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An Assessment of NASA Aeropropulsion Technologies—A System Study

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Abstract

Aviation industry's robust growth rate has given rise to growing concerns about the contribution that aviation emissions will make to local air quality and global climate change. Over the last several years, NASA has been engaged in the development of aeropropulsion technologies with specific objectives to reduce aircraft emissions. A system analysis was performed to evaluate the potential impact of these propulsion technologies on aircraft CO_2 (directly proportional to fuel burn) and NO_x reductions. A large subsonic aircraft, with two 396-kN thrust (85,000-pound) engines was chosen for the study. Performance benefit estimates are presented for each technology, with a summary of potential emissions reduction possible from the development of these technologies. The results show that NASA's aeropropulsion technologies have the potential to significantly reduce the CO_2 and NO_x emissions. The results are used to support informed decision-making on the development of aeropropulsion technology portfolio for CO_2 and NO_x reductions.

Introduction

Because of aviation industry's rapid growth rate, there is increasing concern over local air quality and global climate change impacts of air transportation. In 2003, the transportation sector accounted for about 27% of total US greenhouse gas emissions, with aircraft contributing 9% of the transportation sector total.[1] Because of strong growth in demand, aviation is projected to contribute an increasingly larger share of CO_2 and NO_x, against a background of emissions reductions from many other sources.[2] If not addressed, environmental impacts may well be the fundamental constraint on air transportation growth in the 21st century.

Improvements in propulsion system technology have continuously reduced the amount of emissions generated from aircraft over the past fifty years, and are expected to continue to do so to minimize the effect of aviation growth.[3] Over the last several years, NASA has been engaged in the development of aeropropulsion technologies with specific objectives to reduce aircraft emissions. These technologies feature weight-reduction and/or efficiency improvement to specifically reduce fuel consumption (and hence CO_2), and improved combustor design to reduce NO_x emissions. Two specific development projects are described herein. They are the NASA *Ultra Efficient Engine Technology (UEET)* project and *Intelligent Propulsion System (Propulsion 21) Technology* project.

A probabilistic system assessment is performed to quantify the potential of these advanced technologies on aircraft CO_2 and LTO (landing and takeoff) NO_x reductions. The statistical approach quantifies the uncertainties inherent in these new propulsion technologies and their influence on the likely outcomes of engine performance. Consequently, it provides additional insight into the risks associated with new technologies, which are often needed by the decision-makers to determine the benefit and return-on-investment of new propulsion technologies.

UEET Project

The *UEET* project was designed to develop advanced propulsion and propulsion/airframe integration technologies with specific objectives to reduce aircraft CO_2 (or fuel burn) and NO_X, relative to state-of-the-art systems. Initially, the technology portfolio included adaptive and control technologies, which were later book-kept under the *Propulsion 21* project. Its most-recent portfolio featured advanced aeropropulsion technologies that included:

Tech no.	Technology name
tech-1	Advanced low NO_x combustor
tech-2	Highly loaded compressor technology
tech-3	Highly loaded high-pressure turbine system
tech-4	Highly loaded low-pressure turbine system
tech-5	Ceramic matrix composite (CMC) turbine vane
tech-6	CMC combustor liner
tech-7	Low conductivity ceramic thermal barrier coating (TBC) for turbine airfoils
tech-8	Advanced turbine airfoil and disk alloys

These technologies are described in Table 1.

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Propulsion 21 Project

The Intelligent Propulsion System Technology (*Propulsion 21*) project focused on developing adaptive technologies that would enable commercial gas turbine engines to reduce fuel burn, produce fewer emissions and less noise while increasing reliability. The primary classes of adaptive technologies are flow control, structural control, combustion control, and also enabling technologies that are applicable to each. The entry into service date for most of these technologies was targeted for 2008 to 2012. The project featured adaptive technologies that included:

Tech no.	Technology name
tech-9	Active tip-clearance control for fan
tech-10	Active tip-clearance control for high-pressure compressor (HPC)
tech-11	Active tip-clearance control for high-pressure turbine (HPT)
tech-12	Active tip-clearance control for low-pressure turbine (LPT)
tech-13	Active flow control for LPC
tech-14	Active flow control for HPC
tech-15	Turbine aero-thermal and flow control for HPT and LPT
tech-16	Active combustion control for lean direct injection (LDI) combustor
tech-17	Smart fan containment system
tech-18	High-temperature wireless data communication technology

These technologies are described in Table 2.

Analysis Approach and Procedures

Expert Opinion Elicitation

Expert opinions are an appropriate means of decision support when the scientific research contains few high-quality scientific studies and a valid research synthesis cannot be conducted—a situation that often occurs during the early or "emerging" phase of a technology. An effective expert opinion elicitation process is crucial for performing assessment of emerging technology. More details on the utilization of expert opinion can be found in References 4 and 5. For the current assessment, an expert opinion elicitation process based on the Delphi method[6] is used to elicit opinions from the NASA technologists identified as the domain experts for each of the technologies. The Delphi method is a structured process for collecting and distilling knowledge from a group of experts by means of a series of questionnaires and interviews interspersed with controlled opinion feedback. The focus of the elicitation is to identify the applicable set of propulsion technologies for the vehicle of interest, gather the required information, and compile the data necessary for the system analysis.

The Beta Distribution

Based on the information obtained from the technologists, the 3-point estimates (maximum, minimum, and most-likely values) of the impacts (positive and/or negative) for each of the technologies are quantified. They are summarized in Tables 3 and 4.

For the current assessment, the beta distribution is used to quantify the uncertainties. In practice, in the absence of real measured data, one should try different distributions to see if the results change significantly. If they do, more expert opinions are needed.

A four-parameter beta distribution is created for each of the technologies. The probability density function (PDF) of the beta distribution is:

$$f(x) = \frac{1}{B(p,q)} \frac{(x-a)^{p-1}(b-x)^{q-1}}{(b-a)^{p+q-1}} \tag{1}$$

and the cumulative density function (CDF) is

$$CDF(t) = \frac{1}{B(p,q)} \int_0^t y^{p-1}(1-y)^{q-1} dy \tag{2}$$

with the transformation

$$t = \frac{(x-a)}{(b-a)}$$

where the parameters a and b are the minimum and maximum values of the variable x, respectively; p and q are the distribution shape parameters and B is the beta function defined by

$$B(p,q) = \frac{\Gamma(p)\cdot\Gamma(q)}{\Gamma(p+q)} = \int_0^1 t^{p-1}(1-t)^{q-1} dt \tag{3}$$

The shape parameters p and q depend on whether the mode (most-likely value) is to the left or right of the midrange. They are determined using the method described in Reference 7. These three equations are solved numerically, and are coupled with the Fast Probability Integration (FPI) computer code.[8] Together, they are used to perform the probabilistic system simulation of the propulsion technologies.

System Analysis

In an era of shrinking development budgets and resources, a system analysis, performed in the early stages of a technology program, is critical to the successful development of new aeronautics technologies. It assesses the impact of a new technology on the aircraft system, in terms of the metrics such as fuel burn, emissions and noise reductions, etc.

For the current assessment, the system analysis simulates the thermodynamic cycle using NPSS

Table 1: Description of UEET Technologies

Tech no.	Technology description
tech-1	*Advanced low NOx combustor*—a low NO_x emission combustor concept features lean burning concept.
tech-2	*Highly loaded compressor technology*—technology that will enable higher compressor stage work factors. Lower system weight, improved overall performance will result in lower fuel burn and lower CO_2.
tech-3	*Highly-loaded high-pressure turbine (HPT) system*—technology that will allow reduction in number of turbine stages and hence reduction part counts and cooling air requirements, which will result in CO_2 (or equivalent fuel burn) reduction.
tech-4	*Highly-loaded low-pressure turbine (LPT) system*—technology covers development of LPT and aggressive transition duct. Both of these technologies use flow control technique and will reduce number of LP stages.
tech-5	*Ceramic matrix composite (CMC) turbine vane*—CMC that will allow HPT vanes to operate at significantly higher turbine inlet temperature (hence reduce the cooling), which will result in CO_2 reduction.
tech-6	*CMC combustor liner*—CMC technology that will allow combustor liners to operate at higher liner temperatures, which will result in NO_x reductions.
tech-7	*Low conductivity ceramic thermal barrier coating (TBC) for turbine airfoils*—TBC that will allow turbine airfoils to operate at significantly higher temperatures, which will result in CO_2 reduction.
tech-8	*Advanced turbine airfoil and disk alloys*— (1) light-weight single crystal super-alloy with improved temperature capability that will allow turbine blades and vanes to operate at higher operating temperatures, which will result in CO_2 reduction. (2) dual microstructure nickel base super-alloy turbine disks which can be tailored to optimize the disk behavior in high-temperature environment.

Table 2: Description of Intelligent Propulsion System (*Propulsion 21*) Technologies

Tech no.	Technology description
tech-9	*Active tip* clearance *control applied to the fan casing*—this technology has an estimated gain on fan efficiency. The fan casing is constructed with shape memory alloy (SMA) and actively controlled through electric heating. A weight increase is assumed for the casing.
tech-10	*Active tip clearance control applied to the high-pressure compressor (HPC) casing*—this technology has an estimated increase on HPC efficiency. The clearance control, utilizing SMA, is added to all stages.
tech-11	*Active tip clearance control applied to the high-pressure turbine (HPT)*—the SMA material is envisioned to be applied to the casing. The turbine is sufficiently hot enough that the SMA material would be passively controlled by the temperature difference between takeoff and cruise. This technology's primary benefit is an efficiency increase for the HPT of a deteriorated engine.
tech-12	*Active tip clearance control applied to the low-pressure turbine (LPT)*—this technology has the same properties and benefits as the one for the HPT.
tech-13	*Active flow control applied to LPC*—active and passive flow control technology to enable higher LPC blade loading, improved compressor efficiency and operation stability.
tech-14	*Active flow control applied to HPC*—this technology has the same properties and benefits as the one for the LPC.
tech-15	*Turbine aerothermal and flow control technology for HPT and LPT*—to develop flow control schemes in turbines to enable safer operation of highly loaded blades in high/low pressure components.
tech-16	*Active combustion control technology for lean direct injection (LDI) combustor*—provides closed loop, dynamic control of fuel injection, fuel air mixing, and staging of fuel sources. It focuses on 3 areas: combustion instability control, burner pattern factor control, and emission minimizing control. The technology is focused primarily on NO_X reduction.
tech-17	*Smart fan-containment system*—smart material/structural concepts for improved (lighter) weight, impact damage tolerance, and noise-reducing fan containment case.
tech-18	*High-temperature wireless data communication technology*—electronics with a high-temperature capability (~600 °C) for wireless power transmission and data communication.

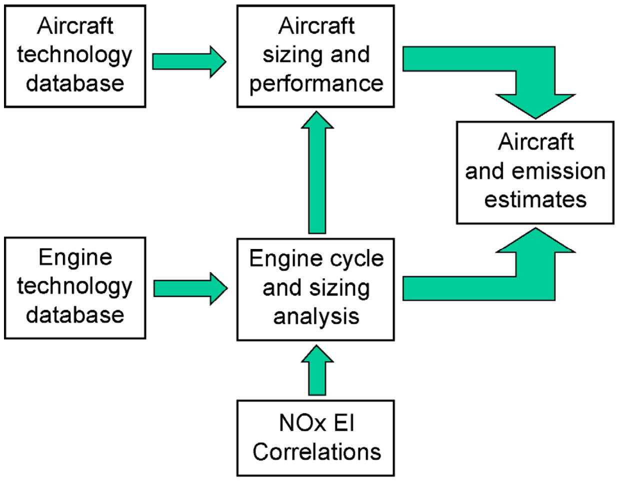

Figure 1: System analysis schematic.

(Numerical Propulsion System Simulation),[9] engine weight estimation is done using WATE (Weight Analysis of Turbine Engines),[10, 11] and aircraft mission sizing is done using FLOPS (FLight OPtimization System).[12] The system analysis schematic is shown in Figure 1.

The computer code NPSS is used to calculate engine thrust, specific fuel consumption and LTO NO_x emissions. The engine weight is calculated by the WATE code. The results from NPSS and WATE are used by FLOPS for performing airplane mission and sizing analyses, and ultimately calculate the CO_2 emission (or fuel-burn) based on a 5556-kilometers (3000 nautical miles) economic mission.

Probabilistic Analysis

In a system analysis that involves several design parameters, X_i, with uncertainties, it is often desired to find the probability of achieving response value (Z) below a critical value of interest Z_0. This critical value can be used to form a limit state function $g(X)$, which can be described as:

$$g(X) = Z(X_1, X_2, X_3, \ldots \ldots Xn) - Z_0 \tag{4}$$

where values of $g(X) \geq 0$ are undesirable. Here the objective would be to compute probability $P[g(X) \leq 0]$. Given the joint probability density function $f_X(x)$ of the limit state function $g(x)$, we can formulate the limit-state probability $P[g \leq 0]$ as

$$P = P[g(X) \leq 0] = \int_{\Omega} \ldots \int f_X(x)dx \tag{5}$$

where Ω describes the domain of integration. This multiple integration is, in general, very difficult to integrate analytically. Many approximation methods, such as Monte Carlo simulation, have been developed to evaluate the equation (5). For large-scale high fidelity problems, the inefficiency of Monte Carlo simulation renders it impractical for use. Many efficient methods have been developed to alleviate the need for Monte Carlo simulation. These methods include the first and second- order reliability method (FORM and SORM),[13] the advanced mean value family of methods (AMV),[14] and the response surface method (RSM).[15] These methods replace the original deterministic model with a computationally efficient analytical model in order to speed up the analysis.

For more than a decade NASA Glenn has been engaged in developing efficient probabilistic methods. As a result of this intensive effort, the computer code, FPI (fast probability integration), was developed to solve a large class of engineering problems. FPI was developed by Southwest Research Institute for NASA Glenn.[16] It offers several techniques to find the probability of a given limit state function value for the response function. For the current assessment, an advanced first-order reliability method is used. This method, based on the most-probable-point (MPP) concept frequently used in structural reliability analysis, is one of the several methods in the FPI code. The role of FPI is to perform probabilistic analysis utilizing the results generated by NPSS, WATE, and FLOPS. A schematic of the integrated approached is shown in Figure 2.

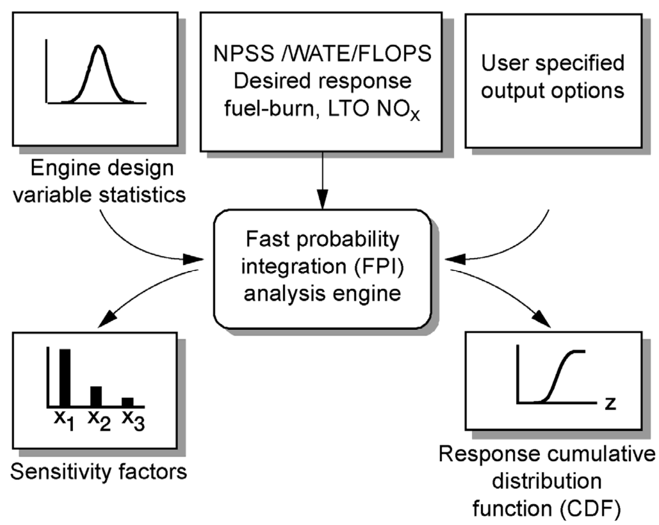

Figure 2: Fast probability integration input/output schematic.

LTO NO_x Emissions

The LTO (landing and takeoff) NO_x emissions are computed based on engine fuel flow and the combustor emission index (EI). Fuel flow itself is a strong function of power setting during the LTO cycle, which involves four different throttle modes mandated by the ICAO (International Civil Aviation Organization): 10% (takeoff), 85% (climb), 30% (approach), and 7% (idle). Time in mode is simulated as follows: 0.7 minute for takeoff, 2.2 minutes for climb, 4 minutes for approach,

Table 3: UEET Technologies and Their Uncertainties for a Large Subsonic Transport

Technology Identification	Technology	Baseline values	Maximum benefit (and/or minimum penalty)	Minimum benefit (and/or maximum penalty)	Most-likely benefit (and/or most-likely penalty)
tech-1	Advanced low NO_x combustor	AST correlation	75% LTO NO_x reduction correlation	70% LTO NO_x reduction correlation	72% LTO NO_x reduction correlation
tech-2	Highly-loaded compressor	0.2745 HPC work factor; 0.9066 HPC poly. eff.	+45% HPC work factor –0.16 pt HPC poly. eff.	+27% HPC work factor –1.16 pts HPC poly. eff.	+38% HPC work factor –1.66 pts HPC poly. eff.
tech-3	Highly-loaded HP turbine	0.848 loading; 0.92 adia. eff.	+21% HPT loading +0.5 pt. adia. eff.	+19% HPT loading –0.5 pts. adia. eff.	+20% HPT loading
tech-4	Highly-loaded LP turbine	1.25 loading; 0.93 adia. eff. 0% bleed	+30% LPT loading +3 pts. LPT adia. eff. +0.5% HPC bleed	+25% LPT loading +1.0 pt. adia. eff. +2.0% HPC bleed	+28% LPT loading +2 pts. adia. eff. +0.5% HPC bleed
tech-5	CMC turbine vane	1366 K (2460 °R) vane temp. Nickel-based alloy 1st stage vane	+389 K (700 °R) HPT vane temp. CMC 1st stage HPT vane	+361 K (650 °R) HPT vane temp. CMC 1st stage HPT vane	+389 K (700 °R) HPT vane temp. CMC 1st stage HPT vane
tech-6	CMC combustor liner	15% cooling flow	reduce cooling flow by 60%	reduce cooling flow by 53%	reduce cooling flow by 57%
tech-7	Low conductivity thermal barrier coating (TBC) for turbine airfoil	1366 K (2460 °R) 1st stage HPT vane temp.; 1329 K (2360 °R) rest of the HPT and LPT blades and vanes temp.	+167 K (300 °R) HPT & LPT blade and vane temp. (reduce cooling flow)	+83 K (150 °R) HPT & LPT blade and vane temp. (reduce cooling flow)	+111 K (200 °R) HPT & LPT blade and vane temp. (reduce cooling flow)
tech-8a*	Advanced turbine airfoil and disk alloys	HPT blades and vanes temp. same as above; Hi-temp nickel-base alloy HPT blades and vanes	+56 K (100 °R) HPT blade and vane temp. (reduce cooling flow); –3.85% HPT blade & vane densities	+28 K (50 °R) HPT blade and vane temp. (reduce cooling flow)	+43 K (78 °R) HPT blade and vane temp. (reduce cooling flow) –2.24% HPT blade & vane densities
tech-8b*	Advanced turbine airfoil and disk alloys	LPT blades and vanes temp. same as above; Hi-temp nickel-base alloy LPT blades and vanes	+57 K (102 °R) LPT blade and vane temp. (reduce cooling flow); –4.15% LPT blade and vane densities	+44.4 K (80 °R) LPT blade and vane temp. (reduce cooling flow) –0.32% LPT blade and vane densities	+52 K (94 °R) LPT blade and vane temp. (reduce cooling flow); –2.56% LPT blade and vane densities

*Note: results of tech 8a and 8b are combined to show the benefit of advanced turbine airfoil and disk alloys technology

Table 4: Intelligent Propulsion System Technologies and Their Uncertainties for a Large Subsonic Transport

Technology identification	Technology	Baseline value	Maximum benefit (and/or minimum penalty)	Minimum benefit (and/or maximum penalty)	Most-likely benefit (and/or most-likely penalty)
tech-9	Active tip-clearance control for fan	0.90 fan poly. eff., 7435 kg (16392 lbs.) engine dry weight, 74.5 kW (100 hp) power extraction total for the system	+1.00 pt fan poly. eff., +9 kg (+15 lbs) eng. wt. +0.37 kW (0.5 hp) power requirement	+0.00 pt fan poly. eff., +15 kg (+25 lbs) eng. wt. +1.12 kW (1.5 hp) power requirement	+0.50 pt. fan poly. eff., +12 kg (+20 lbs) eng. wt. +0.75 kW (1 hp) power requirement
tech-10	Active tip-clearance control for HPC	0.90 HPC poly. eff., 7435 kg (16392 lbs.) engine dry weight,	+0.50 pt HPC poly. eff, +6 kg (10 lbs) engine wt. +0.37 kW (0.5 hp) power requirement	+0.25 pt HPC poly. eff., +12 kg (20 lbs) engine wt. +0.75 kW (1 hp) power requirement	+0.40 pt HPC poly. eff., +9 kg (15 lbs) eng. wt. +0.37 kW (0.5 hp) power requirement
tech-11	Active tip-clearance control for HPT	0.93 HPT adia. eff.	+1.00 pt HPT adia. eff +6 kg (10 lbs) engine wt.	+0.65 pt HPT adia. eff. +12 kg (20 lbs) engine wt.	+0.90 pt HPT adia. eff +9 kg (15 lbs) engine wt.
tech-12	Active tip-clearance control for LPT	0.93 LPT adia. eff.	+0.20 pt. LPT adia. eff. +6 kg (10 lbs) engine wt.	+0.00 pt. LPT adia. eff. +12 kg (20 lbs) engine wt.	+0.10 pt. LPT adia. eff. +9 kg (15 lbs) engine wt.
tech-13	Active flow control for LPC	0.90 LPC poly. eff.	+2.0 pt. LPC poly. eff	+1.0 pt. LPC poly. eff	+1.5 pt. LPC poly. eff
tech-14	Active flow control for HPC	0.90 HPC poly. eff.	+2.0 pt. HPC poly. eff	+1.0 pt. HPC poly. eff	+1.5 pt. HPC poly. eff
tech-15	Turbine aero-thermal and flow control for HPT and LPT	1449 ºC (2640 ºF) T41, 23% of HPC flow used for turbine cooling	+222ºC (400ºF) T41, +1 pt. HPT adia. eff, reduce turbine cooling by 25%, +2 pt. LPT adia. eff.	+56ºC (100ºF) T41, +.25 pt. HPT eff, reduce turbine cooling by 5%, +1 pt. LPT eff.	+83ºC (150ºF) T41, +.5 pt. HPT eff, reduce turbine cooling by 10%, +1.5 pt. LPT eff.
tech-16**	Active combustion control for LDI combustor	LTO NOx -31.5% below 1996 ICAO rule, 7435 kg (16392 lbs.) engine dry weight,	Additional 6% LTO NOx reduction, -33ºC (-60ºF) T4 margin , +9 kg (+15 lbs) eng. wt., +1 HP power requirement	Additional 2% LTO NOx reduction, -11ºC (20ºF) T4 margin , +15 kg (+25 lbs) eng. wt., +2 HP power requirement	Additional 4% LTO NOx reduction, -22ºC (40ºF) T4 margin , +12 kg (+20 lbs) eng. wt., +1.5 HP power requirement
tech-17	Smart fan containment system	2768 kg/m^3 (0.1 lbs/in^3) case material density	–50% fan case wt.	–10% fan case wt.	–25% fan case wt.
tech-18	High-temperature wireless data communication technology	7435 kg (16392 lbs.) engine dry weight	–113 kg (–250 lbs) engine wt.	–48 kg (–105 lbs) engine wt.	–77 kg (–170 lbs) engine wt.

**Note: benefit due to control/adaptive technology only; benefit of LDI combustor technology not considered and 26 minutes for taxi-ground idle. The sum of the emissions at these four conditions is used to determine the amount of NO_x emitted per LTO cycle. The calculation is:

$$\text{LTO NOx} = \sum \text{fuel flow x EINOx x time in mode} \qquad (6)$$

The EI correlation used for the current calculation is based on the lean combustor flame-tube tests[17] and is defined as:

$$EI_{NOx} = K(P_{t3})^{0.5945}\exp[(T_{t3} - 459.67)(0.002867)] \times (FAR/delphi)^{1.6876}[(1 - P_{t4}/P_{t3})x100]^{-0.5651} \qquad (7)$$

where

K	technology constant
P_{t3}	combustor inlet total pressure, psia
P_{t4}	combustor exit total pressure, psia
T_{t3}	combustor inlet total temperature, Rankine
FAR	fuel air ratio
delphi	1 – fraction of combustor inlet air used for liner cooling

Results and Discussion

For the UEET technologies, the results of individual technology impacts on aircraft CO_2 emission, at 75% and 95% probability levels, are shown in Figure 3. They are relative to those of the current state-of-the-art 300-passenger airplane (baseline). They show that most of the technologies are beneficial toward reducing CO_2 emission, with tech-4 (*highly-loaded LPT*), tech-7 (*low conductivity thermal TBC for turbine airfoil*) and tech-8 (*advanced turbine airfoil and disk alloys*) show particular promise. Tech-2 (*highly loaded compressor technology*) has a negative impact on the CO_2 emission. The component-efficiency penalty associated with this technology increases the SFC (specific fuel consumption) significantly. The advanced *low NOx combustor* technology (tech-1) shows no impact on CO_2 emission, but its target benefit is NO_x reduction which is shown below. Other technologies have minimal impact on CO_2 emission. Cumulatively at 95% probability level, the eight UEET technologies can potentially reduce CO_2 emission by 9.4%, as shown in Figure 4.

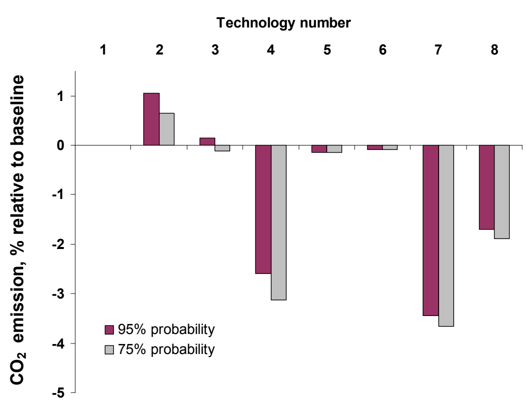

Figure 3: Individual *UEET* technology impacts on CO_2 emission.

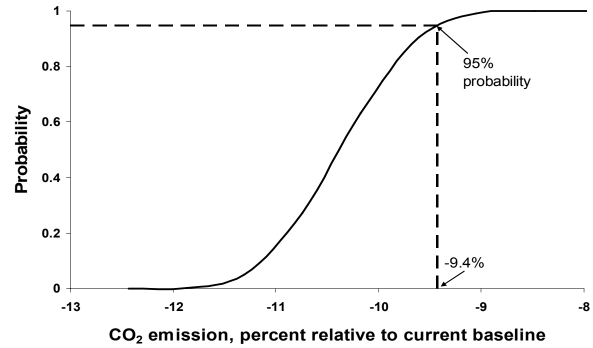

Figure 4: Cumulative distribution function of CO_2 emission – from *UEET* technologies.

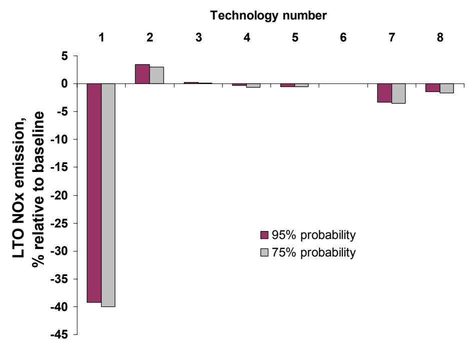

Figure 5: Individual *UEET* technology impacts on LTO NO_x emissions.

The results of individual technology impacts on LTO NO_x emissions, at 75% and 95% probability levels, are shown in Figure 5. They are relative to those of the current state-of-the-art 300-passenger airplane (baseline). They show that tech-1 (*advanced low-NO_x combustor*) has the dominant impact on the LTO NO_x emissions. Tech-2 (*highly loaded compressor*) has a negative impact on the LTO NO_x. The component-efficiency penalty associated with this technology increases the SFC significantly, which also increases the LTO NO_x emissions. Cumulatively at 95% probability level, excluding tech-2, the seven UEET technologies can potentially reduce LTO NO_x emissions by 42% relative to the current baseline (or 73% reduction relative to 1996 ICAO standard), as shown in Figure 6.

For the *Propulsion 21* technologies, the results of individual technology impacts on aircraft CO_2 emission

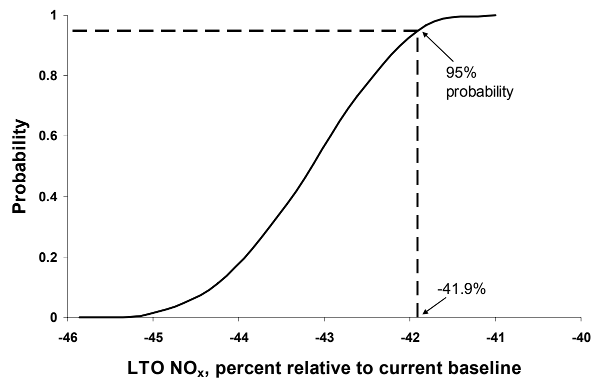

Figure 6: Cumulative distribution function of LTO NO_x emission – from *UEET* technologies.

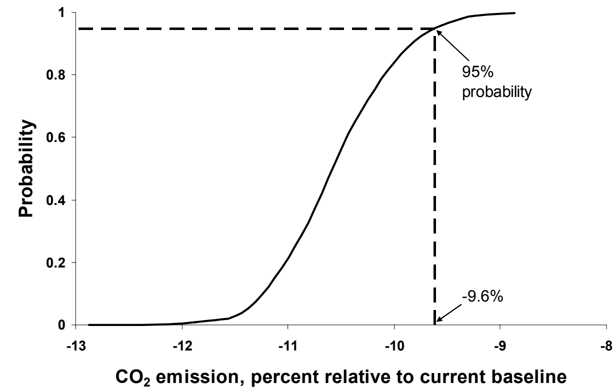

Figure 8: Cumulative distribution function of CO_2 emission – from *Propulsion-21* technologies.

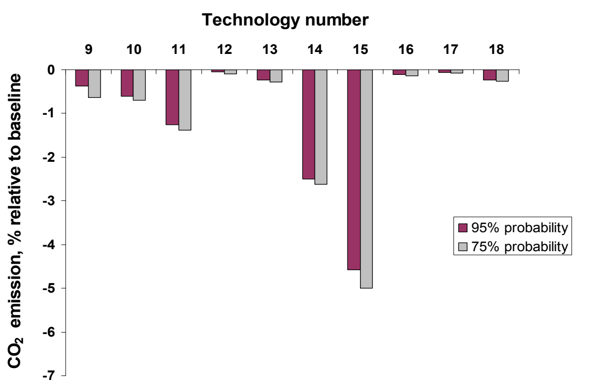

Figure 7: Individual *Propulsion-21* technology impacts on aircraft CO_2 emission.

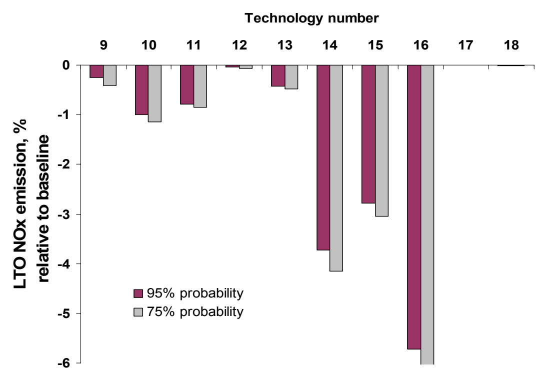

Figure 9: Individual *Propulsion-21* technology impacts on LTO NO_x emissions.

are shown in Figure 7. They are relative to those of the current state-of-the-art 300-passenger airplane (baseline). They show that all of the adaptive technologies are beneficial toward reducing CO_2 emissions, with flow control technologies tech-15 (*turbine aero-thermal and flow control for HPT and LPT*) and Tech-14 (*active flow control for HPC*) show particular promise. For the structural control technologies, a large benefit is possible from the tech-11 (*advanced HPT tip-clearance control technology*). The impact of tech-9 and tech-10 (*active tip-clearance control technologies for fan and HPC*) are moderate. The tech-16 (*active combustion control technology*) shows relatively small CO_2 reductions, but its target benefit is NO_X reduction which is shown below. Other technologies have minimal benefit on CO_2 reduction. Cumulatively at 95% probability level, the ten adaptive technologies can potentially reduce CO_2 emission by 9.6%, as shown in Figure 8.

The results of individual technology impacts on LTO NO_x emission, at 75% and 95% probability levels, are shown in Figure 9. They are relative to those of the current state-of-the-art baseline. They results show that tech-16 (*active combustor control for LDI combustor*) provides the biggest benefit. Tech-14 (*active flow control for HPC*) and tech-15 (*turbine aero-thermal and flow control for HPT and LPT*) also provide significant benefit. These two flow-control technologies decrease the SFC significantly, which also decrease the LTO NO_x. Other technologies have minimal or no impact on the LTO NO_x emissions. Cumulatively at 95% probability level, the ten adaptive technologies can potentially reduce NO_x emission by 14.5%, as shown in Figure 10.

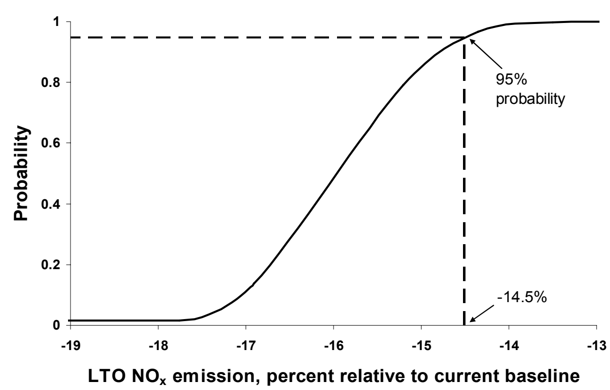

Figure 10: Cumulative distribution function of LTO NO_x emission – from *Propulsion-21* technologies.

All the *Propulsion 21* (adaptive) technology evaluations are based on new engines, using existing baseline engine design. The inclusion of engine degradation models will show significant additional emission-reduction benefits because adaptive technologies inherently compensate for many forms of degradation, such as erosion and wear.

Conclusions

A probabilistic system analysis has been performed to assess the impact of a variety of NASA aeropropulsion technologies on aircraft CO_2 and NO_x emissions. CO_2 reduction was modeled as directly proportional to reduced fuel burn. The results show that these technologies reduce fuel burn and emissions by reducing engine and aircraft weights, improving propulsion efficiency, improved combustor design and combustion control, and have the potential to significantly reduce aircraft CO_2 and NO_x emissions. As a group, the flow-control technologies are the most beneficial for CO_2 reduction. They also provide significant benefit for LTO NO_x reduction. Large benefits are also possible from the Highly-Loaded LPT and Low-Conductivity TBC technologies. For NO_x reduction, the combustor and combustion control technologies show the biggest benefit.

Most of the technologies described are still under development, so the results presented are based on expert predictions of expected benefits and penalties. The fidelity of these assessments will continue to improve as more test data becomes available showing measured performance in relevant conditions. Also, the degree of difficulty (or cost) in technology development and implementation has not been considered in the current study. To prioritize the development of the most promising technologies for CO_2 and NO_x reductions, a cost-benefit analysis should also be performed.

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