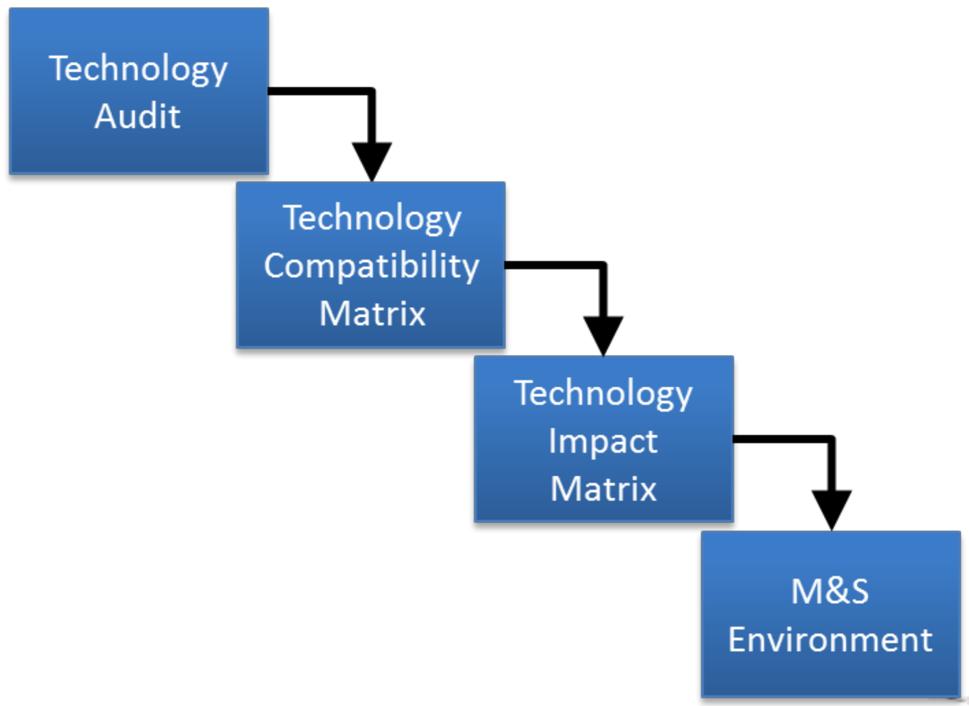


Representing Technologies in EDS

- Technology impacts at component level and compatibilities/interactions between technologies are represented through matrices
- EDS models combine technology impacts to ascertain rolled up system level impacts
- Bottom up approach to evaluate interdependencies of system metrics for various concepts and technology packages

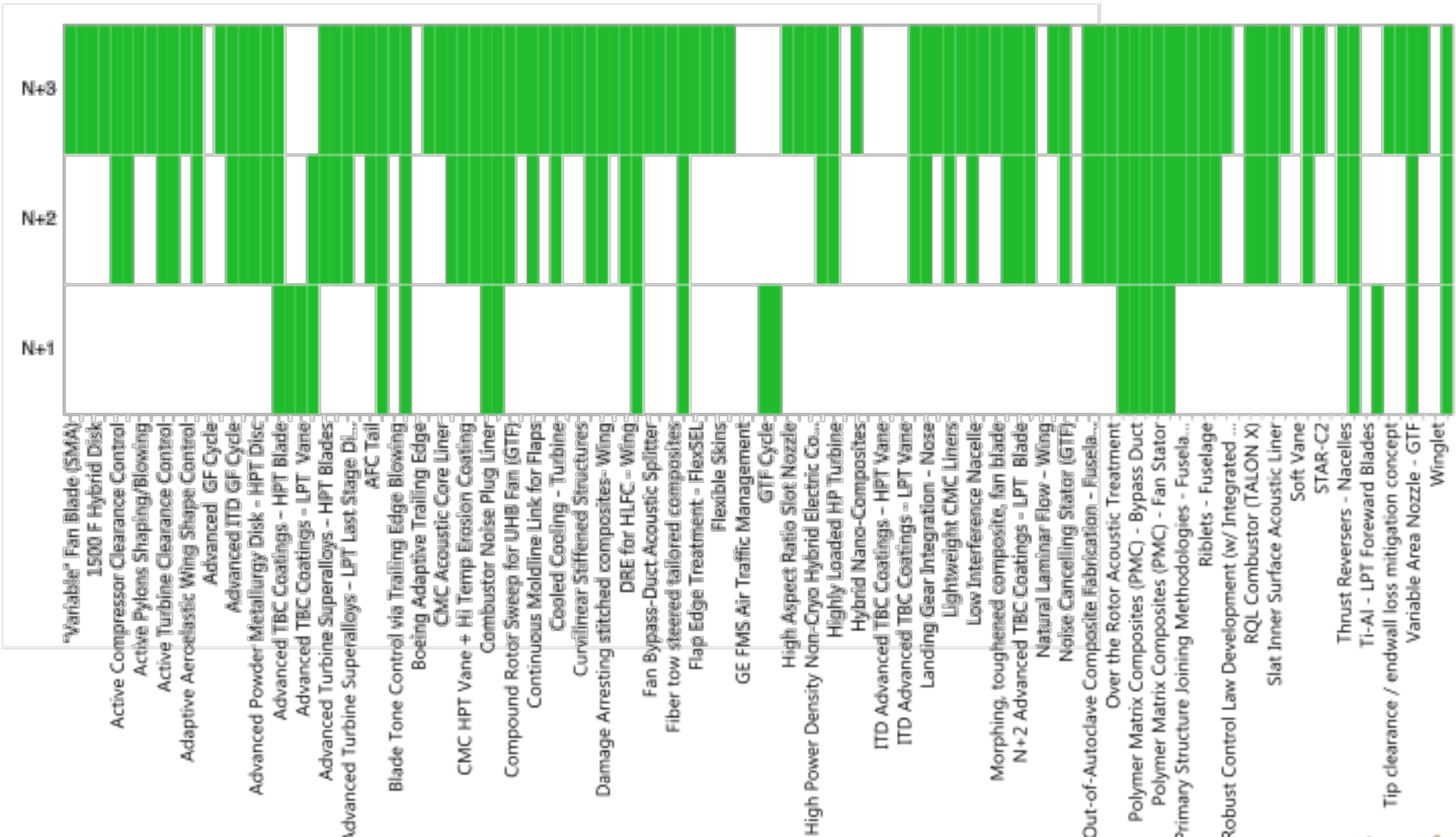
Technology Impact Matrix

DoE Name	Units	Tech Combo Rule	T11.1 Natural Laminar Flow - Wing			T32 Highly Loaded Compressor		
			LTA	LSA	LTA-HWB	LTA	LSA	LTA-HWB
HPC_Dutip	Ft/S	Absolute				-337.8	-326.0	-337.8
HPC_FSPRmax	NONE	Absolute				1.845	1.930	1.845
HPCPR	NONE	Absolute				29.42	25.91	29.42
TRUW	%	Delta	19	40	14			
XLLAM	NONE	Switch	1	1	1			



Technologies Assessed

Vetted with FAA and NASA SMEs



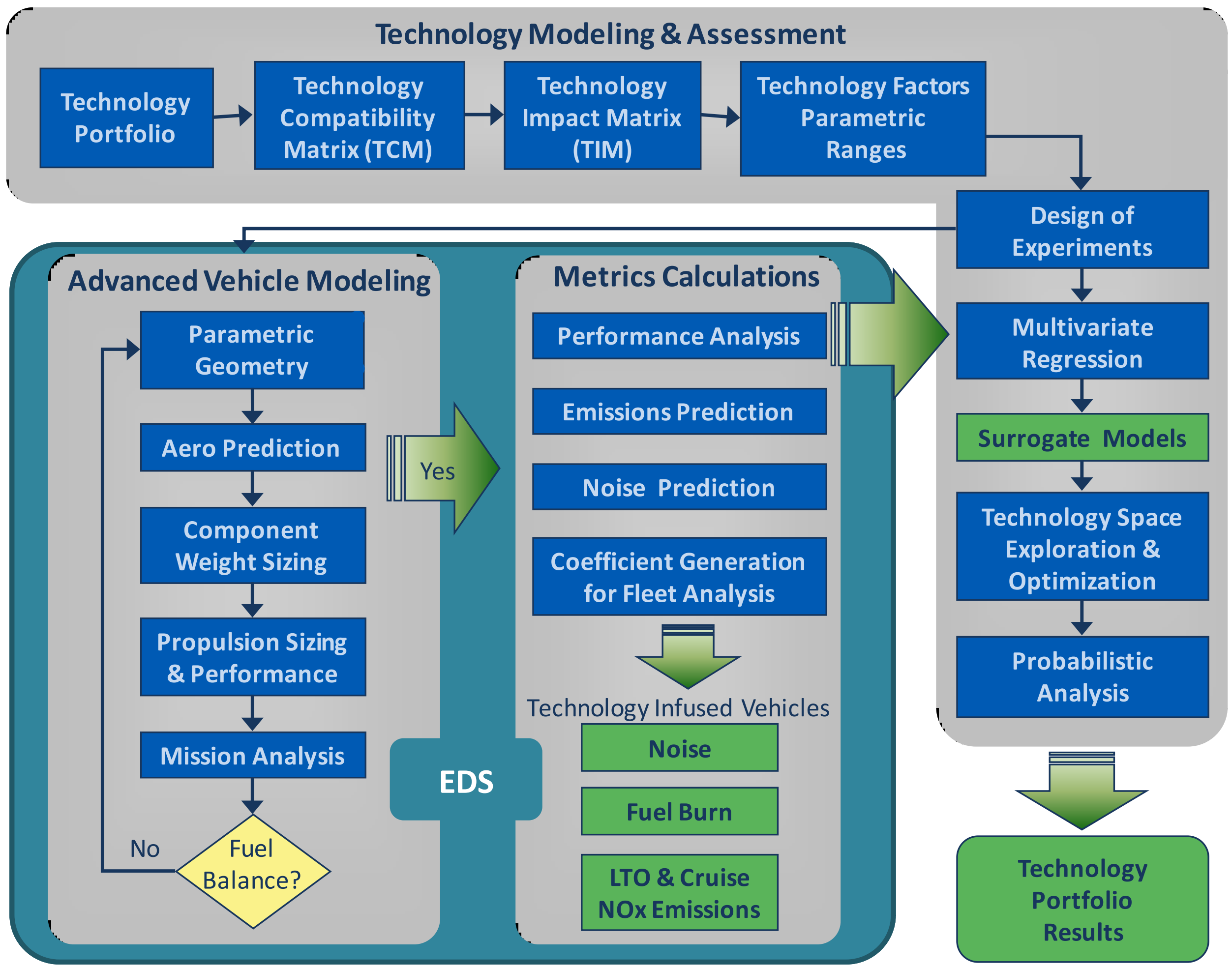
Vehicle Level Assessment Approach

Vehicle Level Assessment Methodology

- Vehicle assessment method combines technology impact modeling with vehicle modeling, sizing and synthesis to evaluate performance metrics

- Technology impacts are modeled at component level
  - Allowed to propagate through EDS in order to determine the system level benefits

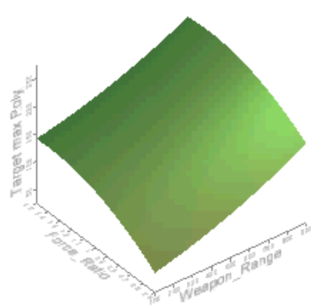
- Utilizes ***surrogate modeling*** to evaluate technology trade space for multiple vehicle configurations and classes

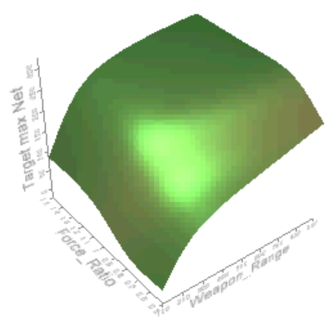


Surrogate Modeling

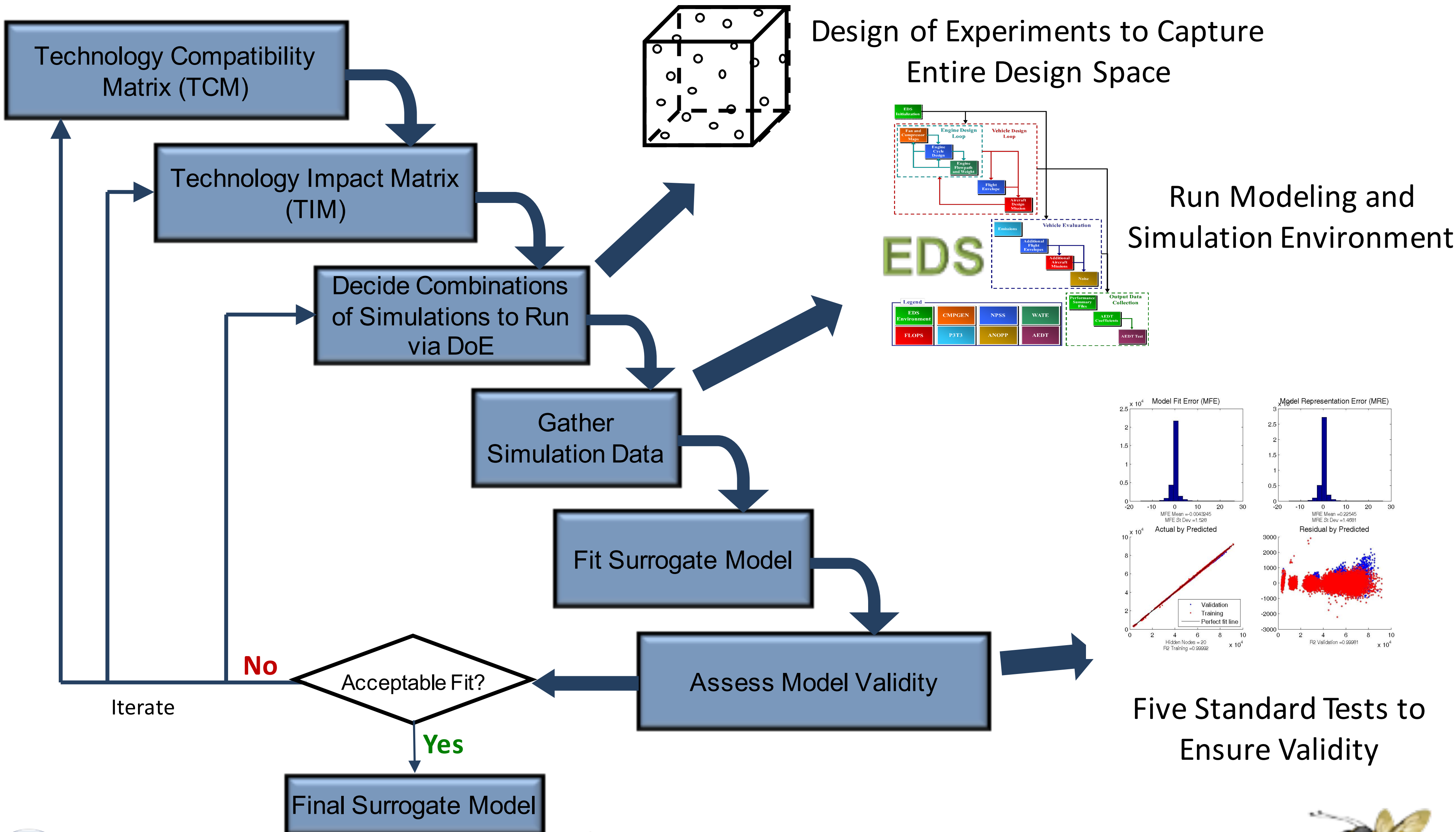
Enabler for Quantitative Analysis

- Surrogate modeling is an enabling technique for rapid assessments with variable fidelity analysis codes
- Surrogate models provide the following capabilities:
  - Speed up processes
  - Protect proprietary nature of codes used
  - Overcome organizational barriers (protectionism of tools and data), allow for the framework to be tool independent (no need for direct integrations of codes)
  - Enables the desire for variable tool fidelity formulations
  - Allow the designer to perform requirements exploration
  - Technology infusion trade-offs and concept down selections during the early design phases (conceptual design) using physics-based methods
- These surrogate models can also be used at the integrated system level to determine responses at that level. This will allow us to move from deterministic, serial, single-point designs to dynamic parametric trade environments



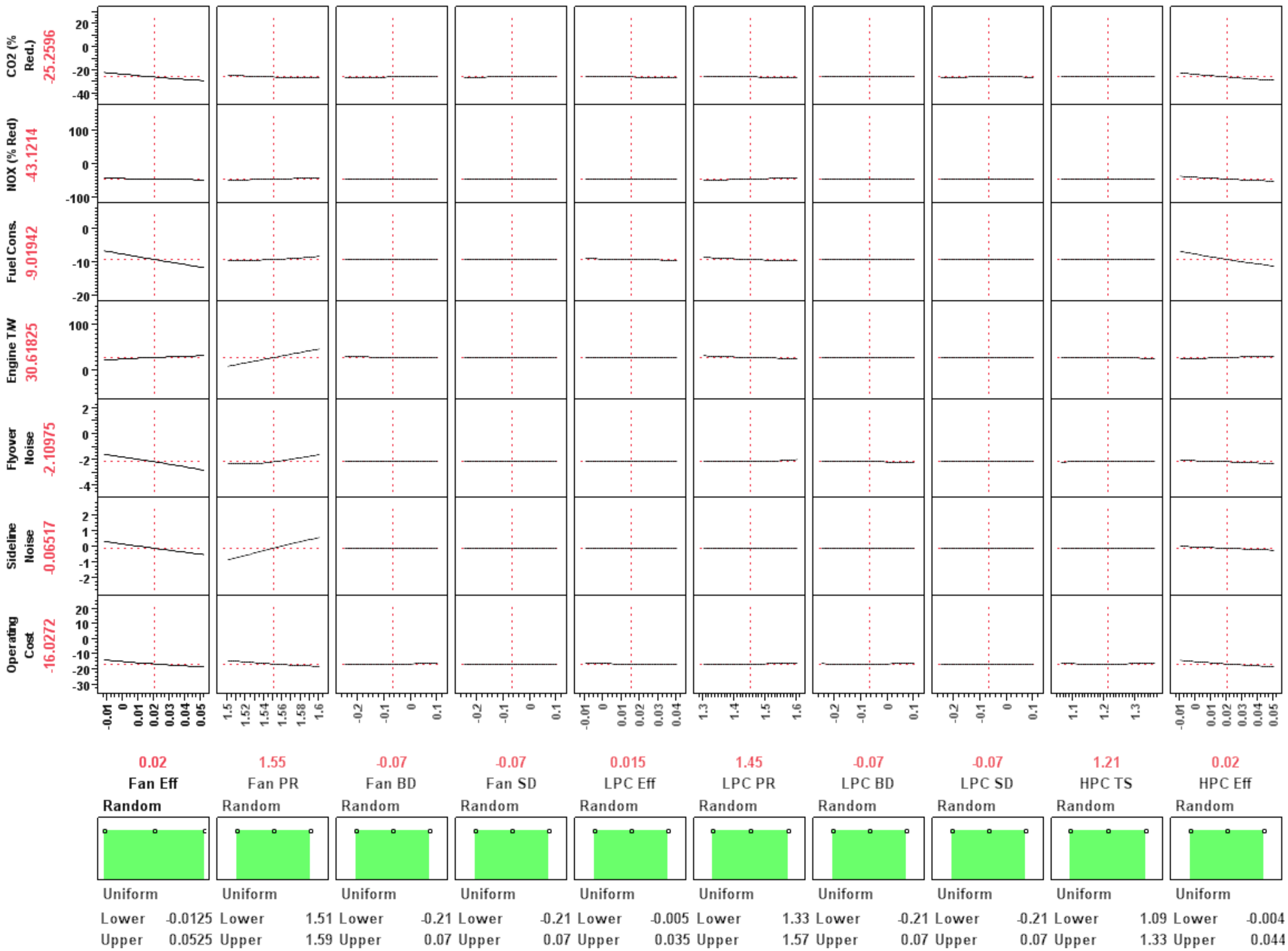


Surrogate Generation Process



Notional Example of Quantitative Analyses

Prediction Profiler



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Notional Example of Quantitative Analyses

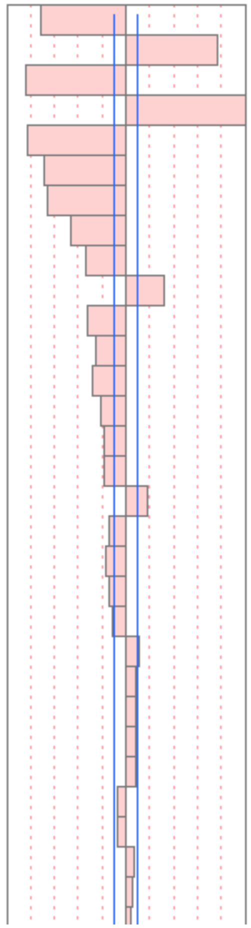
Pareto Analysis

Screening

Screening for CO_2 (% Red.)

Contrasts

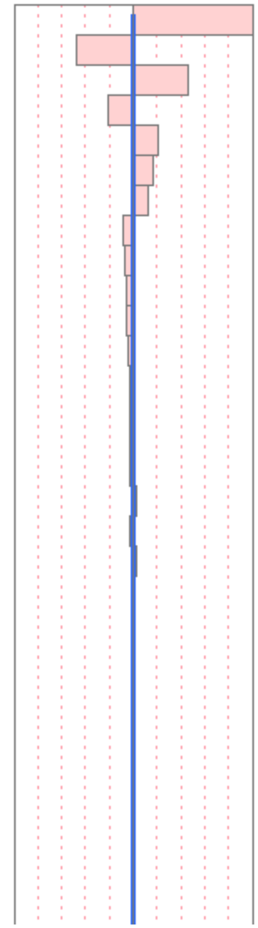
Term	Contrast
LPT Eff	-0.381812
Drag Coeff	0.412201
Fan Eff	-0.452695
T/W	0.538686
HPT Eff	-0.442756
HPC Eff	-0.368793
HPT Blade Temp	-0.352748
HPC PR	-0.252358
Fan PR	-0.179444
Turbine Temp (T4)	0.169683
LPT Load	-0.173364
HPT 2nd Vane Temp	-0.139164
W/S	-0.152227
LPT VT	-0.113781
HPC 1st Stg. PR	-0.096984
Utilization	-0.099864
HPT MaxMT	0.098751
LPC Eff	-0.074455
LPT BT	-0.091648
LPC PR	-0.074113
HPT Loading	-0.063570
LPC SD	0.058250
LPT BD	0.047375
LPT SD	0.044339
LPC BD	0.047810
Fan BD	0.042353
LPT MaxMT	-0.034110
Comb_D	-0.037462
HPT BD	0.038969
Fan SD	0.032813
HPT 1st Vane Temp	[illegible]



Screening for NOX (% Red)

Contrasts

Term	Contrast
k-Emissions	5.74328
Combustor Cooling	-2.72106
Turbine Temp (T4)	2.66960
HPC Eff	-1.21648
HPC PR	1.17655
LPC PR	0.94797
Fan PR	0.74850
Fan Eff	-0.48532
HPT Eff	-0.41137
HPT Blade Temp	-0.29744
HPT 2nd Vane Temp	-0.28293
W/S	-0.27375
LPT Eff	-0.17952
LPC Eff	-0.17483
LPT Load	-0.16218
Utilization	-0.15743
Comb_D	0.13776
HPC 1st Stg. PR	-0.15292
LPC BD	0.12325
LPT MaxMT	-0.11995
LPT SD	-0.11850
Fan BD	0.10489
LPC SD	-0.08087
HPT 1st Vane Temp	0.07507
HPT SD	-0.05906
LPT BD	-0.06170
HPT MaxMT	0.05908
Fan SD	-0.06008
HPT BD	0.05014
HPC TS	0.03897
LPT BT	[illegible]



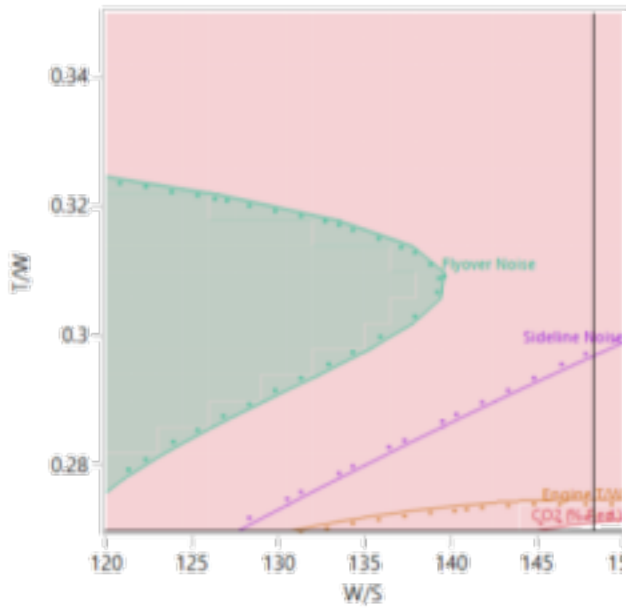
Notional Example of Quantitative Analyses

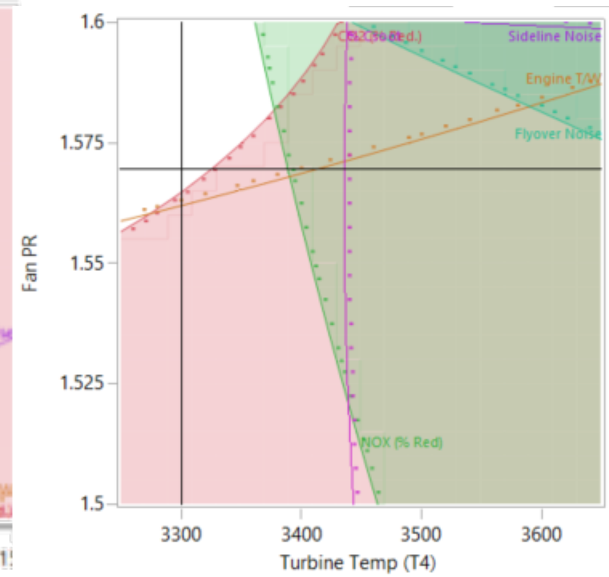
Dynamic Interactive Constraint Analysis

Contour Profiler

Horiz	Vert	Factor	Current X
		Fan Eff	0.01061
		Fan PR	1.5696
		Fan BD	0.1
		Fan SD	-0.2262
		LPC Eff	0.04
		LPC PR	1.5033
		LPC BD	-0.25
		LPC SD	0.1
		HPC TS	1.36
		HPC Eff	0.05
		HPC PR	20
		HPC 1st Stg. PR	1.6
		Comb_D	0.1
		Turbine Temp (T4)	3300.9299
		HPT Eff	0.05
		HPT Loading	0.25
		HPT 1st Vane Temp	1000
		HPT 2nd Vane Temp	400
		HPT Blade Temp	400
		HPT BD	-0.25
		HPT SD	-0.7
		HPT MaxMT	400
		LPT Eff	0.0301887
		LPT Load	0
		LPT VT	200
		LPT BT	400
		LPT BD	0.1
		LPT SD	-0.25
		LPT MaxMT	154.71698
		Drag Coeff	1
●		W/S	148.30189
	●	T/W	0.27
		Combustor Cooling	1
		k-Emissions	10
		Utilization	0.15

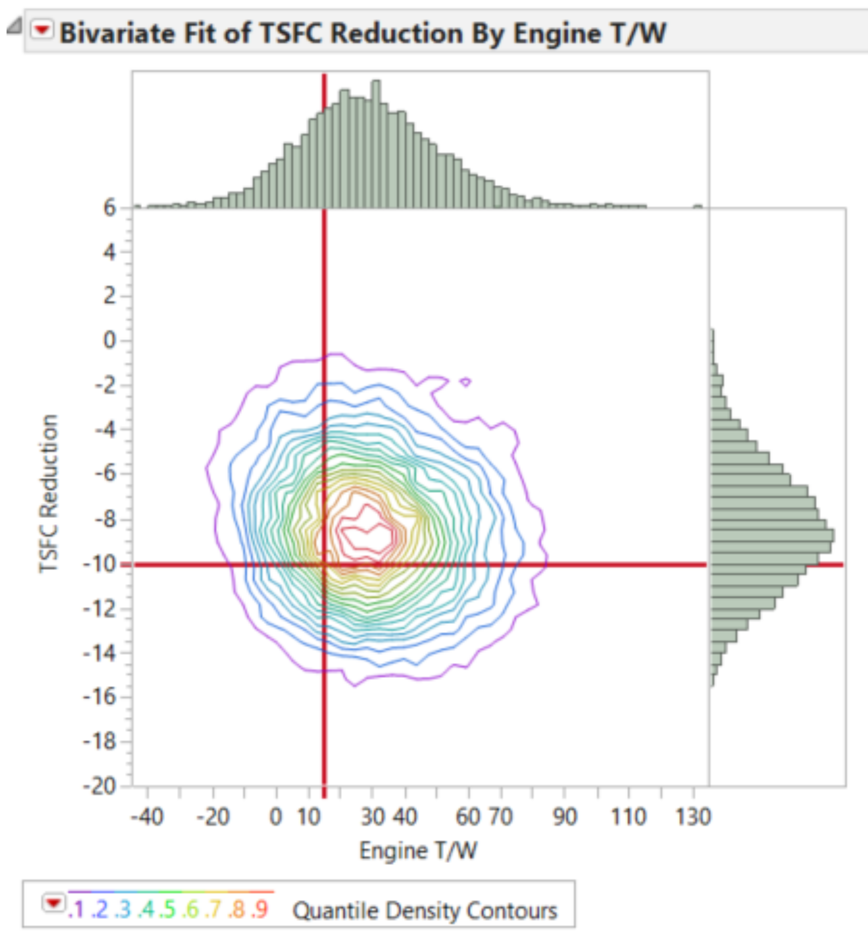
Response	Contour	Current Y	Lo Limit	Hi Limit
CO2 (% Red.)	-25	-25.11511	.	-25
NOX (% Red.)	-90	-90.98316	.	-90
Fuel Cons.	-7	-11.82564	.	.
Engine T/W	45	48.327535	.	.
Flyover Noise	-1.125	-1.635484	.	-1.125
Sideline Noise	0	-0.446288	.	.
Operating Cost	-3.75	-21.27837	.	.
% HC	15.045997	29.371535	.	.
% Csoot	33.173986	5.93436	.	.

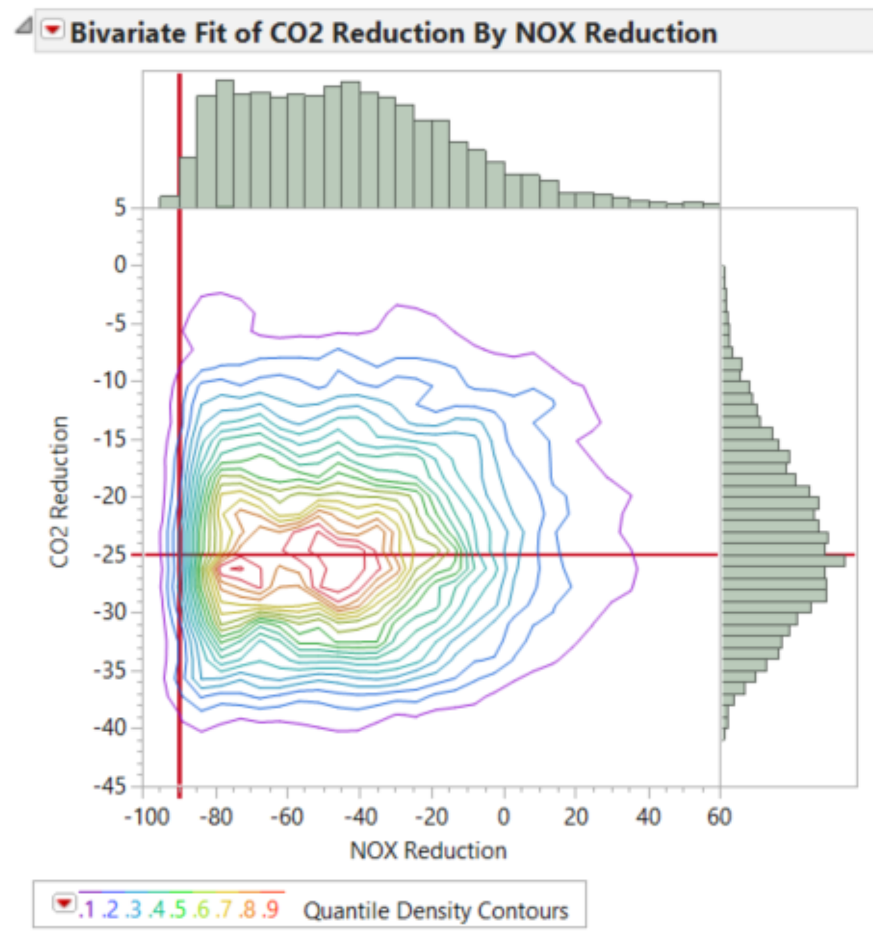




Notional Example of Quantitative Analyses

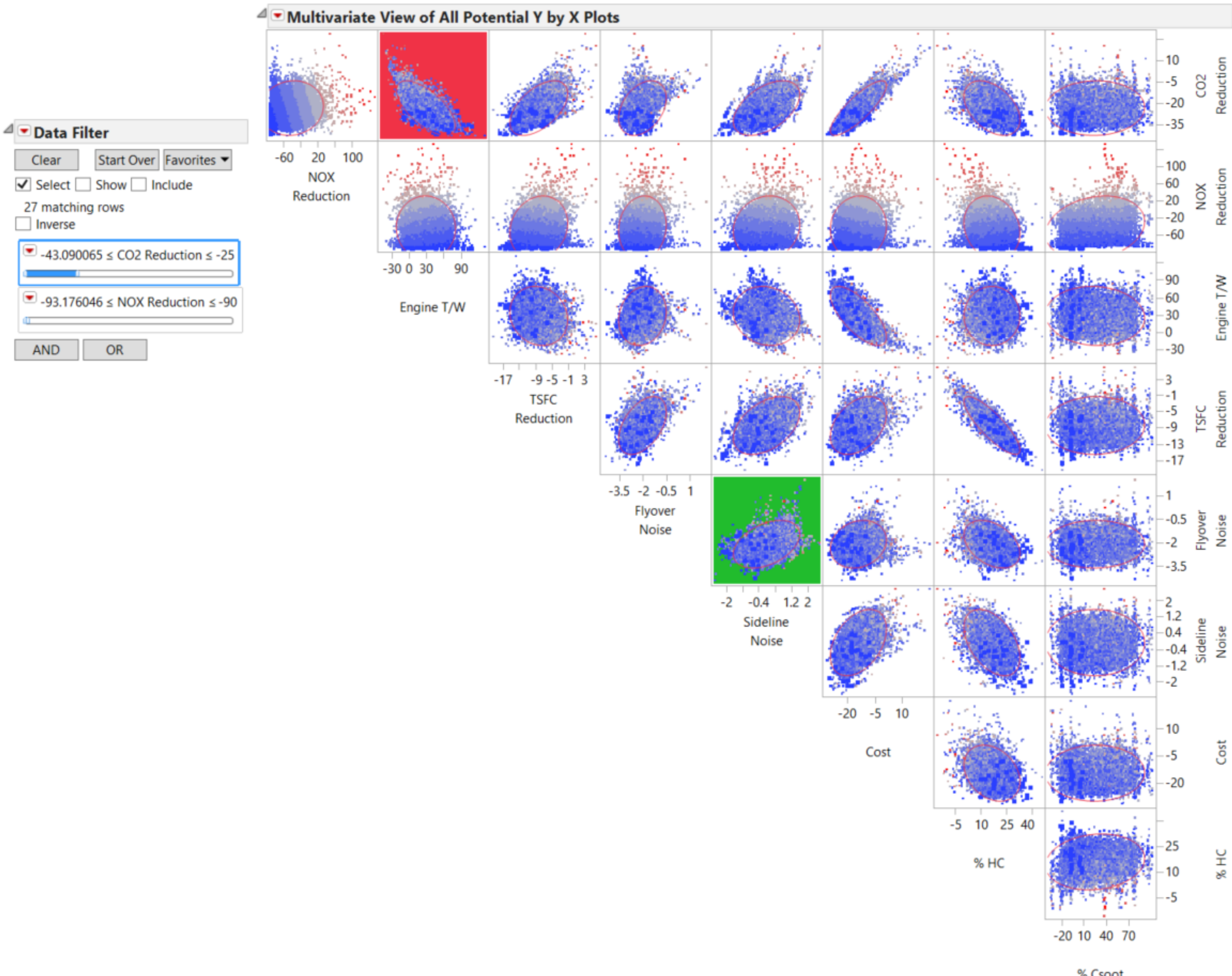
Bivariate Plots





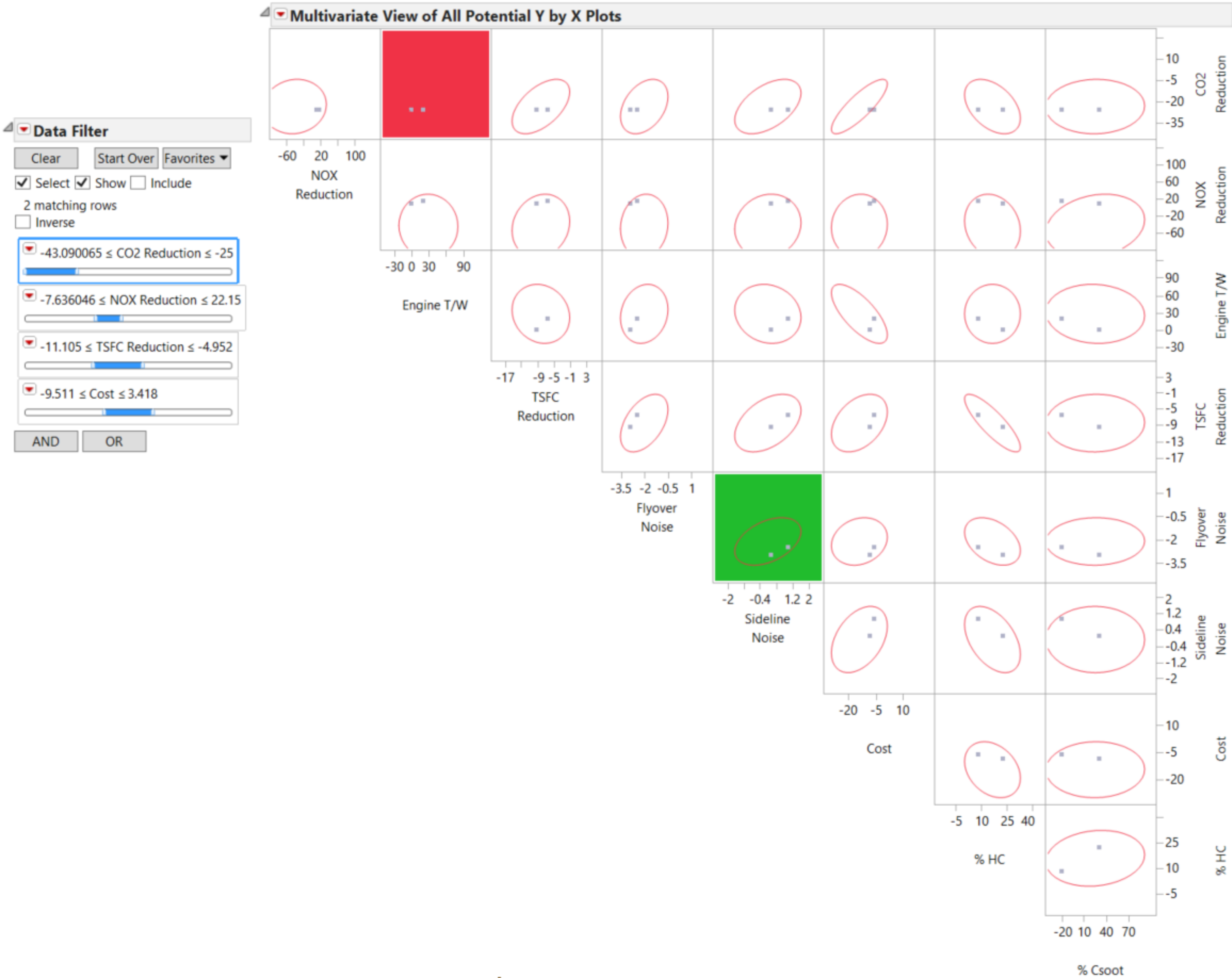
Notional Example of Quantitative Analyses

Scatterplot Matrix



Notional Example of Quantitative Analyses

Filtered Monte Carlo



Creating an Interactive Dashboard

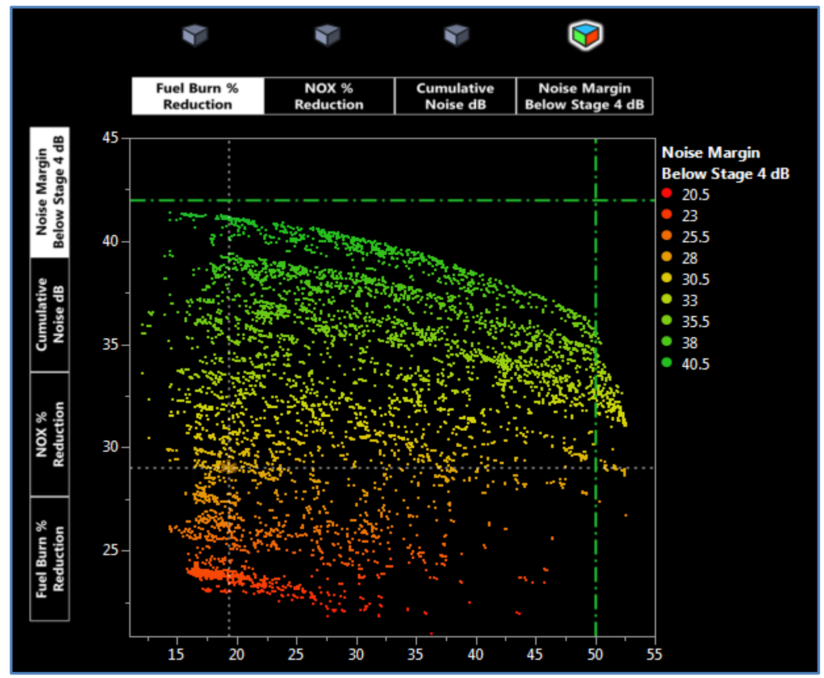
- All of these techniques were utilized to analyze the technologies and vehicle concepts investigated for the ERA program
- An interactive, parametric dashboard was created within the JMP environment
- The surrogate models are behind the scene of the dashboard and are utilized for rapid performance assessments
- The dashboard provides a ‘zooming’ capability because performance information is provided from the technology impact level all the way to the fleet level
- The dashboard is utilized by NASA decision makers analyze the performance of technology packages and make vehicle and fleet level tradeoffs

ERA Dashboard for N+2 Decision Support

Vehicle class and configuration selection with ability to handpick technologies

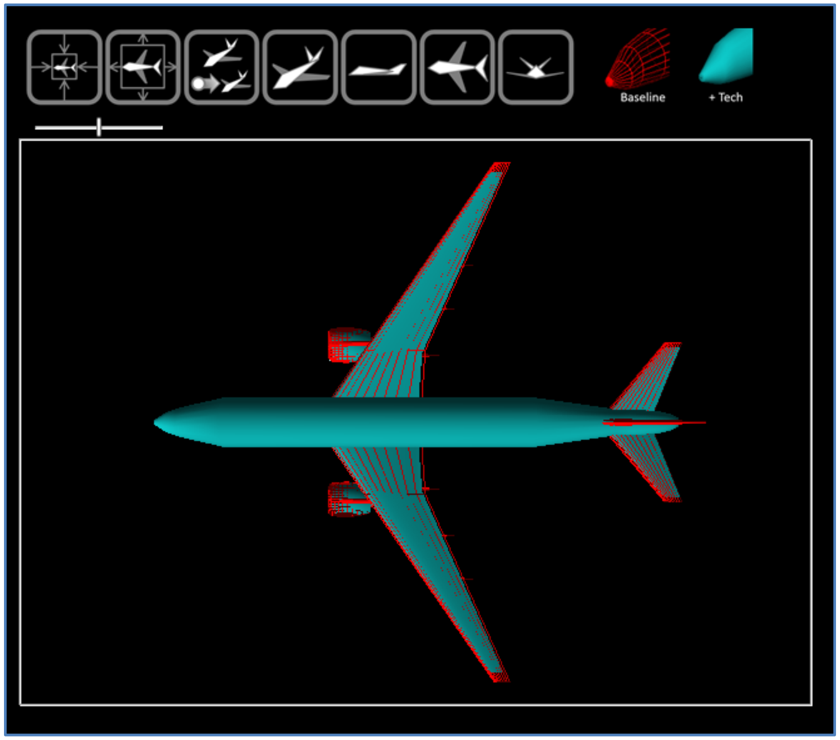
Provides Pareto frontiers showing the potential benefits in metrics and returns the technology packages for selected point

- Results of systems assessments aggregated and displayed in a user-friendly decision support tool
- Gives policy makers and technologists ability to see the potential system impacts of various aircraft configurations, technology packages, and fleet compositions

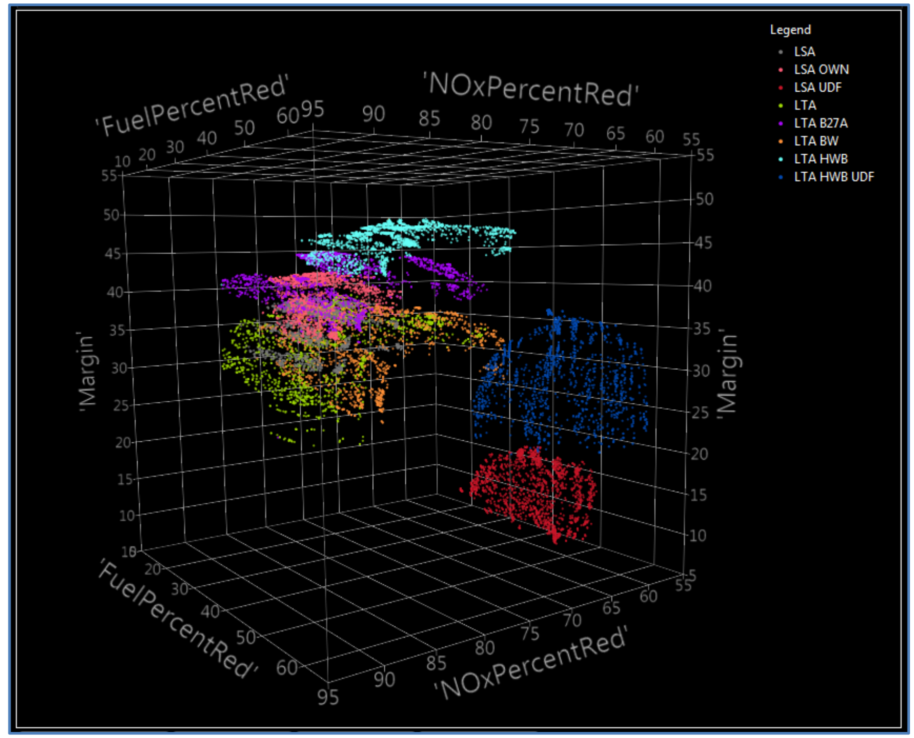


ERA Dashboard for N+2 Decision Support

Displays how technologies influence the aircraft configuration



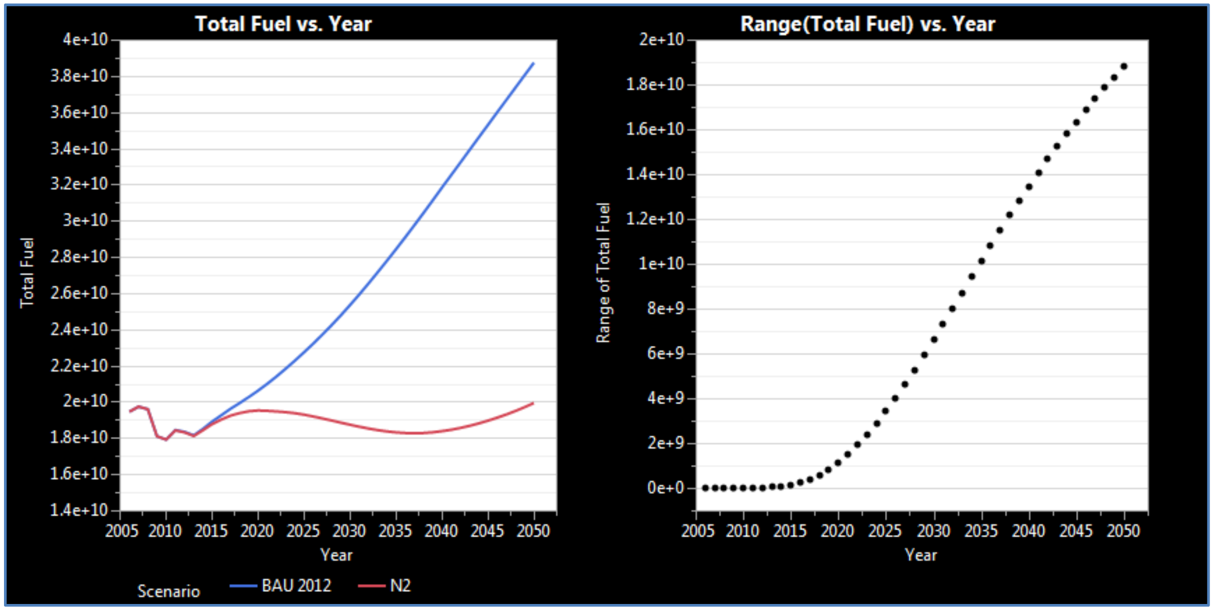
Allows for the user to compare performance metrics across multiple vehicles simultaneously

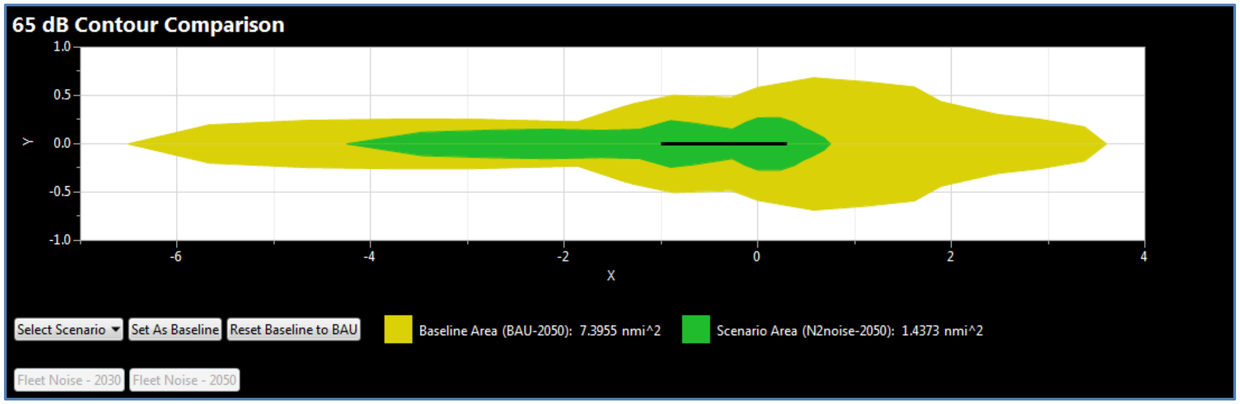


- Integrated within the decision support tool is the result of technology uncertainty propagation from the individual technology impacts to the vehicle/fleet performance metrics

ERA Dashboard for N+2 Decision Support

Provides user with ability to manipulate fleet composition to observe effects on fuel burn and emissions





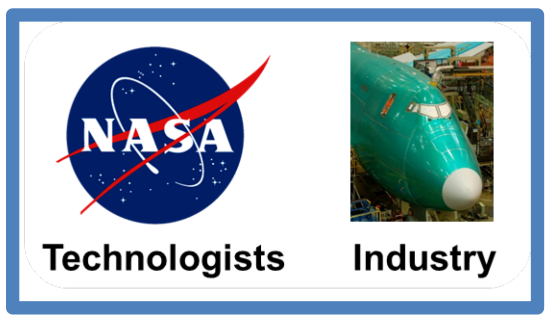
- Output and results are visualized at both the vehicle system level and at a fleet-wide impact level
- Provides insight on which technologies and configurations should be pursued in order to meet system level goals – whether it be fuel burn, emissions, noise, or a compromise between all three

Compares impacts on airport noise contours for a generic runway configuration to give insight on how technologies reduce and reshape contours

ERA ITD Uncertainty Assessment

ITD Goals and ASDL Opportunity

- Each ITD goal is to “mature each technology with required supporting technologies to reduce uncertainty of benefit projection”
  - Accomplished through:
    - Computational analysis
    - Relevant field and/or flight testing
- The ability to link the experimental data collected from the ITD experiments to the system level analysis already being conducted, and propagate the uncertainty, was an identified gap in the ERA process, which provided an opportunity for a collaboration with ASDL
- A team of ASDL PhD students were embedded into the technology development teams, which provided a profound opportunity
- Working with the ERA ITD teams provided a profound opportunity
  - Chance to work with experimental data
  - Access to NASA and industry technologists
  - Gain an insight into technology development processes and how decisions are currently made



ERA Technical Challenges and Technologies

Innovative Flow Control for Drag Reduction
Demonstrate drag reduction of 8 percent

- 12A+: AFC Enhanced Vertical Tail and Advanced Wing Technology Flight Experiments

Advanced Composites for Weight Reduction
Demonstrate weight reduction of 10 percent compared to state of the art composites

- 21A: Damage Arresting Composites
- 21C: Adaptive Compliant Trailing Edge

Advanced UHB Engine Design for SFC and Noise Reduction
Demonstrate UHB efficiency to achieve 15 percent TSFC reduction, while reducing engine system noise and minimizing weight, drag, NOx and integration penalties at system level

- 30A: Highly Loaded Front Block Compressor
- 35A: Second Generation UHB Integration

Advanced Combustor Designs for NOx Reduction
Demonstrate reduction of LTO NOx by 75% from CAEP 6 and cruise NOx by 70% without penalties in stability and durability of the engine system

- 40: Low NOx Fuel Flexible Combustor Integration

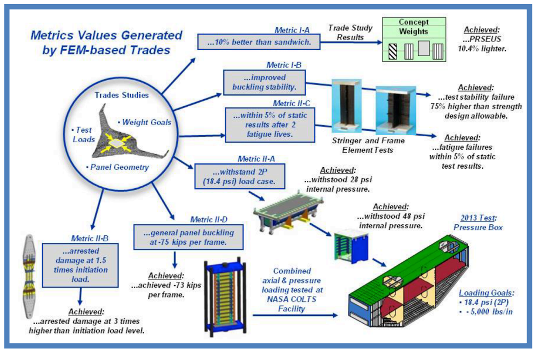
Airframe and Engine Integration Concepts for Community Noise and Fuel Burn Reductions
Demonstrate reduced component noise signatures leading to 42 EPNdB to Stage 4 noise margin for the aircraft system while minimizing weight and integration penalties

- 50A: Flap Edge and Landing Gear Noise Reduction
- 51A: UHB Integration for Hybrid Wing Body

Technology Uncertainty Approach

- Each ITD goal is to "mature each technology with required supporting technologies to reduce uncertainty of benefit projection"
- Experimental data collected from the ITD experiments was linked to the system level analysis, which enabled the propagation of uncertainty for performance progression tracking

ITD 21C: Damage Arresting Composites



Experimental Measurements

Forces (Loads)
Strains
Deflections

Uncertainty Sources

- Model fidelity
- Design allowables
- Material stiffnesses
- Panel imperfections
- Panel repairs, etc…

Uncertainty Assessment

Uncertainty Mapping

Weight Estimation Inputs

- Allowable knockdowns
- Minimum M.o.S.
- Material stiffnesses
- Non-Optimal Factor
- Laminate density, etc…

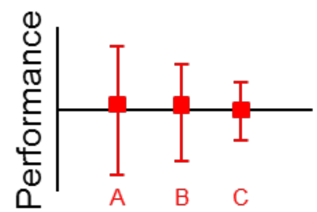
Weight Estimation

Change in Structural Weight

- Centerbody (HWB)
- Wing (HWB)
- Fuselage (T&W)
- Wing (T&W)

KPP: ΔW_S
(Total Vehicle Structure)

FLOPS System Resizing



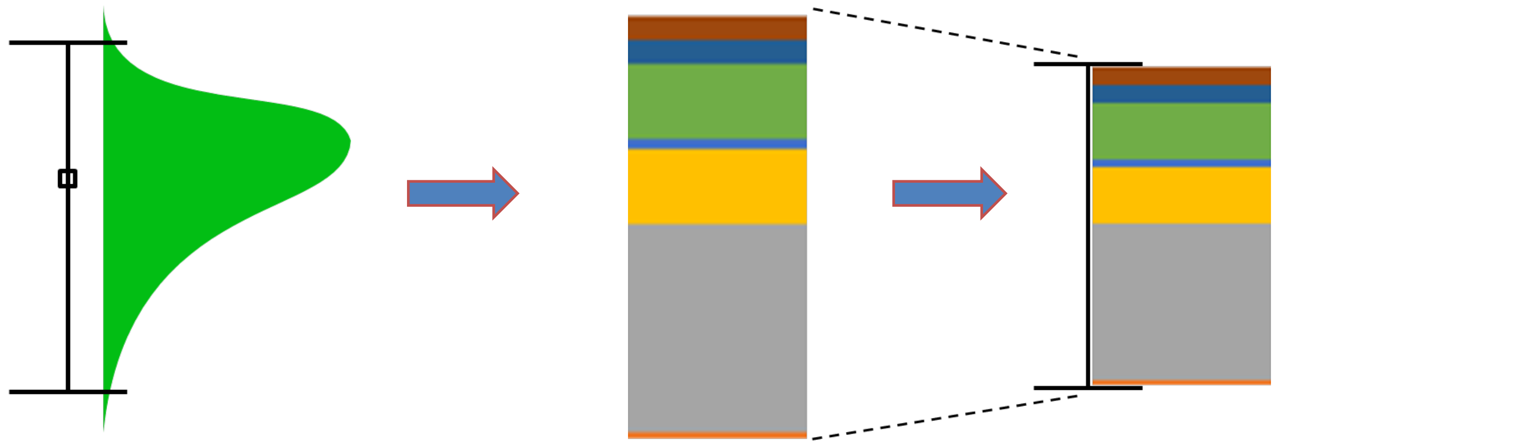
Plans similar to this were performed for each ITD to produce the performance progression over time

Example Uncertainty Assessment Results

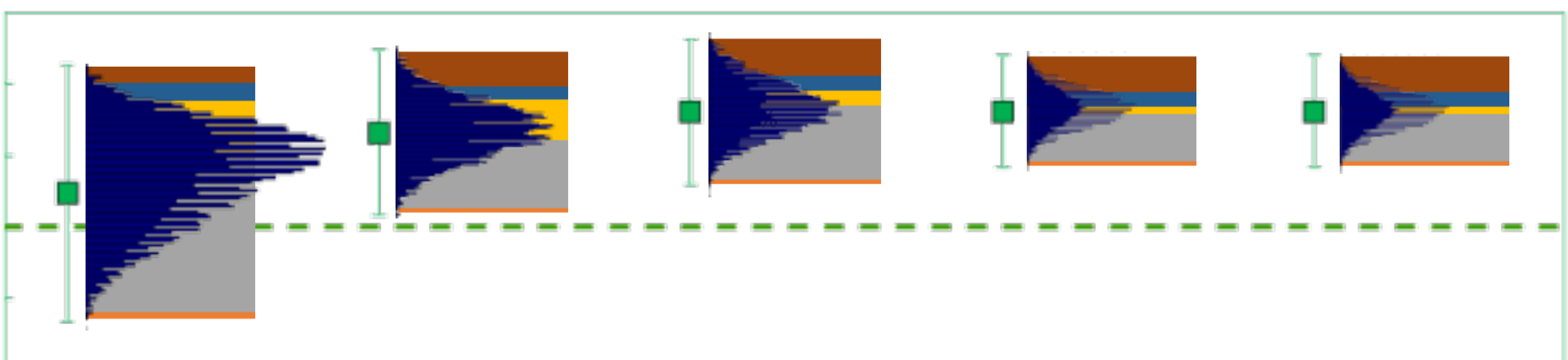
Monte Carlo simulations provide distribution

Sensitivity analysis provides uncertainty source breakdown

Scaled impact - percent contribution remains the same



KPP$_{2025}$ Chart



■ - Represents the statistical mean

**Numbers have been removed to protect proprietary nature of the data

Fleet Level Analysis Approach and Sample Results

Technology Evaluation Process beyond the Vehicle

There are three different levels at which technologies are evaluated in the strategic planning and prioritization dashboard

Technology Assessment Levels

Aircraft Level

Impact of technology implementation at the vehicle level:
- LTO NOx,
- Fuel Burn
- Noise

Airport Level

Impact of technology implementation with local spatial consideration. Accounts for airport specific characteristics.
- Noise contours
- Local NOx

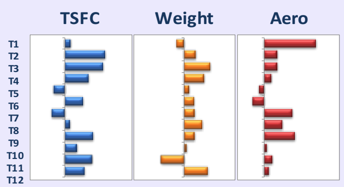
Fleet Level

Impact of technology implementation scaled at the entire US traffic:
- Global NOx - Scaling of the vehicle-level data
- Global fuel Burn - Scaling of the vehicle-level data

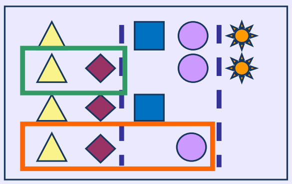
Connecting Vehicle and Fleet Assessments

Technologies

- Benefit
- Cost
- Applicability
- Availability



Technology Roadmaps



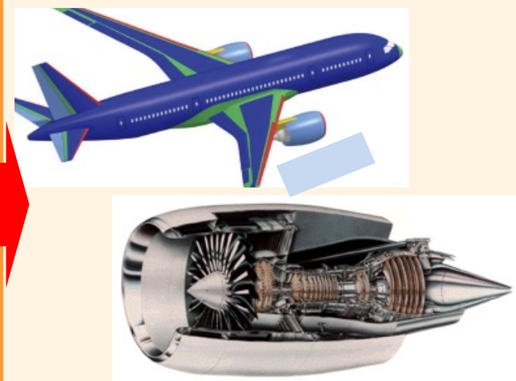
Time

Scenarios

Scenario 1
Scenario 2
⋮

EDS

Generic Vehicles



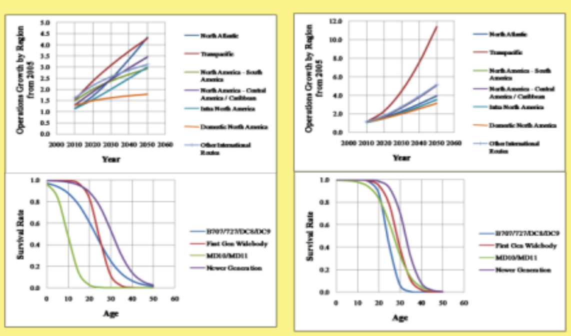
Vehicle Performance Characteristics

AEDT: Aviation Environmental Design Tool

GREAT: Global and Regional Environmental Analysis Trade-off

Operations

- Demand Forecast
- Aircraft Retirements
- Replacements Schedule

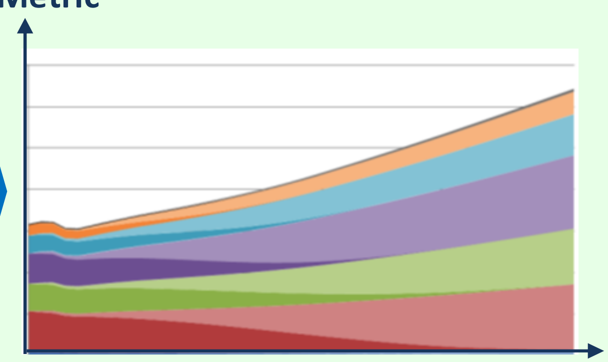


AEDT or GREAT

Fleet Analysis

- FB/Operation
- Total Ops
- Total FB

Fleet Impact



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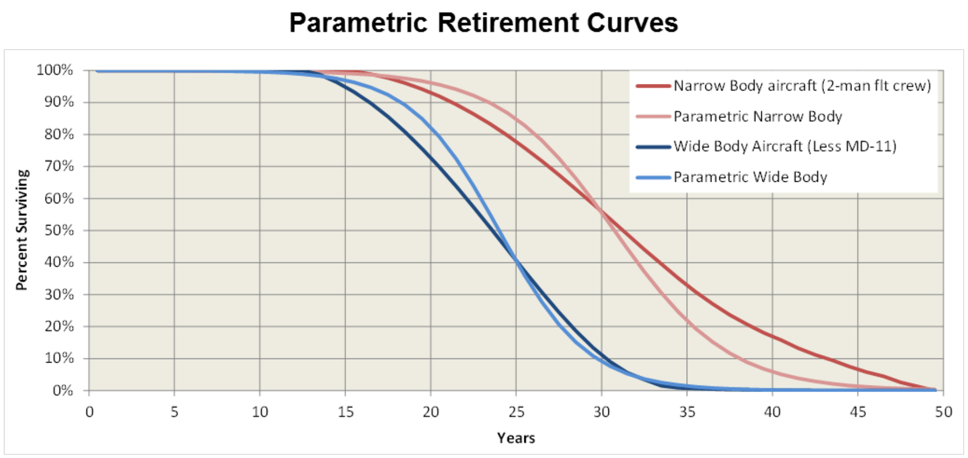
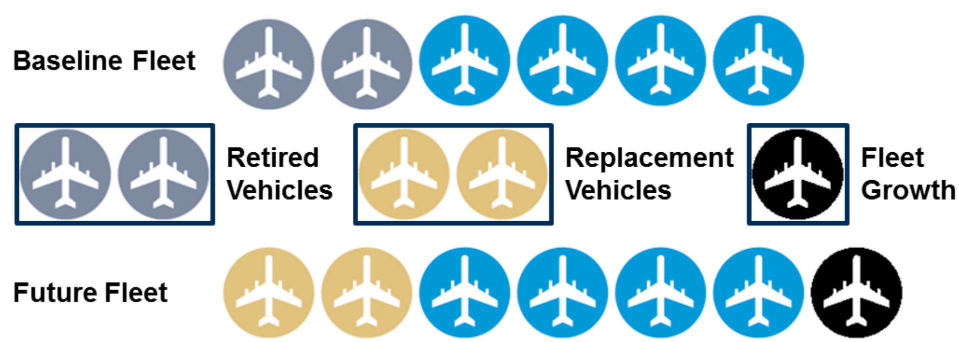
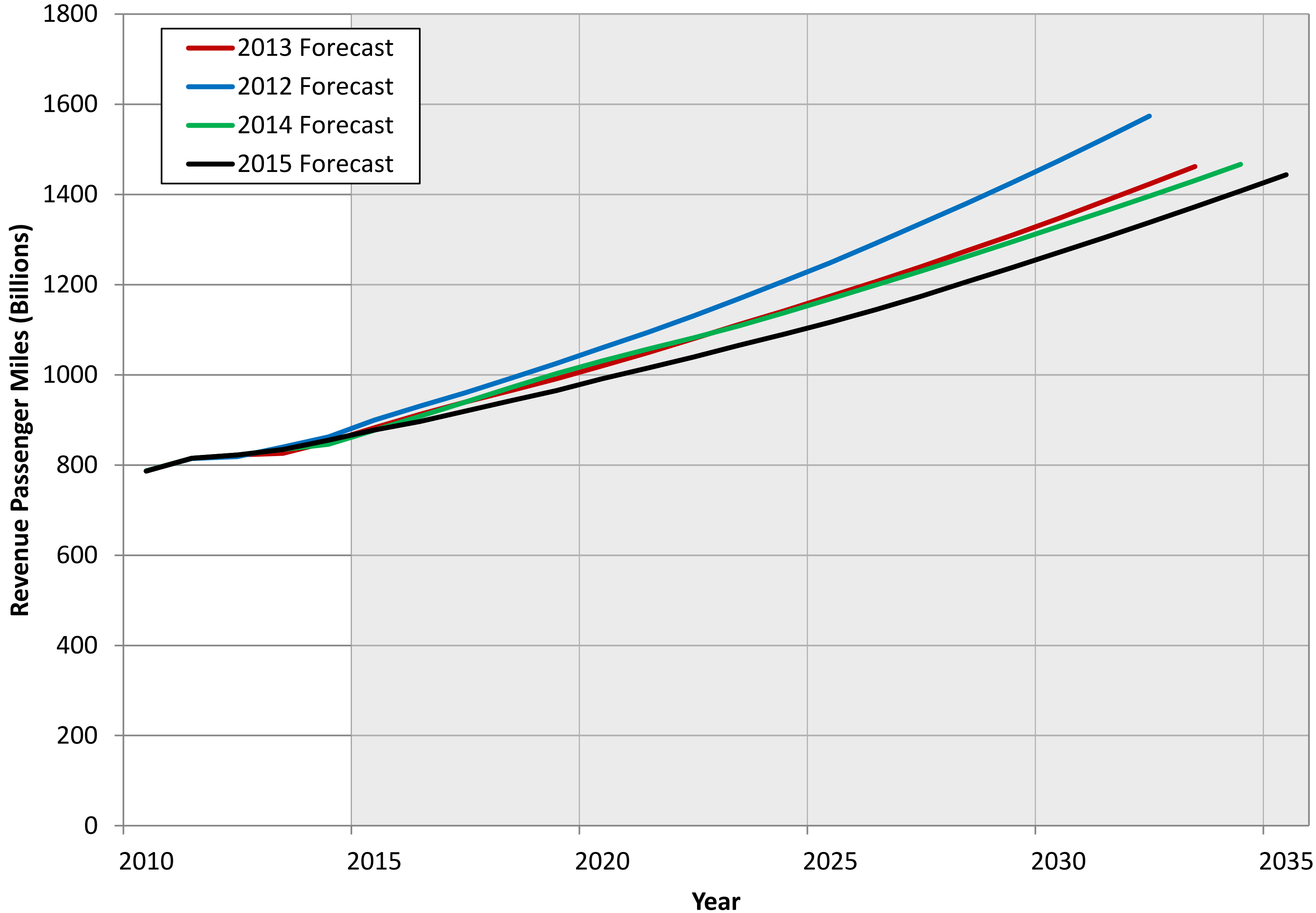
Connecting Vehicle and Fleet Assessments

- To determine future fleet composition, the following need to be considered:
  - Retirements
  - Replacements
  - Fleet growth
- Parametric retirement curves are derived based on historical trends for different vehicle classes
- Advanced technology fleet vehicles are included in the fleet as replacement aircraft and additional aircraft due to demand growt
- The technology level of these advanced aircraft (N+1, N+2, N+3) are determined based on introduction timeframe
- The system assessment has capability to assess both standard and aggressive technology introduction rates



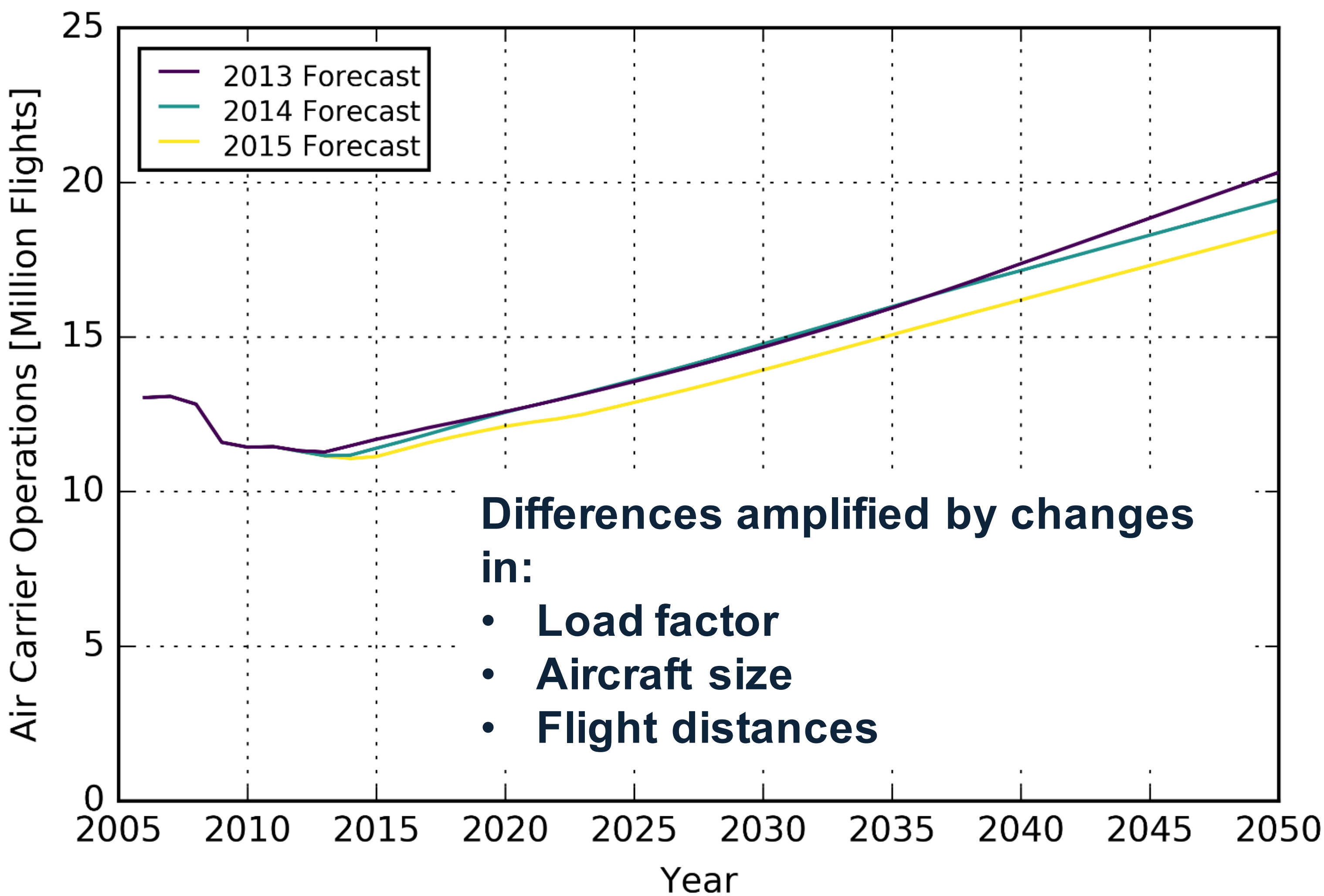


Forecast Changes



Reduced Growth: Recovery slower than expected

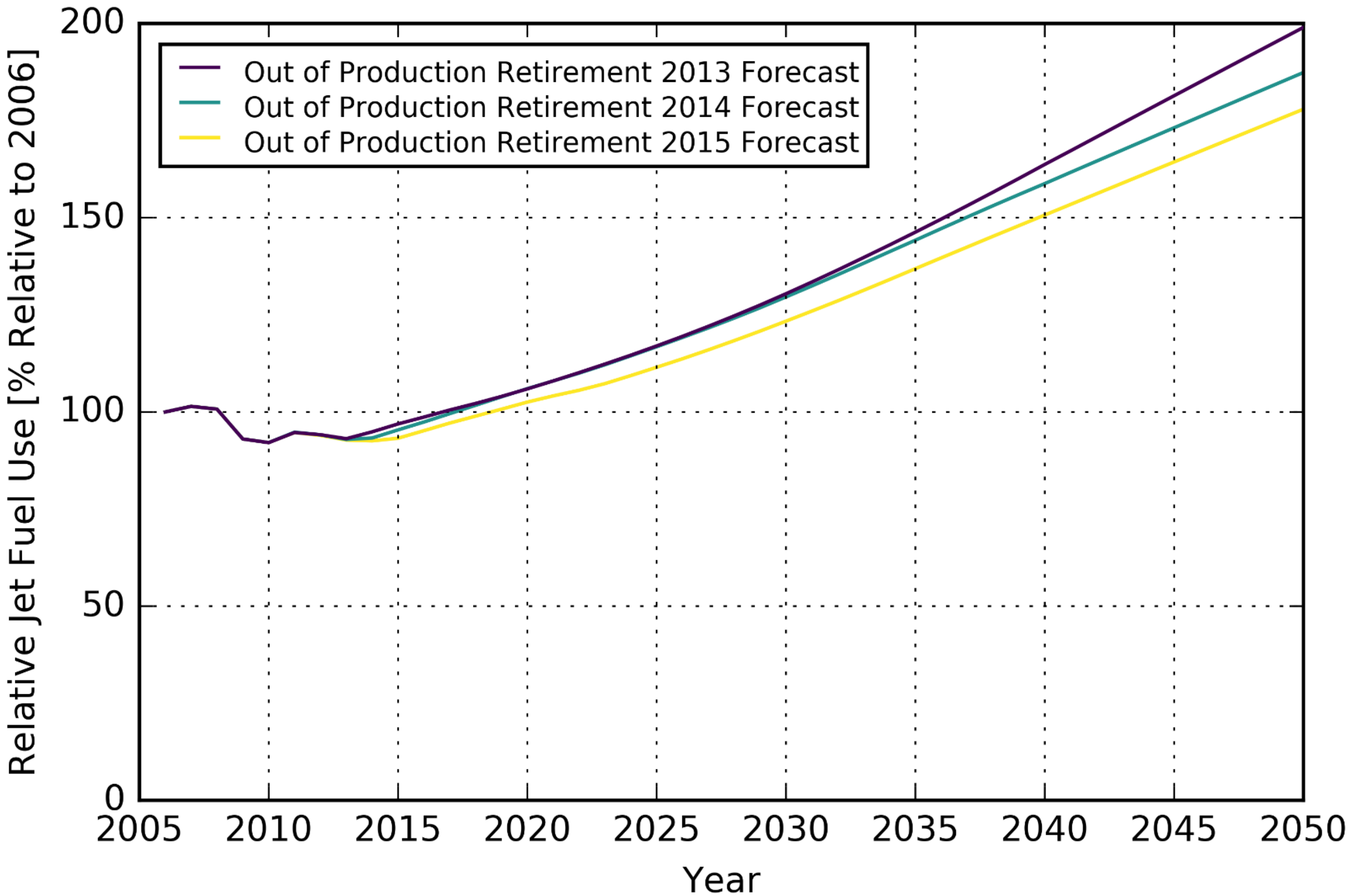
Forecast Operations



Differences amplified by changes in:

- **Load factor**
- **Aircraft size**
- **Flight distances**

Forecast Comparison

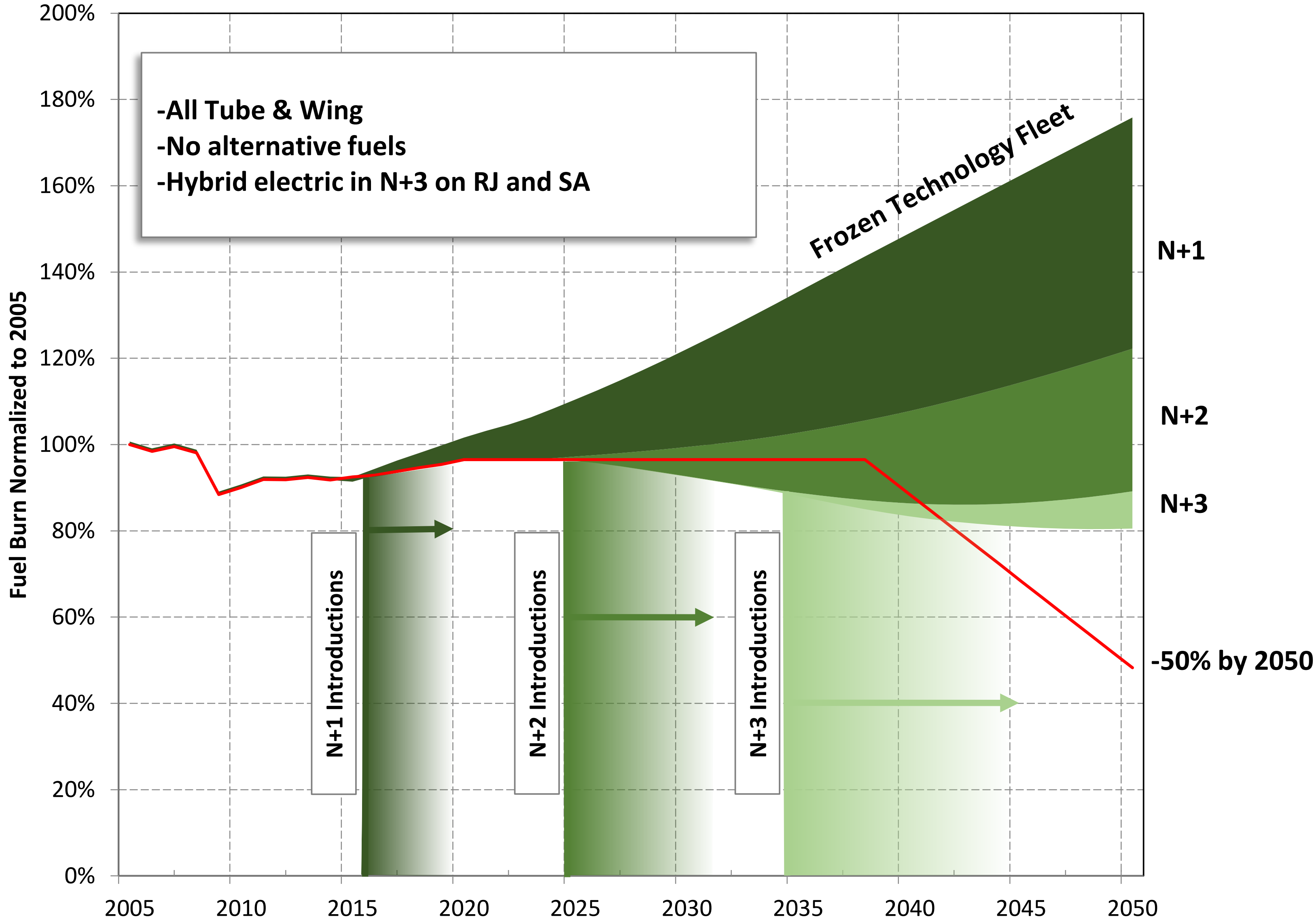


Progressively lowered forecast has major impact on results

Assumptions for N+1, N+2, and N+3 Results

- Airline network scales differentially by airport as per forecast
- Forecast traffic will be possible without increasing delays/inefficiencies (Forecast is used to allocate infrastructure funds to try to meet required capacity)
- Network covers domestic flights (US Air Carrier Operations) plus international departures
- No significant size shift on a per route basis, except
  - Regional jets get larger/somewhat shift to single aisles
  - Single aisle replacements have more seats
- All N+x technologies are available simultaneously in the projected year
- Production line shift to new aircraft requires on average four years to complete
- Retirement of older aircraft does not deviate from historical averages
- Long economic life leads to slow turnover of the fleet so that new aircraft require time to penetrate the operational fleet in significant numbers

Vehicle Technology and Fleet Goals



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Final Remarks

- Developed and implemented a trusted process for system analysis
- Developed technology uncertainty propagation and quantification method that demonstrated uncertainty burn-down
- Generated results for both vehicle system and fleet levels
- Accomplished assessments with inter-agency and industrial partnerships
- Fleet analysis shows that technology impacts at the fleet level will not be seen for several years after introduction until sufficient aircraft have been placed into the fleet
- With the process at hand, you can see how much of gap has been closed and what remains to be accomplished next