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Adaptive Engine Technologies for Aviation CO₂ Emissions Reduction

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Adaptive Engine Technologies for Aviation CO₂ Emissions Reduction

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Abstract

Adaptive turbine engine technologies are assessed for their potential to reduce carbon dioxide emissions from commercial air transports. Technologies including inlet, fan, and compressor flow control, compressor stall control, blade clearance control, combustion control, active bearings and enabling technologies such as active materials and wireless sensors are discussed. The method of systems assessment is described, including strengths and weaknesses of the approach. Performance benefit estimates are presented for each technology, with a summary of potential emissions reduction possible from the development of new, adaptively controlled engine components.

Nomenclature

<i>BWB</i>	=	blended-wing body
<i>CO₂</i>	=	carbon dioxide
<i>FLOPS</i>	=	Flight Optimization System
<i>HP</i>	=	horsepower
<i>HPC</i>	=	high-pressure compressor
<i>HPT</i>	=	high-pressure turbine
<i>IPSFT</i>	=	Intelligent Propulsion Systems Foundation Technology
<i>LPC</i>	=	low-pressure compressor
<i>LPT</i>	=	low-pressure turbine
<i>NO_x</i>	=	oxides of nitrogen
<i>NPSS</i>	=	Numerical Propulsion System Simulation
<i>PAX</i>	=	passenger
<i>REVCON</i>	=	revolutionary concepts
<i>RSE</i>	=	response surface equation
<i>SMA</i>	=	shape memory alloy
<i>UEET</i>	=	Ultra-Efficient Engine Technology
<i>WATE</i>	=	Weight Analysis of Turbine Engines

I. Introduction

EMISSIONS reduction is a worldwide priority. Chemical emissions of concern consist of anything that affects local air quality, global climate, or atmospheric ozone, including CO₂, NO_x, sulfur oxides, water vapor and particulates.¹ The transportation sector accounted for about 27% of total US greenhouse gas emissions in 2003, with aircraft contributing 9% of the transportation sector total, or about 2% of total greenhouse gas emissions.² Aviation is projected to contribute an increasingly larger share of CO₂ emissions as air traffic continues to grow.³ Improvements in 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 aircraft growth.⁴

Aircraft emissions are the by-products of burning jet fuel, and can be reduced by reducing vehicle drag and weight and by improving propulsion system efficiency. This paper addresses adaptive turbine engine technologies being developed to reduce weight and/or improve efficiency to specifically reduce fuel consumption, and hence

CO₂. It should be noted that NO_x generation is a function of the combustor design, and may or may not decrease with decreased fuel burn.

This paper contains a brief description of some representative adaptive turbine engine technologies, followed by a description of the methodology used to assess their benefit for emissions reduction. A table is presented showing potential emissions reduction for each as a function of vehicle class.

II. Adaptive Engine Technologies

There are numerous technologies that are under development to adaptively modify turbine engine performance. These adaptive technologies can lead to improved engine component efficiency and/or reduced weight, both resulting in overall fuel burn reduction. As a rule of thumb, for a large subsonic aircraft a 1000 pound reduction in weight yields a 0.5-0.7% reduction in jet fuel consumed. For carbon based fuels, there is a 1:1 relationship between the amount of fuel burned and the amount of CO₂ generated. Alternative fuels were not considered.

The primary classes of adaptive technologies are flow control, structural control, combustion control, and also enabling technologies that are applicable to each. Representative technologies from each of these classes are briefly described below.

A. Flow Control

Flow control technologies directly manipulate air flow through or around a specific engine component. The manipulation is enacted by actively injecting or extracting air, by inserting small mechanical protuberances into the flow, or by using plasma actuators. Injected air can be supplied by bleed from a rear compressor stage, or by forming “synthetic” jets from a local cavity with an oscillating membrane that cyclically entrains and discharges air. Air injection is then used to energize low momentum regions within the main flow. The protuberances can be actively inserted and retracted based on flow conditions, or they can be designed to passively react to the flow; in both cases the intent is to influence boundary layer separation. Plasma actuators employ electrical actuation rather than pneumatic.

Subsonic inlet flow control can be used, for example, to maintain performance, engine stability, and engine durability under a variety of flow conditions. This leads to shorter and more conformal inlet designs with reduced weight. Since for a large subsonic aircraft engine, inlets can contribute about 10% of the engine system weight, this reduction can be substantial.⁵ For supersonic inlets, bleed drag is often found to be the most significant component of inlet drag at cruise. Therefore, eliminating the bleed drag and the weight and complexity of the bleed system is a major thrust in modern flow control for supersonic inlet design.

Similarly, fan flow control enables the fan to operate with poorer quality flow from the inlet. This can allow a tighter integration of the inlet and fan, providing good performance over a wide range of operating conditions with a shorter, lighter inlet.

Flow control can be used to improve compressor performance by sensing pressure disturbances preceding flow separation, then energizing the air ahead of the separation line. Flow can be controlled through the airfoil to improve flow quality, and in the end-wall region to enable safe compressor operation at reduced stall margins. Both offer the potential to increase aerodynamic loading per blade without reducing aerodynamic efficiency, and thus offer the promise of reducing the number of airfoils (and therefore compressor weight) needed to achieve a given pressure ratio.^{6,7} Reduced stall margins can also enable compressor operation closer to the peak efficiency operating point. For a large subsonic aircraft engine, compressor stages can be 15% of the engine’s weight, and a 1% improvement in high-pressure compressor efficiency can lead to 2% reductions in fuel burn.

Flow control can be used to cool structures as well, such as closed-loop cooling control for turbine blades. By sensing hot-spots as they occur and only cooling as necessary, the total mass of bleed air can be reduced. Bleeding air from the compressor directly reduces the percentage of inlet air available for combustion, so bleed air reduction translates directly into propulsion efficiency improvement.

B. Structural Control

Actively controlling the clearances between rotating blades and shrouds directly improves fan, compressor, and turbine efficiency by reducing leakage through the clearances at each stage. Current engines are designed with sufficient clearance to minimize rubbing during flight. Typically these clearances are sized to prevent rubbing during take-off, and are thus larger than necessary during cruise. Excess clearance allows leakage through the gap, diverting air away from its intended path through the core or bypass ducts. Current open-loop clearance control systems use compressor and/or fan bleed air to cool the case during cruise and therefore close the gap. Closed-loop clearance control promises finer control of the gap while preventing rub-induced component degradation. For a

large subsonic aircraft engine, each 10 mils of excess clearance increases specific fuel consumption by roughly 1%. This will require an increase in exhaust gas temperature margins by about 10 °C,⁸ in order to maintain the same engine thrust level. The ability to maintain tight clearances can provide both a substantial fuel-burn reduction and increased engine life. These closed-loop active clearance control systems require robust, accurate and precise sensors and actuators.⁹

High-temperature, high-loading magnetic bearings and self-tuning vibration absorbers for engine blades can be used to adaptively control structural vibrations.¹⁰ Conical magnetic bearings can also be used for active compressor stall control.¹¹ Prime reliant magnetic bearings can eliminate the need for existing oil systems, reducing the weight of engine peripherals. However, weight penalty can be large if auxiliary bearings are needed to handle blade-out load and as safety backup, in addition to the weight of the electrical power and control systems required for operation.

Variable-area fan nozzles have been considered to enable low fan-pressure-ratio, high bypass-ratio thermodynamic cycles that operate well during both low speed operation (take-off and landing) and high speed cruise. These cycles improve propulsion efficiency, and therefore reduce fuel burn and emissions, although their benefits diminish with increasing fan pressure-ratio. Shape memory alloys have been investigated to provide up to 20% nozzle area variability, and are substantially lighter than conventional hydraulic actuators.¹²

C. Combustion Control

Combustion control technologies are being developed to both enable lean-burning combustors and to directly control the local combustion process thus providing more uniformly efficient burning. A new generation of lean-burning combustors is being developed to reduce emissions, but they are more susceptible to combustion instability and flame-out.¹³ Active combustion control provides closed-loop, dynamic control of fuel injection, fuel air mixing, and fuel source staging to disrupt the coupling between the combustion process and combustor acoustics leading to instabilities.¹⁴ Pressure sensors are used to monitor the combustor acoustics, and control laws are used to dynamically modulate high-response-rate actuators in the fuel line. To achieve uniform burning, sensor arrays determine the planar cross-sectional temperature distribution to drive actuators in individual fuel injectors. The larger the number of fuel injectors, the finer the control of the spatial distribution.

“Pattern factor” control is also being investigated to produce spatially uniform combustion, eliminating hot and cold spots that generate NO_x and CO₂ emissions, respectively. Sensors determine either the local temperature distribution across a cross-section of the combustor, or sense emissions directly for use in closed-loop fuel injector control.¹⁵

D. Enabling Technologies

Adaptive control can be either active or passive. Passive techniques include self-triggered mechanisms such as thermally-triggered shape memory alloys or microstructures triggering flow disturbances after a specific velocity has been reached. Active techniques require at a minimum a sensor, control logic, and an actuator. To achieve these, some subset of sensors, electronics, materials, actuators, wireless communications, power generation, and control logic are required. These technologies do not reduce emissions on their own, but they are critical for the practical embodiment of the aforementioned flow, structural, and combustion control technologies that directly reduce emissions.

Specific sensors of use for adaptive engine components include: temperature and pressure sensors (both static and dynamic), surface and gas; mass flow, surface strain, and blade tip clearance sensors. Applications exist for each of these sensors throughout the engine, including the hot sections of the turbine and nozzle. In addition, specialized sensors for the combustor include fuel flow, chemical species, and temperature sensors that can withstand high temperatures (typically 1000 °C) and can operate in the presence of by-products from burning jet fuel. Not only the sensors need to operate at elevated temperatures; each sensor system typically includes processing electronics, and weight is reduced (hence fuel-burn reduced) by using wireless communications and locally-scavenged power.¹⁶ Actuators are needed for flow control in the inlet, fan, compressor, and turbine; clearance control in the compressor and turbine; and for fuel modulation. Desirable actuator characteristics include fast response times, low weight and bulk, and reliable operation in the engine environment. Active materials such as piezoelectric and shape memory alloys can be used as both actuators and sensors, including in the hot sections.^{17,18}

Finally, control logic must also be included as a critical component of any actively controlled system. Aircraft engines are complex, nonlinear systems with significant interaction between components. Multivariable control methods provide the ability to optimize the performance of the whole system¹⁹ and/or the performance of individual components.^{20,21}

III. Assessment Methodology

E. Systems Analysis Overview

A typical systems analysis effort consists of quantifying the potential impact, both positive and negative, of a new technology against some established baseline. For example, the baseline for the 300-passenger subsonic system is the NASA approximation of a Boeing 777 airplane with an engine that was in service in 1999. An interactive process between the technology expert and system analyst is required to ensure an accurate representation of the technology. Then computational simulations generate the thermodynamic, aero-mechanical and environmental characteristics of the “advanced technology” propulsion system. These data are then utilized by an aircraft synthesis program to resize the baseline aircraft to meet a requisite mission.

For the NASA in-house assessments detailed below, the analysis simulates the thermodynamic cycle using NPSS (Numerical Propulsion System Simulation),²² engine weight estimation is done using WATE (Weight Analysis of Turbine Engines),²³ and aircraft mission sizing is done using FLOPS (FLight OPTimization System).²⁴ A schematic of the integrated approach is shown in Figure 1.

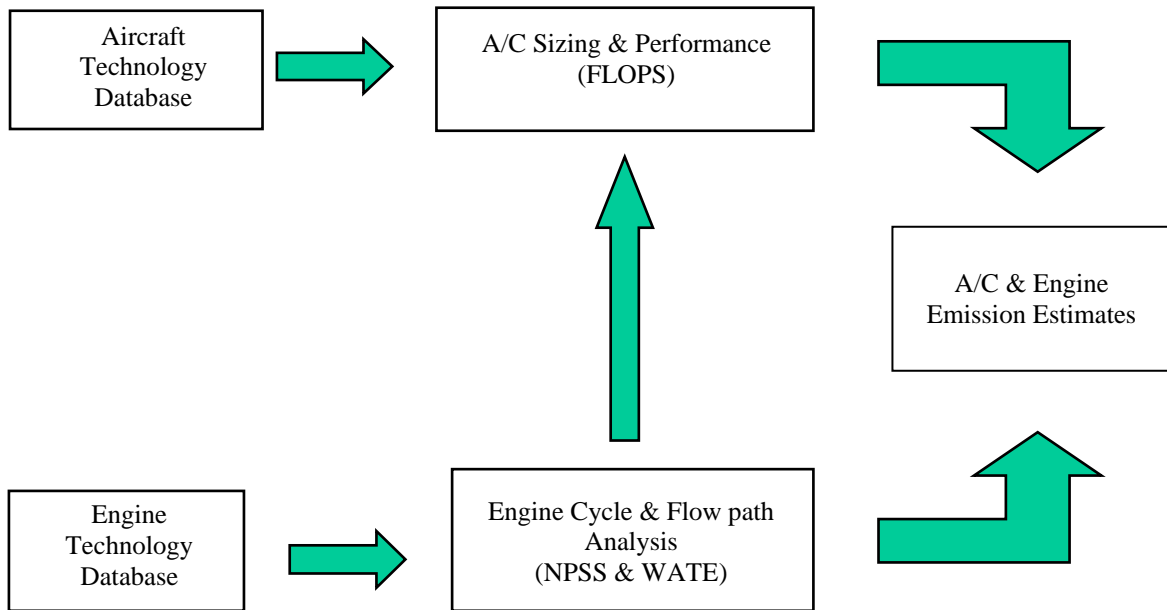


Figure 1. System analysis schematic

NPSS calculates engine thrust and specific fuel consumption at numerous operating conditions throughout the flight envelope. Required thermodynamic data are then forwarded to the WATE code that, in combination with appropriate aero-mechanical inputs, generates an engine weight estimate. The results from NPSS and WATE are used by FLOPS to perform airplane mission and sizing analyses that produce a mission fuel-burn, which is directly proportional to the amount of CO₂ generated.

F. Description of Previous Assessments

A number of programmatic benefit assessments have been conducted by NASA over the last several years to quantify the emission reduction potential of advanced technology. Although none of the technology development efforts involved adaptive engine technologies exclusively, there were technologies of this type in each of the portfolios evaluated. Four specific assessments will be described herein. They are the NASA *Intelligent Propulsion System Foundation Technologies Assessment* (2004), the NASA *Ultra Efficient Engine Technology Portfolio Assessment* (2003),²⁵ the NASA *Aeronautics Enterprise Assessment* (2003), and the *Revolutionary Concepts in Aeronautics Review* (2001). Note that a systems assessment of intelligent propulsion control technologies was completed in 2001 under the Ultra Efficient Engine Technology program; the results of this assessment were used in subsequent assessments.

As part of each assessment, technical experts provided descriptions of their technology and the potential impact, both positive and negative, of that technology for each reference configuration employed in that study. The benefits

were to be defined at the component or sub-component level (i.e., component/sub-component weight reduction, component efficiency improvement), and not at the system level (i.e., specific fuel consumption reduction, overall engine weight reduction). Often, multiple iterations between the technologist and system analyst were required to determine the full range of possible impacts. Even then, the full impacts of some of the adaptive technologies could not be captured.

1. Intelligent Propulsion System Foundation Technologies (IPSFT) Assessment

The objective of NASA's IPSFT project was to develop adaptive engine technologies that would enable commercial gas turbine engines to operate with reduced fuel burn, fewer emissions and less noise while increasing reliability. The entry into service date for most of these technologies was targeted for 2008 to 2012. The IPSFT task contained a specific system study work element dedicated to assessing the potential benefits of each technology. The focus of the system study was to assess and prioritize advanced technologies so that they can be integrated to achieve an optimal balance of system benefits between dissimilar, and possibly contradictory, figures of merits. The technology list included:

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. The power needed to control the casing at takeoff is estimated at 1 horsepower.

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.

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.

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.

Active flow control applied to LPC and HPC — active and passive flow control technology to enable higher blade loading, improved compressor efficiency and operation stability.

Turbine aerothermal and flow control technology — develop flow control schemes in turbines to enable safer operation of highly loaded blades in high/low pressure components.

Active combustion control for lean direct injection technology — 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.

Using NPSS/WATE/FLOPS as described above, response surface equations (RSEs) were generated for use in the technology evaluation. The construction of a response surface equation involved four steps. First, a parametric engine design model was built using NPSS/WATE/FLOPS. Then design-of-experiments methods were used to determine the critical number of cases necessary to accurately represent key control parameters such as fan pressure ratio, component efficiencies, and cooling flows, thereby generating the desired responses such as specific fuel consumption, fuel burn, range, emission indices, and propulsion system weight. The RSE was created from these responses through the use of a commercial statistic tool.²⁶ Finally, the accuracy of the RSE was validated by comparing actual data with predicted values produced within the RSE. If needed, the fit of the RSE was improved by including additional cases. This response surface methodology has been used extensively in aircraft design and technology assessment;^{27,28,29} its theoretical aspects are described by Box and Draper.³⁰

For the IPSFT technologies, a 300-passenger (300 PAX) aircraft with two 396-kN thrust (85,000-lb) engines was used as the reference configuration.

2. Ultra Efficient Engine Technology (UEET) Portfolio Assessment

NASA's UEET program was designed to develop advanced propulsion and propulsion/airframe integration technologies with specific objectives to reduce aircraft fuel burn, or CO₂, and NO_x, relative to state-of-the-art systems. Annual assessments of the current technology portfolio were conducted. The results provided insight to UEET program management to assist in creating a robust technology suite capable of meeting aggressive emission reduction goals. The assessment used two "best in service" subsonic reference vehicles (a 50-passenger regional jet and a 300-passenger, long-range transport) and two current technology notional vehicles (a 10-passenger supersonic business jet and a 468-passenger blended-wing body, or BWB) to determine potential impacts on systems with varying design requirements. The following three technologies were identified as adaptive during the assessment:

Active Flow Control for S-Inlets – use of small input of air to re-energize inlet boundary layer flow to keep flow from separating and to impart momentum into flow to counteract secondary flow swirl effects. (Applicable on BWB only)

Rotating Machinery Clearance Management – actively minimize working fluid leakages between turbine engine rotating blades and static cases, could be used ultimately in fans, compressors and turbines. (Applicable on 50-passenger regional jet, 300-passenger transport and BWB)

High Temperature, Wireless Data Communication — development of high temperature (~600 deg. C) electronics to replace existing sensor wiring. Would include development of 3C-SiC material to enable high frequency (~1 GHz), high temperature transistors for RF circuits. (Applicable on all 4 reference systems)

3. *Aeronautics Enterprise Technology Portfolio Assessment*

From 1997 through 2003, NASA's Aeronautics Enterprise conducted annual assessments to quantify the benefits of aeronautics research and development activities against long term objectives (10 to 25 year time horizons). Included in these objectives was the goal to develop technologies that could enable CO₂ emission reductions of 25% within 10 years and 50% within 25 years for new subsonic commercial aircraft. NASA systems analysts conducted annual surveys with each Aeronautics program to identify, and then quantify, the impacts of applicable technologies. Since the goal was to improve emissions across the entire commercial fleet, six "best in service" aircraft were used to represent the breadth of seat classes. From the 60+ technologies queried, nine were identified as adaptive engine technologies. From that list of nine, five technologies were able to be modeled in sufficient detail to produce quantifiable benefits. Two additional technologies were tabbed as enablers.

Compressor Technology Flow Control – active and passive flow control schemes to allow for higher blade loading, improved compressor efficiency and operation stability. (Applicable on all reference systems)

Turbine Aerothermal & Flow Control – develop flow control schemes in turbines to enable safer operation of highly loaded blades in high/low pressure components. (Applicable on all reference systems)

Structural Dynamics & Magnetic Bearing Development – develop high-temperature, high-loading magnetic bearings and self-tuning vibration absorbers for engine blade applications. (Applicable on all reference systems)

Pattern Factor Reduction – sensors to measure spatial temperature distributions within the combustor, providing input to a closed-loop combustion control system.

Instruments and Sensors – develop instrumentation and sensors which are reliable at high operating temperatures and are minimally intrusive. (Applicable on all reference systems)

Nano & Autonomous Systems – develop non-lead based and high displacement, piezoelectric material for pressure sensing and frequency agile applications, develop shape memory alloys and composites for use up to 1000 deg. C, develop intelligent system using integrated miniature sensors, electronics and actuators for engine self-diagnosis, self-reconfiguration and self-repair. (Not analyzed – advanced concept)

Rotating Machinery Clearance Management – see description above. (Applicable on all reference systems)

High Temperature, Wireless Data Communication - see description above. (Not analyzed – enabler)

4. *Revolutionary Concepts in Aeronautics (REVCON) Project*

The objective of REVCON was to accelerate the exploration of high-risk breakthroughs in aeronautics technologies. The adaptive engine technology that was assessed under this project was:

Shape-memory-alloy (SMA) actuated variable area fan nozzle for a geared turbofan engine — the objective is to develop a jet nozzle capable of changing up to 20 percent in area on demand using a revolutionary lightweight shape-memory-alloy based actuator, to improve efficiency and provide a measure of vectored thrust. Such a nozzle could be the springboard for the next generation of efficient high bypass ratio jet engines.

G. Assessment Results

A summary of the inputs to assessments are shown as benefits and penalties in Table 1. This data was used to calculate the impact of each of the technologies on the system performance, specifically CO₂ emission reduction (or equivalent mission fuel-burn). NO_x reductions were not quantified, other than by direct fuel burn reduction, because of the uncertainty in assessing combustor-design changes on NO_x generation. The results are also summarized in Table 1.

One observation from this table is that all of the adaptive technologies show benefits toward reducing CO₂ emissions, and flow control technologies show particular promise for the given assumptions (as much as 13% for a blend-wing body aircraft). For the structural control technologies, a large benefit is possible from the shape-memory alloy actuated nozzle for a low fan-pressure-ratio/high bypass-ratio engine application. However, as mentioned in section IIB, the benefit of fan nozzle variability diminishes with increasing fan pressure ratio. Combustion control technologies show relatively small CO₂ reductions, but their target benefit is NO_x reduction which is not shown here.

Note that it is not generally possible to make direct comparisons between the benefits listed in Table 1, nor is it possible to sum up the benefits to determine an overall potential emissions reduction level. The benefits can not in general be directly added because they are not all derived from the same baseline, and particular benefits have limits and can not be necessarily improved simultaneously by multiple technologies.

In addition, there are variations in predicted benefits even for the same technology when assessed at a different time. There are three primary reasons for these variations: 1) Different technologists will estimate different values of a given technology's potential benefits and penalties, particularly for relatively immature technologies such as adaptive propulsion technologies. Different systems analysts may also interpret and/or question these estimates differently, where the questioning is used to elicit consideration of the full spectrum of benefits and penalties, 2) The baselines used are often refined from year to year, incorporating usually small perturbations to parameters such as blade counts and local temperatures and pressures, and 3) Some assessments are done using response surfaces, and others are done using single-point runs. Although the response surface equation (RSE) was validated for its accuracy (as mentioned in the previous section), small numerical error could result from its prediction due to the approximate nature of the RSE. The benefit of using response surfaces is assessment speed, enabling the comparison of many what-if scenarios. Differences in predicted benefits attributable to baseline changes and uncertainties caused by response surface interpolation are in general much smaller than those generated by benefit/penalty assessments for technologies that haven't yet been tested in representative systems.

H. Modeling Shortfalls

One assumption common to each of the assessments described in this paper is that the technologies were being added, one at a time, to a newly produced engine, using an existing engine design. Candidate technologies might yield higher benefits if they were incorporated into totally new designs. Also, engine deterioration over time was not modeled, nor were system transients or other time-dependent effects. Also, the models captured at most axial variations; radial and full three-dimensional spatial distributions were not considered. For conceptual design comparisons, one- or zero-dimensional models are sufficient, but omitting effects caused by degradation shortchanges the potential benefits that might be realized by adaptive technologies. Adaptive technologies by their very nature compensate for degradation over time, potentially preventing substantial increases in fuel burn between scheduled engine overhauls. This operational benefit is not captured in Table 1.

Another difficulty with our current assessment practice is the lack of a systematic means to ensure that all assumptions made for a given result are retained with those results for comparison with future studies. As previously mentioned, small changes to baselines are common, and these can accrete to perhaps a significant change over time. The temptation is to directly compare results with the same baseline (e.g. "300 PAX"), without delving into the specifics of the assumptions. A standardized table of all parameters, stored with the results, would be helpful for understanding direct comparisons.

One final consideration has been previously mentioned, namely the variability in benefits and penalty estimates given by different technical experts. Often a single person provides estimates for any given assessment. Perhaps more confidence in these values could be obtained by reaching consensus among several experts from different organizations. However, a more reliable way to improve the estimates is to further develop the technologies so that direct test data can be used.

IV. Conclusion

Several system assessments have been run to assess the ability of a variety of adaptive engine technologies to reduce the amount of CO₂ generated from aircraft. CO₂ reduction was modeled as directly proportional to reduced fuel burn. These assessments show that the adaptive technologies described here reduced fuel burn by reducing aircraft weight, improving propulsion efficiency, and/or reducing drag, and have the potential to significantly reduce aircraft CO₂ emissions, given a variety of assumptions and assessment techniques. Possible emissions reduction values range from a fraction of one percent for enabling technologies, to 13% for flow control in "s" shaped inlets for blended-wing bodies. As a group, the flow-control technologies are the most beneficial for CO₂ reduction. For the structural-control technologies, a large benefit is possible from the shape-memory alloy actuated nozzle for a low fan-pressure-ratio/high bypass-ratio engine application. However, 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 CO₂ reduction, a cost-benefit analysis should also be performed.

For the assessments described here, only “new engines” were modeled, using existing baseline engine designs. We expect that the inclusion of degradation models will show significant additional CO₂ reduction benefits because adaptive technologies inherently compensate for many forms of degradation, such as erosion and damage. These adaptive technologies described are relatively undeveloped, 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 experimental data becomes available showing measured performance in relevant conditions.

Table 1: Adaptive engine technology impacts on reference systems

Technologies	Assessment Inputs		Assessment Results	Assessments						
	Benefits	Penalties		Aeronautics Enterprise (subsonic fleet average)	UEET (300 PAX)	UEET (BWB)	UEET (SBI)	IPSFT (300 PAX)	RevCon (300 PAX)	Industry Results (CO2 reduction)*
FLOW CONTROL										
Flow control for S-inlets	-6% inlet ram drag	+300 to +1030 lbs. inlet weight	4 to 13%		X					
Flow control - fans										1 - 5%
Compressor technology	+2 pts LPC/HPC poly eff.		3.0 to 3.5%	X						
flow control	+1.0 to +2.0 pt. LPC/HPC poly. eff		0.4 to 3.1%					X		1 - 5%
Turbine Aerothermal and flow control	+400F T41, +1 pt. HPT eff, +2 pt. LPT eff, -25% turbine cooling		8.5 - 9.0%	X						
			Up to 8.5%**					X		
STRUCTURAL CONTROL										
Active tip clearance control	+0.5 pt. fan polytropic efficiency	+20 lbs engine weight; +1 HP power requirement	Up to 0.84%						X	0.5 - 5%
	+0.25 to +0.50 pt. HPC polytropic efficiency	0 to +30 lbs engine weight +0.5 to +1 HP power requirement	0.4 to 1.0%						X	
	+0.50 to +1.00 pt. HPT adia. eff.	+10 to +30 lbs engine weight	0.8 to 1.7%						X	
	+0 to +0.20 pt. LPT adiabatic eff.	+10 to +30 lbs engine weight	0 to 0.3%						X	
SMA variable fan nozzle	fan nozzle area variation of 20%	+10% fan nozzle weight	Up to 8.3%							
Structural Dynamics & Magnetic Bearing Development	-100% oil system weight (all systems)		0 to 0.3%	X						0.1 - 1%
COMBUSTION CONTROL										
Active combustion control for lean direct injection	-50 to -90 lbs engine weight	+1 to +2 HP power requirement	0 to 0.1%						X	
Pattern factor reduction	-60 °F T4 margin		0.2%	X						
ENABLING TECHNOLOGIES										
High temperature wireless data communication	-15 to -60 lbs controls weight (50 PAX/SBI) -105 to -250 lbs controls weight (300 PAX/BWB)		0.2 to 0.7% (50 PAX) 0 to 0.3% (300 PAX and BWB) 0 to 0.4% (SBI)		X					0.1 - 1%
Instruments and sensors	+1 pt. fan & LPC poly efficiency		Up to 1.9%	X						

*Generic ranges are given here for rough comparison purposes only. No information about baselines is given or implied.

**For high bypass ratio and low fan-pressure ratio cycles

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