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Ultra Efficient Engine Technology Systems Integration and Environmental Assessment

David L. Daggett
Boeing Commercial Airplane Group, Seattle, Washington

July 2002

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EXECUTIVE SUMMARY

This study documents the design and analysis of four types of advanced technology commercial transport airplane configurations (small, medium, large and very large) with an assumed technology readiness date of 2010. These airplane configurations were used as a platform to evaluate the design concept and installed performance of advanced technology engines being developed under the NASA Ultra Efficient Engine Technology (UEET) program.

The four airplane configuration designs were evaluated in two steps; the first was to evaluate the performance improvement of the airplanes using advanced technology airframes with current technology in-production engines. The second step was to evaluate the advanced technology airframes while using UEET advanced technology engines. This way, incremental block fuel reductions could be evaluated for effects of airframe technology improvements alone in step 1 and then for the effects of engine and airframe technology improvements in step 2.

The configuration chosen for the small, medium and large airplanes was a high wing (with winglets), "T" tail (with canard), twin engine, body mounted landing gear, advanced technology tube-and-wing type design as shown in Figure "a". They employed advanced materials in the fuselage, wing, empennage, landing gear and nacelle. In addition, advanced technologies were used for aerodynamic flow control on the wing, fuselage, empennage and nacelles. Other advanced, efficient airframe systems and aerodynamic sensors/antennas were also used on these configurations. The choice of a high-wing configuration enabled an unconstrained engine diameter study to be made.

Figure a, Small, Medium & Large UEET Airplane Configurations

For the very large configuration, a Blended Wing Body (BWB) configuration (Figure "b") was chosen in order to evaluate how UEET may benefit other revolutionary airplane configurations that NASA is sponsoring. The BWB offers a lower wetted area per passenger seat and span loading benefits as compared to the aforementioned configuration. The BWB also uses advanced materials in the construction of the airframe. However, advanced aerodynamic flow control technologies were not used in this configuration.

Figure b, Very Large UEET Airplane Configuration

The study results of the UEET advanced technology airframe with current technology engines showed a 3%, 10% and 13% block fuel improvement in the small, medium and large airplanes respectively over current production airplanes with the same seating arrangements while operating on similar missions. The small airplane experienced additional weight, wetted area and Specific Fuel Consumption (SFC) penalties due to increases in passenger comfort levels and cruise speed. These were included to reflect realistic market drivers and probable evolutionary design considerations. The airframe technologies used in this study were designed to evaluate the best potentially available block fuel use reductions one could achieve based on "revolutionary" technologies that may be ready for application in the year 2010. Their marketability has yet to be determined, but they represent worthwhile avenues of exploration.

Upon installation of the UEET engines onto the UEET advanced technology airframes, the small and medium airplanes both achieved an additional 16% increase in fuel efficiency when using GE advanced turbofan engines. The large airplane achieved an 18% increase in fuel efficiency when using the P&W geared fan engine. The very large airplane (i.e. BWB), also using P&W geared fan engines, only achieved an additional 16% that was attributed to a non-optimized airplane/engine combination.

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GLOSSARY

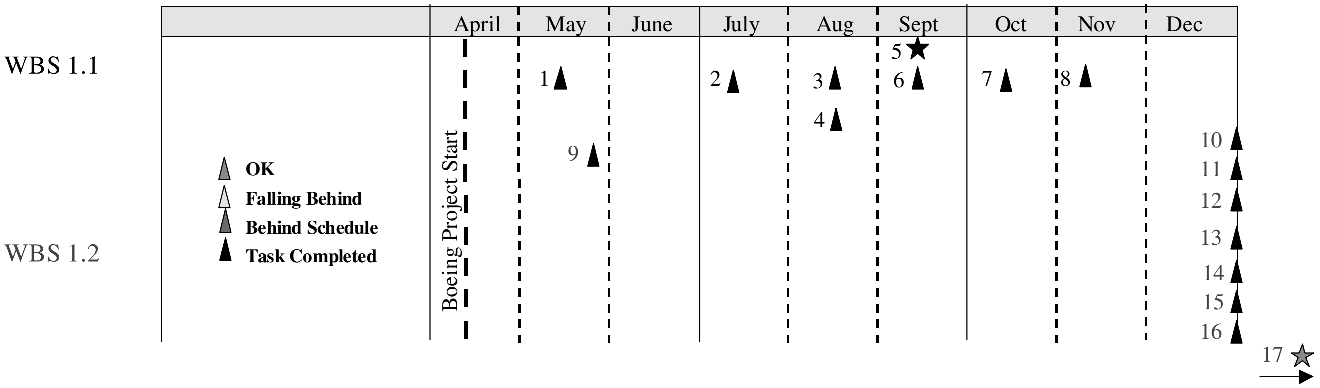
BPR	Bypass Ratio
BWB	Blended Wing Body Aircraft
CAEP	ICAO Committee on Aviation Environmental Protection
CO	Carbon Monoxide
CFR	United States Code of Federal Regulations
EI_{NOx}	Emissions index for NOx given as grams of NOx/Kg fuel
FAR	Federal Aviation Regulation
GEAE	General Electric Aero Engine
HC	Hydro-Carbons
ICAO	International Civil Aviation Organization
kg	kilogram
kts	nautical miles per hour
lb	pound
Load Factor	Percentage of an airplane's seat capacity occupied by passengers
LTO	Landing Take-Off cycle
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration (USA)
NOx	Nitrogen Oxides
NMI	Nautical mile
OPR	Overall Pressure Ratio
P&W	Pratt & Whitney
PAX	passengers
SLST	Sea Level Static Thrust
st-mi	Statute Mile
std	Standard
SFC	Specific Fuel Consumption
TOGW	Take Off Gross Weight
UEET	Ultra Efficient Engine Technology
WBS	Work Breakdown Structure

1.0 INTRODUCTION

This report documents the results from the first year of study on the Ultra Efficient Engine Technology (UEET) Systems Integration task, WBS 1.1, under the NASA Ultra Efficient Engine Technology program.

The objective of this study was to quantify the airplane system-level impacts of UEET engines on future airframes. Additional goals were to provide airplane level sensitivities to changing engine design criteria, such as the increase in fuel burn with increasing aircraft weight and drag. Lastly, recommendations were to be offered as to which technologies and areas of development should be pursued.

The study was an 8-½ month endeavor that was coordinated with an Environmental Assessment task, WBS 1.2. The objective of the environmental assessment study was to provide a 1999 aircraft emissions inventory that may be used in a future study as a tool for evaluating the global atmospheric impact of UEET technology. Figure 1.1 illustrates both task schedules and milestones.



WBS 1.1 (System Integration) Milestones

1. 737/747/777 design sensitivities/parameters
2. Provide base 2010 technology aircraft configurations (4 each)
3. Receive first 4 engine configurations from GE & P/W
4. Obtain UEET engine performance information for noise studies
5. Interim task progress review (at Boeing Seattle)
6. Provide UEET 2010 technology aircraft configurations (4 each)
7. Community noise assessment
8. Preliminary airplane level assessment

WBS 1.2 (Environmental Assessment) Milestones

9. Complete Estimated 1997 global scheduled emissions inventory
10. Complete August 1992 global emissions inventory
11. Full year 1999 global emissions inventory complete
12. Complete draft contractor report on subsonic emissions inventory work
13. Complete HSCT emissions scenarios
14. Complete analysis of SSBJ current/future utilization
15. Complete informal report on HSCT and SSBJ emissions scenarios
16. Provide recommendations and task summary report
17. Oral final presentation at NASA

Figure 1.1, UEET System Integration Program Milestone Schedule

In order to separate the effects of improved airframe technology from UEET propulsion effects, the study first configured four differently sized aircraft (small, medium, large and very large) using conventional technology engines. The second phase of the study involved the installation of UEET engines in place of the conventional engines and optimizing the aircraft configuration to take advantage of the increased engine efficiency.

When considering the installation of the UEET engines onto UEET advanced technology airframes, the wing and control surfaces can be re-sized to account for the engine's improved Specific Fuel Consumption (SFC). Better SFC results in less block fuel required for a given range, which results in less Take Off Gross Weight (TOGW) and a corresponding smaller and lighter wing. Therefore, engine efficiency improvements are compounded when the full system design is considered (e.g. a 10% improvement in engine SFC can equal a 15% block fuel burn improvement in an optimized airplane design).

Both General Electric Aero Engine (GEAE) and Pratt & Whitney (P&W) engine companies were contractors to NASA under the UEET program. Over several years, they will be developing designs and laboratory demonstrations of advanced technology aerospace gas turbine engines. For this study, they participated in developing the preliminary definitions and performance estimates of four study engines that were sized to fit four UEET airplane configurations under study by the New Airplane Product Development team at the Boeing Commercial Airplane Group in Renton, Washington.

GEAE optimally designed a generic engine for use with the medium sized UEET airplane. This engine was then scaled down to fit the small UEET airplane. P&W optimally designed their engine for the large UEET airplane. Additionally, P&W configured a very high bypass ratio engine for the very large UEET airplane with the expectation that this engine would deliver exceptional performance for this particular platform. The engine make and sea level static thrust rating for each size engine is illustrated in Figure 1.2

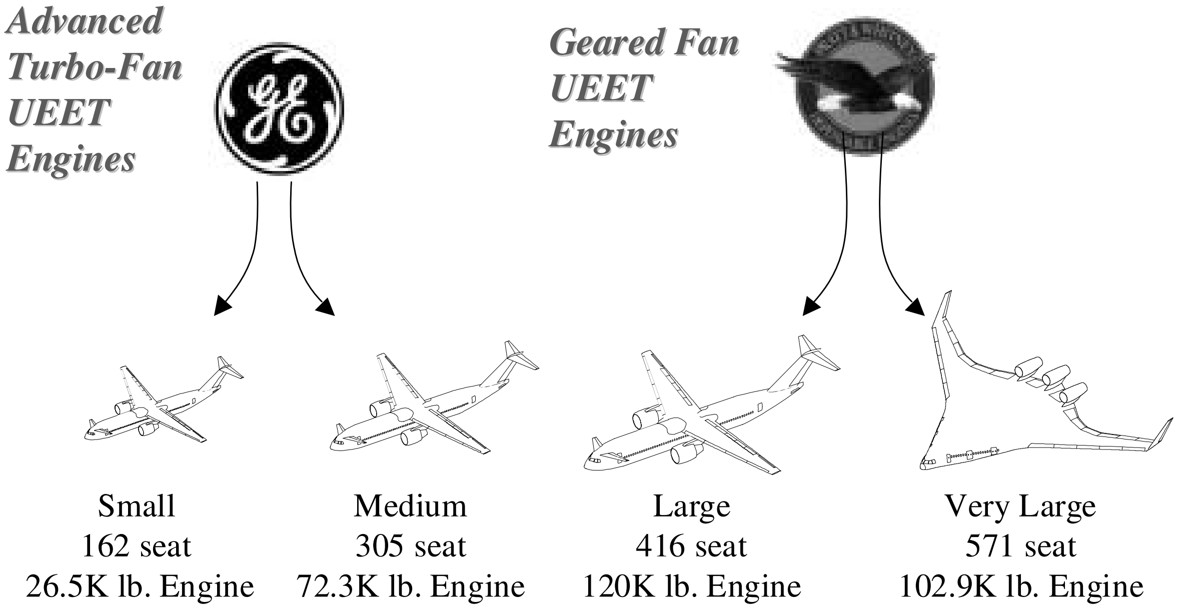


Figure 1.2, Engine Airframe Combinations

2.0 TECHNICAL APPROACH

2.1 Performance Targets

When considering the performance of an aircraft, the airframe is just as important as the engine. Historically, airframe efficiency improvements have been on the same order of magnitude as the engine has achieved (Figure 2.1.1). Thus, when considering the integration of a future, fuel-efficient engine onto a future aircraft, consideration should be taken for the anticipated airframe technology advancements.

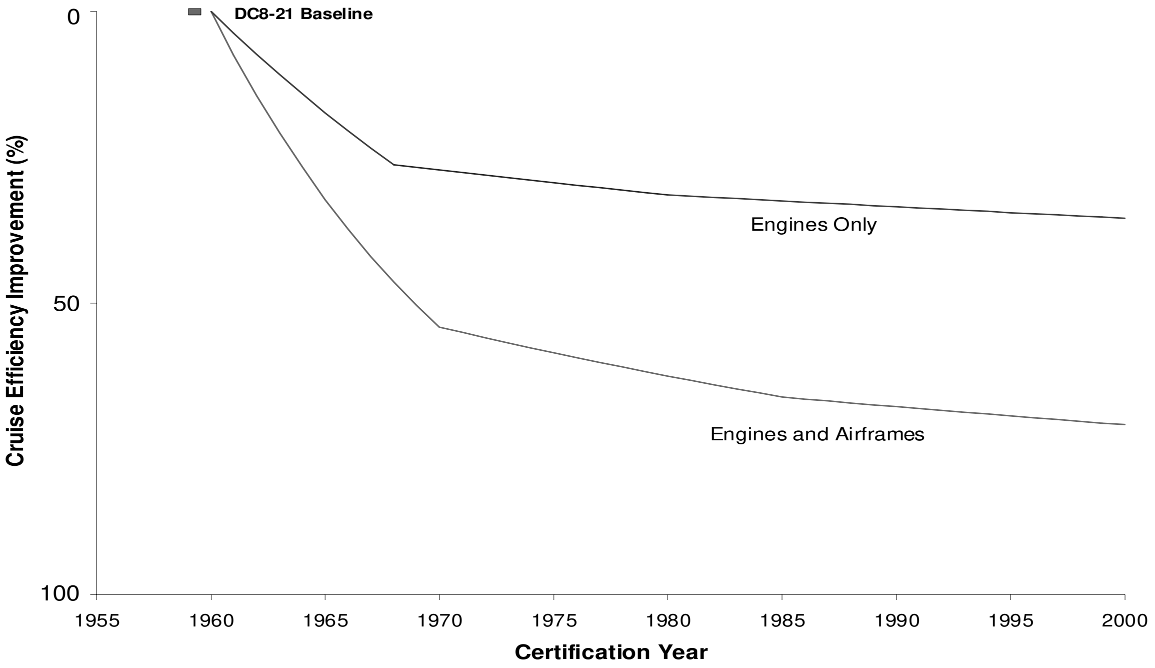


Figure 2.1.1, Engine and Airplane Historical Fuel Efficiency Gains

In order to provide a consistent basis for all the configurations developed and evaluated in the study, a set of ground rules were developed. With these ground rules in mind, requirements and fuel efficiency targets were identified for both the engine and airplane. These were used in developing each configuration and are shown in Figure 2.1.2.

Technology Readiness Date:	Year 2010 (for Entry Into Service date of 2015)
Seating:	Multi-class (70% pax. LF), similar seating # to production airplanes
Landing, Takeoff ICAC & Cruise Speed:	Comparable to baseline airplanes
Engine SFC Fuel Use:	-10%
Engine Block Fuel Use:	-15% (NASA goal)
Airplane Block Fuel Use:	-25% reduction from current technology airplanes (Boeing goal)
LTO Emissions:	NOx = CAEP2 -70% (NASA goal) HC = CAEP -70% (Boeing goal) CO = CAEP -40% (Boeing goal)
Noise:	Stage 3 minus 20dB cumulative, meet QC2 London Dep. (Boeing)

Figure 2.1.2, UEET Airplane Study Ground Rules

2.2. Airplane Performance Comparisons

2.2.1 Baseline Production Airplanes

In order to assess the incremental performance improvement of the UEET airplanes, baseline current technology production airplanes were chosen for comparison as listed below:

- Small Airplane: 737-800 with CFM56-7B27 engine
- Medium Airplane: 777-200ER with GE90-94B engines
- Large Airplane: 747-400 with PW4062 engines

The small airplane was evaluated on a 1,000 NMI mission in a dual class (business and coach) configuration, capable of carrying 162 passengers, and was loaded at 70% passenger load factor. The medium airplane was evaluated on a 3,000 NMI mission in a tri-class (first, business & coach) configuration loaded at 70% passenger load factor. The large airplane was evaluated at the same conditions. None of the aircraft had cargo.

2.2.2 UEET Airframe with Current Technology Engines

Three advanced technology airframes were developed and sized to accept current technology engines for comparison with the baseline small, medium and large production airplanes. Thus, the effects of airframe technology alone on airplane fuel efficiency could be evaluated. These study aircraft were evaluated against the baseline production airplanes using identical seating layouts and mission lengths. In addition, a very large, unconventional airplane configuration was designed with a current technology engine. However, no baseline airplane was available for comparison against the very large UEET airplane. All of the aircraft were to be designed such that they would represent possible future, realistic airplane configurations that offer safe, affordable, high-performing, comfortable, quiet and clean transportation.

2.2.3 UEET Airframe with UEET Engines

The advanced technology airframes were then sized and fitted with UEET engines so that an estimate of the effect of the engine technology alone could be estimated. Per NASA's goals, the effect of engine technology on the airplane was to achieve a 15% improvement in block fuel burn. Figure 2.2.1 illustrates the configuration types along with their performance design goals.

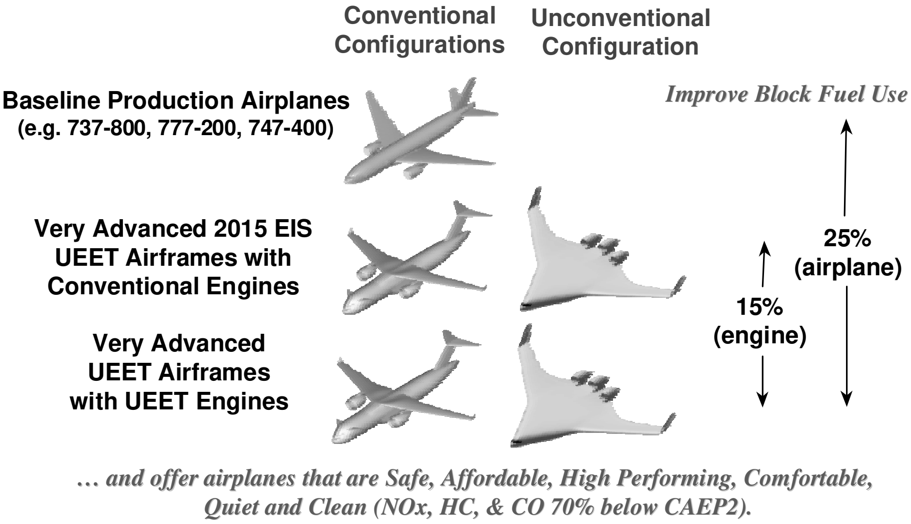


Figure 2.2.1, Baseline Performance

2.3 Airframe Technologies

Several advanced technologies were used on the airframe that would be technologically ready for application by the year 2010, given sufficient development funding. However, their financial worth remains to be proven. Among these are:

Advanced Wing Aerodynamics. – specific technologies to reduce the drag over the upper surface of the airfoil were applied, thereby improving the Lift to Drag ratio (L/D).

Composites: - materials were used in the fuselage, wings, engine nacelles, empennage, and canards to reduce the weight of the aircraft and thereby reduce the amount of takeoff thrust and generated lift required.

Riblets: - these micro-grooved devices were applied to the fuselage, engine nacelles, and empennage in order to reduce skin friction and improve airplane drag.

Canard: - frontal control surfaces were employed on the aircraft to enable a 3-surface configuration. This improves airplane climb-out performance and reduces cruise trim drag by achieving all flying surfaces (i.e. no downward forces generated from the aft horizontal stabilizers).

Fly by Wire (FBW): - this system removes the conventional hydraulic system that powers the aircraft control surfaces and substitutes electrically-driven actuators to reduce weight and also enables a fast-responding electrical sensing system to achieve wing aero load alleviation and an electronic tail skid system as will be discussed below.

Aero Load Alleviation: - when utilizing FBW, the aircraft's wings can be designed lighter due to structural loading considerations. For instance, when a sudden gust of wind is encountered, the aircraft's aileron (or elevator) would deflect to attenuate the resulting increase in lift on the airfoil, thereby reducing the peak loading and enabling a more efficiently designed airfoil.

Electronic Tail Skid: - if FBW is utilized on an aircraft, over-rotation of the aircraft during takeoff can be sensed and corrected electronically by limiting the elevator travel thereby preventing the aircraft's tail from dragging on the runway. This system saves weight by removing the current mechanical tailskid.

Modular Flight Deck: - a common, lighter-weight flight deck was utilized on the study aircraft.

Flush Sensors & Antennas: - use of a composite structure allows antenna and sensors to be mounted inside the structure thereby reducing parasitic drag.

Advanced Mechanical Systems: - other aircraft mechanical systems were upgraded to reflect advances that are anticipated by the year 2010. The benefit of these systems was realized in overall weight savings.

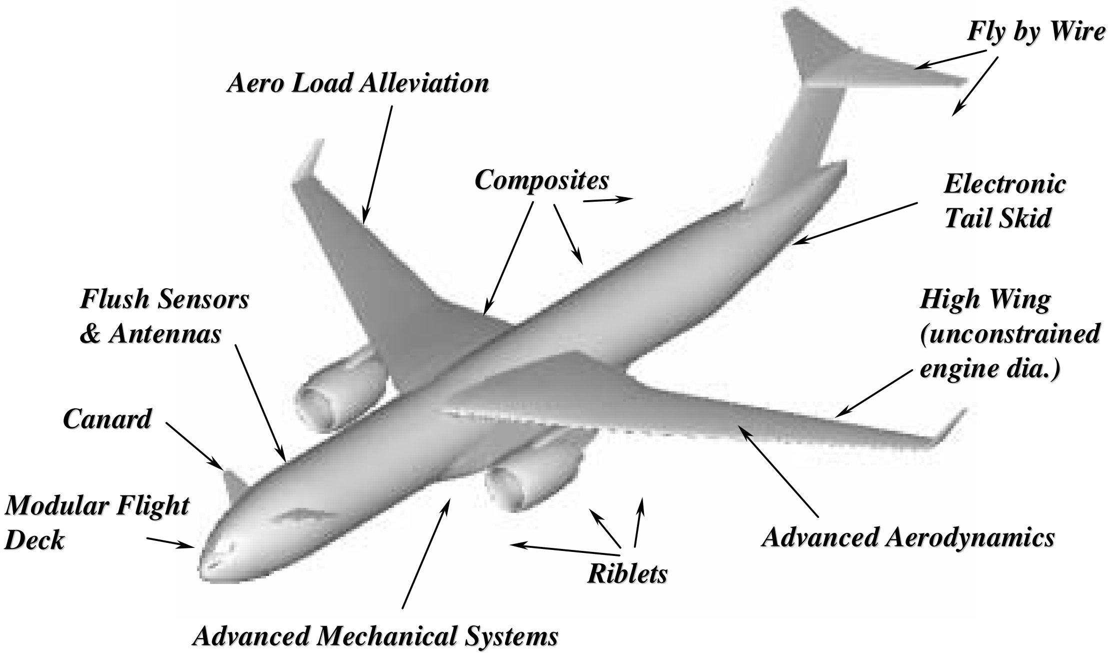


Figure 2.3.1, Wing & Tube Advanced Airframe Technologies

The airframe technologies used on the very large UEET airplane were similar to those used on the wing & tube configurations previously discussed. However, the very large airplane or Blended Wing Body aircraft did not use the advanced wing aerodynamics technologies discussed above. This may have lead to a fuel burn disadvantage for the BWB.

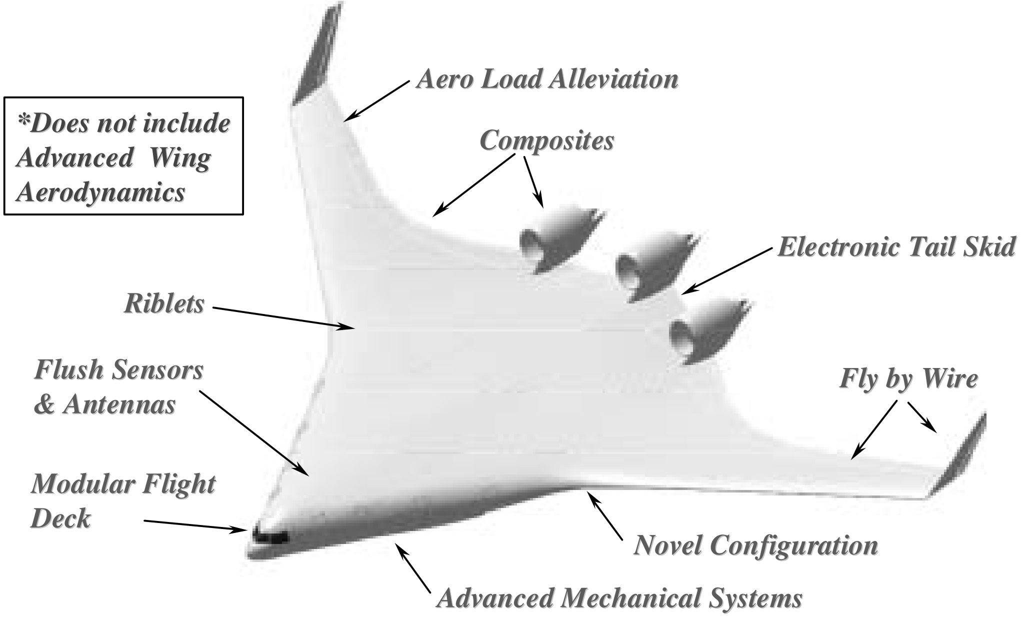
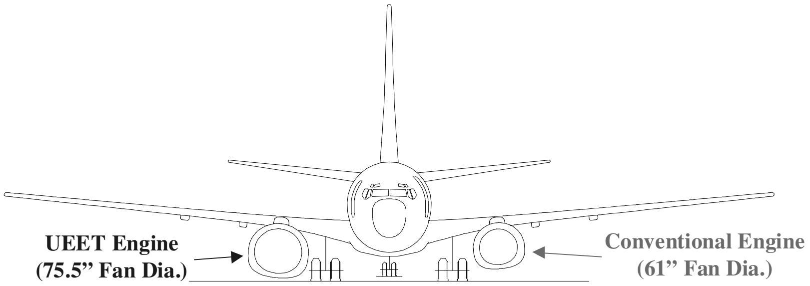


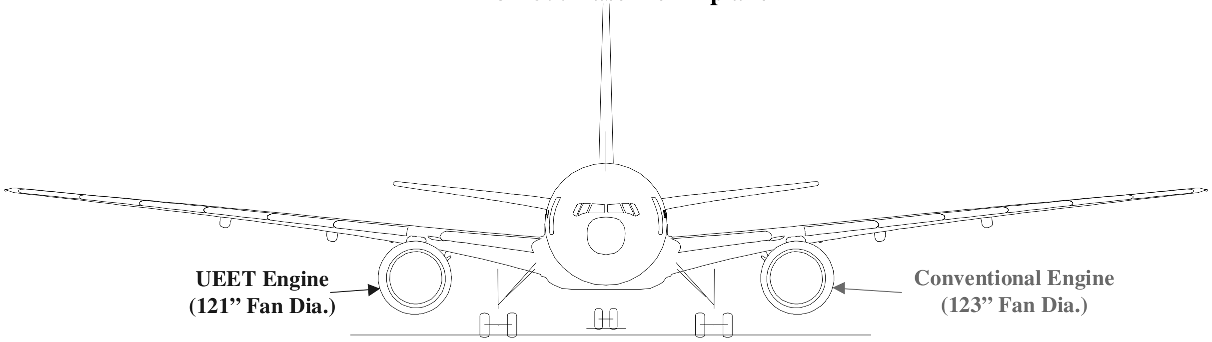
Figure 2.3.2, BWB Advanced Airframe Technologies

2.4 Engine Technologies

There were several technologies that were employed on the aircraft powerplants. For instance, improvements to the engine cycle thermal efficiency reduced internal losses and improved propulsive efficiency. This resulted in an overall reduction to engine SFC. One visible characteristic, for several of these engines, is the increase in nacelle diameter. This could lead to integration difficulties and associated airframe penalties on small low-wing aircraft (e.g. increased landing gear height) as illustrated in Figure 2.4.1. By using high-wing airplane configurations, the engines were unconstrained by airframe limitations and were able to be optimally sized.



737-800 Baseline Airplane



777-200ER Baseline Airplane

Figure 2.4.1, Challenges of Integrating High BPR Engines on Low Wing Airplanes

3.0 AIRCRAFT CONFIGURATION SUMMARY

3.1 Small Baseline Airplane (model 737-800)

The small baseline airplane was a 737-800 with two CFM56-7B27 engines, each producing 27,300 pounds of sea level static thrust. The maximum takeoff gross weight (MTOW) was 174,200 lb with a cruise speed of 0.785 Mach and maximum range of 2,940 NMI and maximum fuel capacity of 6,875 US Gallons. Basic dimensions of a typical 737-800 are listed in Figure 3.1.1 below:

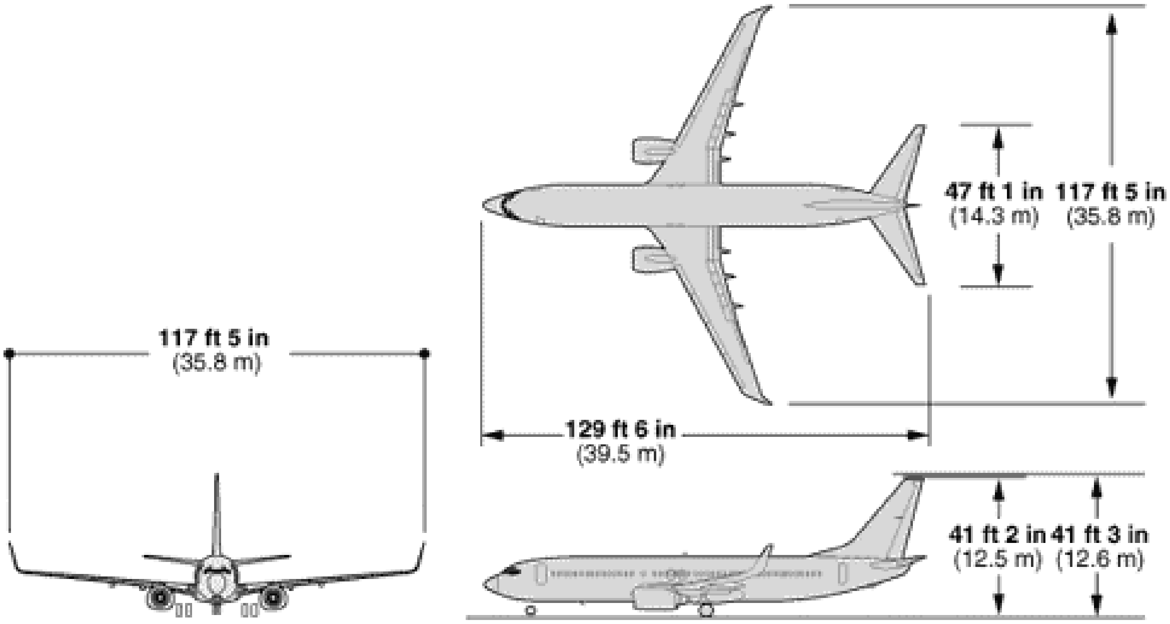


Figure 3.1.1, 737-800 Basic Configuration

The aircraft was configured in a 2-class seating configuration accommodating 162 passengers in a 36” pitch first class and 32” pitch coach arrangement as shown in Figure 3.1.2.

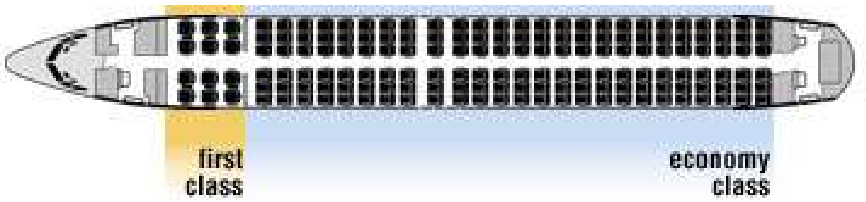


Figure 3.1.2, 737-800 Seating Configuration

3.2 Medium Baseline Airplane (model 777-200ER)

The medium baseline airplane was a 777-200ER with two GE90-94B engines, each producing 94,000 pounds of sea level static thrust. The MTOW was 656,000 lb with a cruise speed of 0.84 Mach and maximum range of 7,695 NMI with a maximum fuel capacity of 45,220 US Gallons. Basic dimensions of the 777-200ER used in the study are listed in Figure 3.2.1 below:

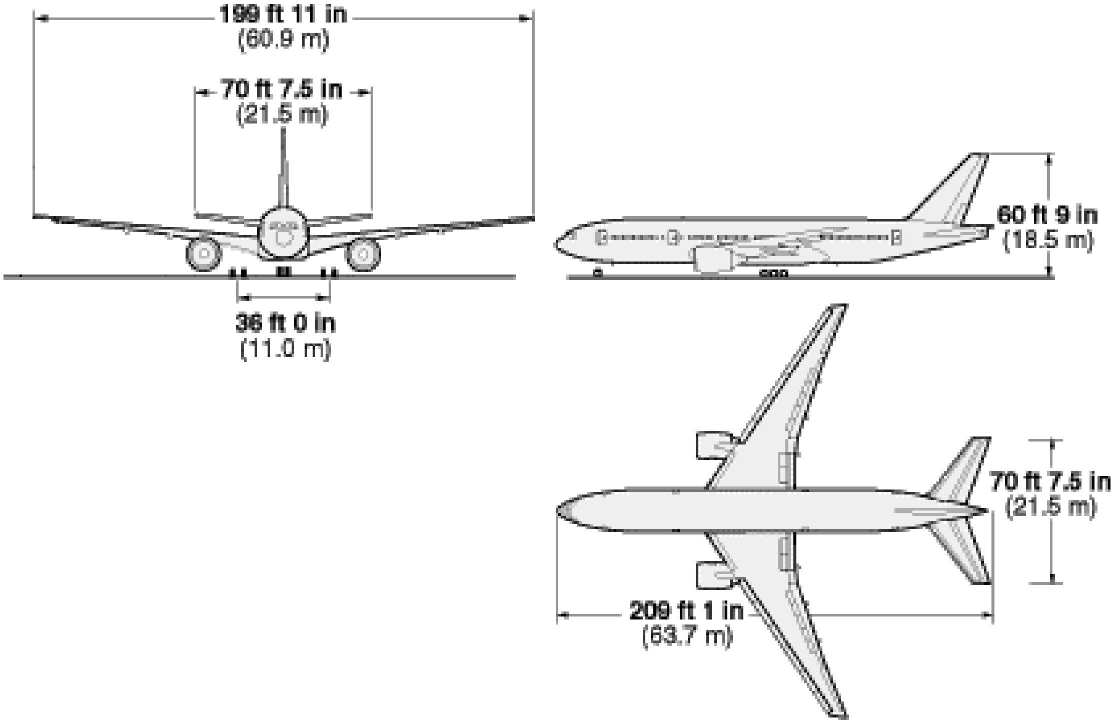


Figure 3.2.1, 777-200ER Basic Configuration

The aircraft was configured in a 3-class seating configuration accommodating 305 passengers in a 60” pitch first class, 38” pitch business class and 32” pitch coach arrangement as shown in Figure 3.2.2.

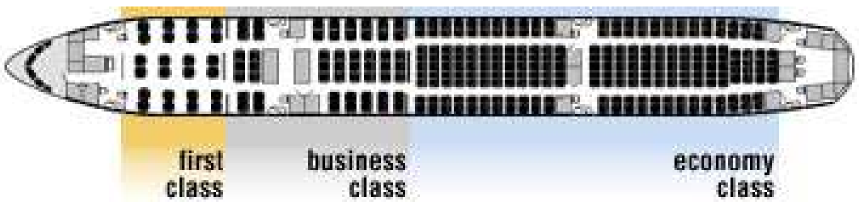


Figure 3.2.2, 777-200ER Seating Configuration

3.3 Large Baseline Airplane (model 747-400)

The large baseline airplane was a 747-400 with four PW4062 engines each producing 63,300 pounds of sea level static thrust. The MTOW was 875,000 lb with a cruise speed of 0.85 Mach and maximum range of 7,330 NMI with maximum fuel capacity of 57,285 US Gallons. Basic dimensions of the 747-400 used in the study are listed in Figure 3.3.1 below:

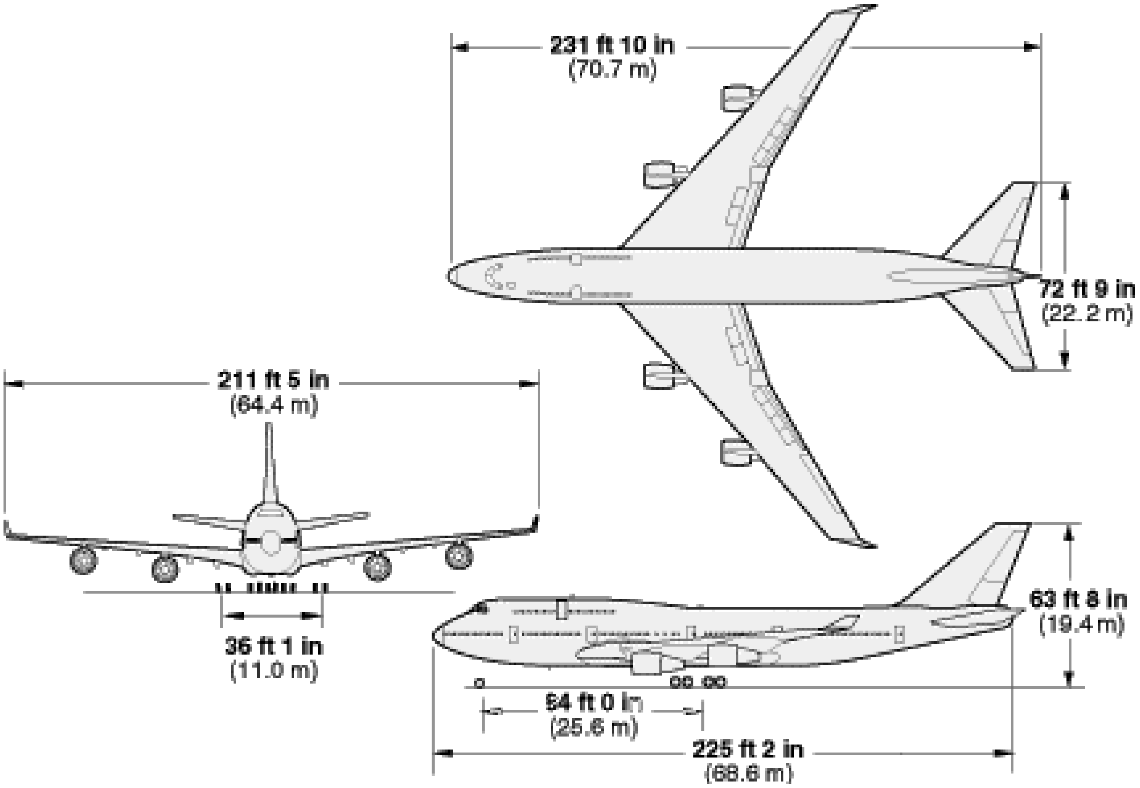


Figure 3.3.1, 747-400 Basic Configuration

The aircraft was configured in a 3-class seating configuration accommodating 416 passengers in a 61” pitch first class, 39” pitch business class and 32” pitch coach arrangement as shown in Figure 3.3.2.

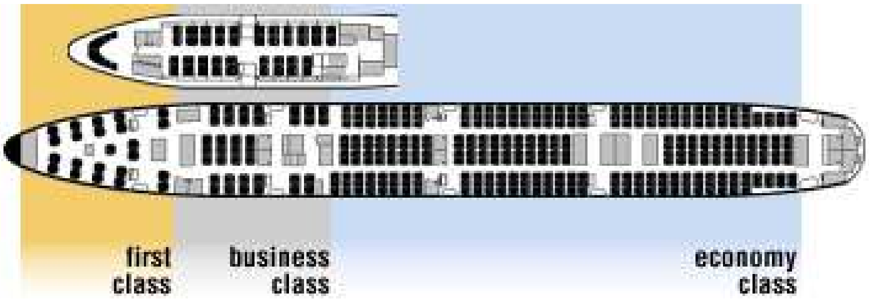


Figure 3.3.2, 747-400 Seating Configuration

3.4 Small UEET Airframe with Current Technology Engines

The small UEET airplane with conventional engines utilized two CFM56-7B27 engines, each producing 26,500 pounds of sea level static thrust. The aircraft has a cruise speed of 0.80 Mach and maximum range of 3,200 NMI. Number and pitch of interior seats was the same as the baseline airplane. Basic shape and interior layout of the small airplane is shown in Figure 3.4.1 below.

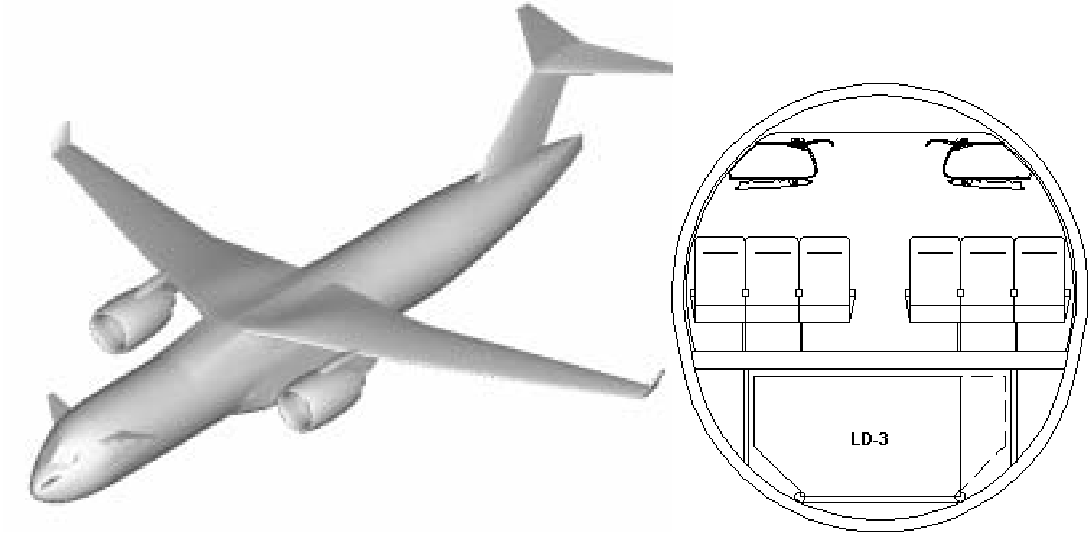


Figure 3.4.1, Small UEET Airplane Configuration

The small airplane experienced additional weight, wetted area and fuel mileage penalties due to increases in passenger comfort levels and cruise speed. These were included to reflect realistic market drivers and probable evolutionary design considerations. Additionally, weight penalties were incurred due to the use of the "T" tail configuration. Additional wetted area was also seen due to the wing box spar protrusion above the fuselage and the necessary body landing gear fairings.

3.5 Medium UEET Airframe with Current Technology Engine

The medium UEET airplane with conventional engines utilized two GE90-77B engines, each producing 79,700 pounds of sea level static thrust. The aircraft has a cruise speed of 0.85 Mach and maximum range of 7,700 NMI. The count and pitch of interior seats were the same as the baseline airplane. Basic shape and interior layout of the small airplane is shown in Figure 3.5.1 below.

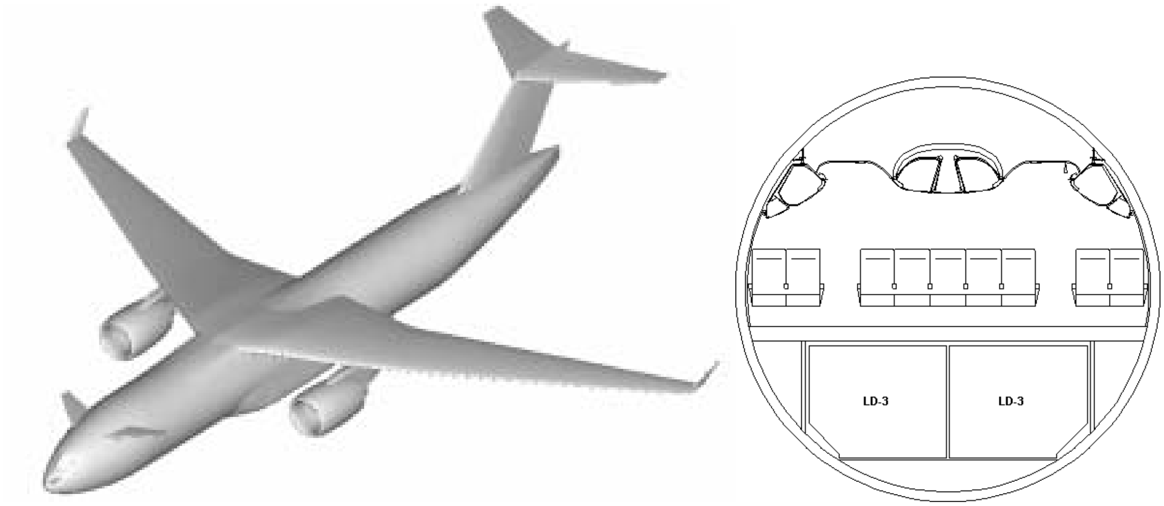


Figure 3.5.1, Medium UEET Airplane Configuration

The airplane experienced a slight increase in wetted area as compared to the baseline airplane due to the body landing gear fairings. Even with the increased fuselage wetted area; L/D declined due to the use of the advanced wing aerodynamics and riblets. Including the “T” weight penalty, the airplane still experienced a weight reduction due to the use of composite materials. The airplane enjoyed a slight increase (0.01 Mach) in cruise speed over the baseline airplane.

3.6 Large UEET Airframe with Current Technology Engine

The medium UEET airplane with conventional engines utilized two GE90-115B engines, each producing 112,800 pounds of sea level static thrust. The aircraft has a cruise speed of 0.85 Mach and maximum range of 7,300 NMI. The count and pitch of interior seats were the same as the baseline airplane. Basic shape and interior layout of the small airplane is shown in Figure 3.6.1 below.

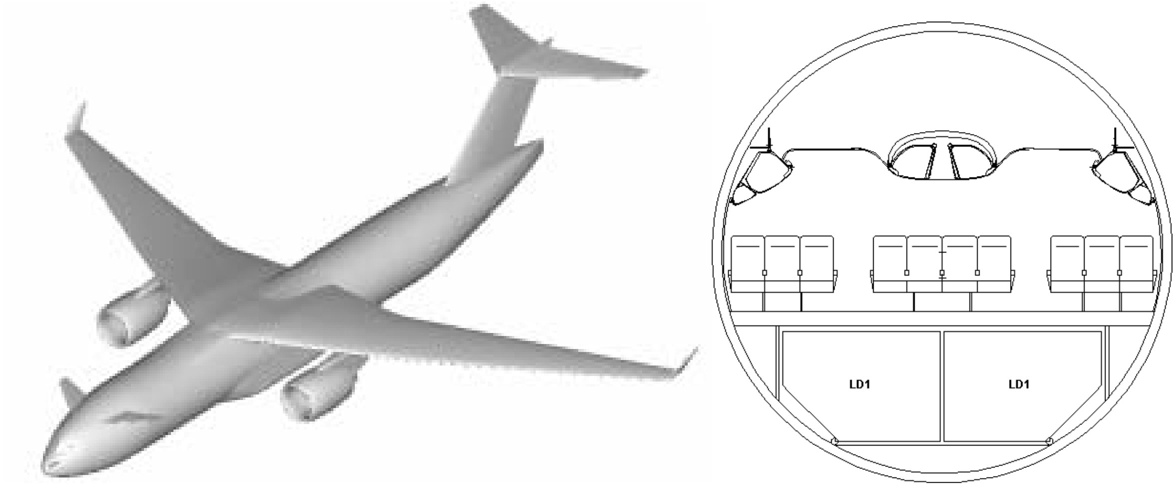


Figure 3.6.1, Large UEET Airplane Configuration

The aircraft utilized a single deck architecture that resulted in a large available space above the main passenger cabin. This area was able to completely house the wing box spar and could also be used for passenger work and leisure space. Thus, the airplane experienced an increase in fuselage-wetted area as well as some minor increase due to the landing gear fairings. "T" tail weight penalties were still incurred.

3.7 Very Large UEET Airframe with Current Technology Engine

The large baseline airplane was a Blended Wing Body aircraft with three PW4098 engines each producing 96,000 pounds of sea level static thrust. The aircraft has a cruise speed of 0.855 Mach and maximum range of 7,100 NMI. Basic layout of the BWB, as used in the study, is shown below in Figure 3.7.1:

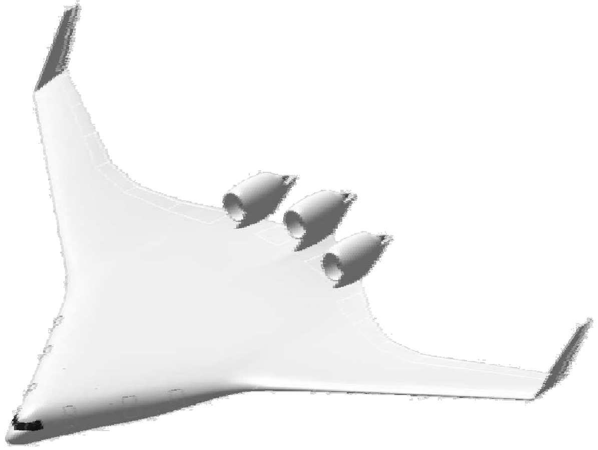


Figure 3.7.1, Very Large UEET Airplane Configuration

The aircraft was configured in a 3-class seating configuration accommodating 571 passengers in a 61" pitch, 33 seat first class, 39" pitch, 110 seat business class and 32" pitch, 428 seat coach arrangement.

3.8 Small UEET Airframe with UEET Engine

The basic layout of the aircraft is the same as discussed under the "Small UEET Airframe with conventional engine" section 3.4. The aircraft used two GEAE Advanced turbofan engines each producing 26,500 pounds of sea level static thrust. The aircraft has a cruise speed of 0.80 Mach and maximum range of 3,200 NMI.

The following performance comparisons are measured against the baseline 737-800 airplane. The airplane saw a 30% reduction in wing area due to improvements in wing aerodynamics and engine fuel burn, requiring less fuel to be carried and a smaller resulting wing. Payload capacity increased 17%. The increased comfort level fuselage primarily resulted in a 23% increase in wetted area with a corresponding 5% loss in L/D and 6% increase in Operating Empty Weight (OEW).

3.9 Medium UEET Airframe with UEET Engine

The basic layout of the aircraft is the same as discussed under the “Medium UEET Airframe with conventional engine” section 3.5. The aircraft used two GEAE Advanced turbofan engines each producing 72,300 pounds of sea level static thrust. The aircraft has a cruise speed of 0.85 Mach and maximum range of 7,700 NMI.

The following performance comparisons are measured against the baseline 777-200ER airplane. The airplane’s wing area decreased 13% due to reduced weight, improved aerodynamics and more efficient engines. Payload capability increased 34% due to weight reduction. L/D improved 3% due to aerodynamic considerations, and OEW decreased 16% due to the use of composite materials.

3.10 Large UEET Airframe with UEET Engine

The basic layout of the aircraft is the same as discussed under the “Large UEET Airframe with conventional engine” section 3.6. The aircraft used two P&W geared fan engines each producing 108,300 pounds of sea level static thrust. The aircraft has a cruise speed of 0.85 Mach and maximum range of 7,300 NMI.

The following performance comparisons are measured against the baseline 747-400 airplane. The airplane’s wing area decreased 11% due to improved aerodynamics and more efficient engines. However, the fuselage-wetted area increased 20% due to the single deck design. L/D still managed to see a 3% improvement due to the use of a twin engine configuration versus quad, improved aerodynamics and a 16% decrease in OEW due to the use of composites.

Payload capability decreased 10% due to a decrease in available engine thrust.

3.11 Very Large UEET Airframe with UEET Engine

The basic layout of the aircraft is the same as discussed under the “Very Large UEET Airframe with conventional engine” section 3.7. The aircraft used three P&W geared fan engines each producing 102,900 pounds of sea level static thrust. The aircraft has a cruise speed of 0.855 Mach and maximum range of 7,100 NMI.

The following performance comparisons are measured against the BWB with conventional engines. The improvements represent “engine-only” impacts. The airplane’s wing area remained the same, but start of cruise L/D improved 4% due the use of more efficient engines and resulting lower fuel load for the 3,000 NMI mission which results in lower weight and less induced drag. Aircraft weight remained essentially the same due to the use of a non-optimized engine, which had an extremely high engine by pass ratio with resulting high fan, nacelle and gearbox weights thereby offsetting the other weight reductions presumably gained in the engine core.

4.0 PERFORMANCE ANALYSIS

4.1 Engine

General Electric Aero Engine (GEAE) supplied study engines that were used on the small and medium airplanes, which use advanced turbofan technology. The following data in this report suggest that improvements to the engine cycle have been made by increasing the engine's thermal (through OPR increases) and propulsive efficiencies (through BPR increases). This typically results in decreasing SFC(1). Figure 4.1.1 illustrates the cross sectional view of the engine.

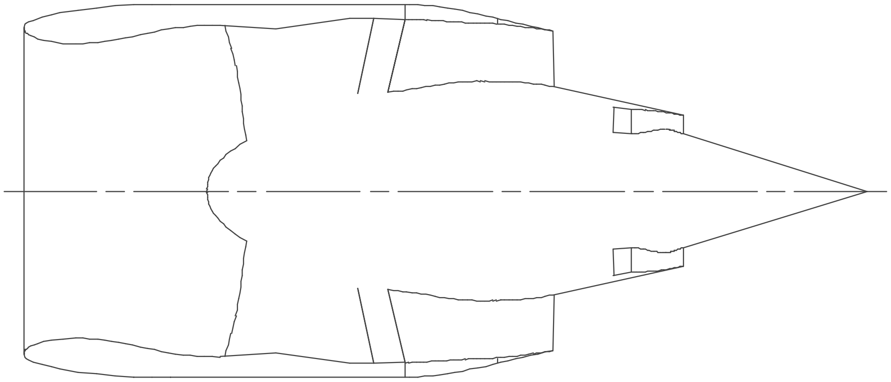


Figure 4.1.1, UEET GEAE Engine Cross Section

The Pratt & Whitney engines used on the Large and Very Large aircraft utilizes geared fan technology. The addition of a gearbox allows the LP turbine speed to be optimized independently of the fan speed. This results in a reduced LP turbine stage count (at efficiency) along with improvements in the fan rotor efficiency and noise. In order to keep the stability of the fan in check; the P&W UEET engines also incorporated variable geometry fan nozzle areas. Relative to the baseline engine, the thermal efficiency of the engine was also higher due to the increased cycle OPR. Figure 4.1.2 shows a cross section of the geared fan.

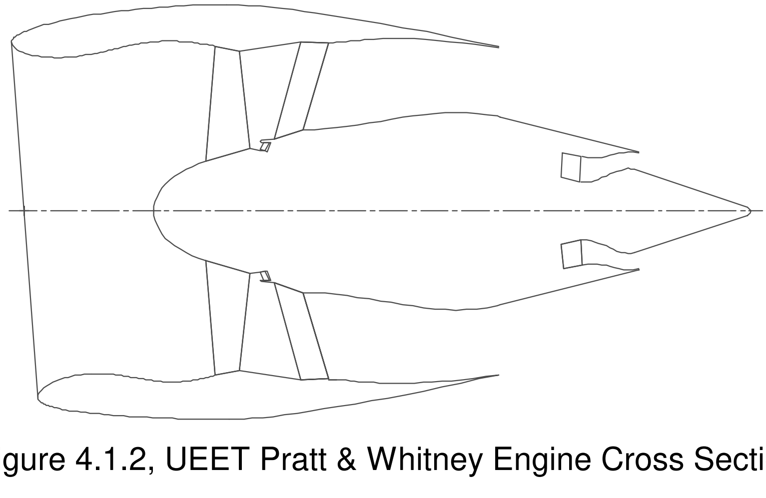


Figure 4.1.2, UEET Pratt & Whitney Engine Cross Section

Figure 4.1.3 shows the thrust levels for the various UEET engines. Airframe improvements resulted in a lower required thrust for the medium and large airplanes. The small airplane required the same thrust level due to the previously discussed increases in cabin comfort and resulting higher thrust requirements. The very large airplane shows an increase in Sea Level Static (SLS) thrust. This is due to the high BPR design of that particular engine and resulting higher SLS thrust level.

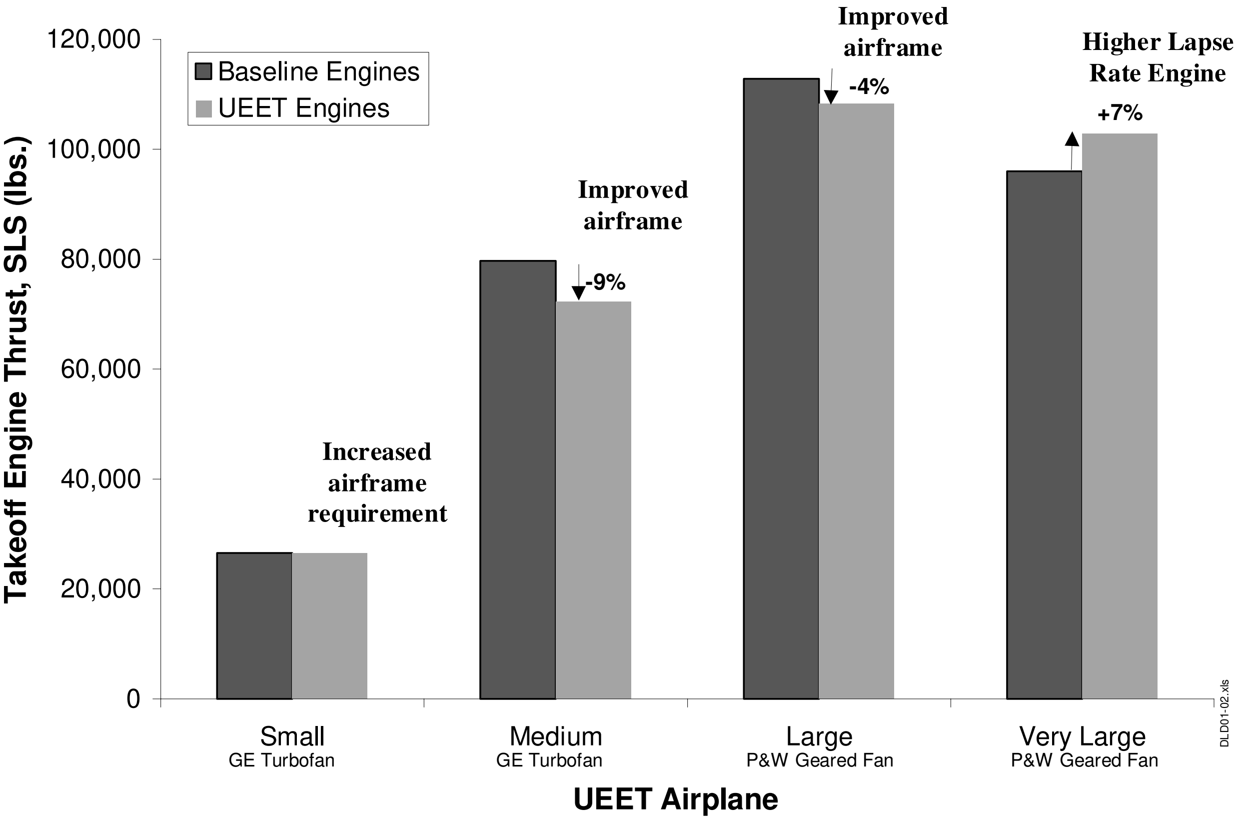


Figure 4.1.3, Engine Thrust Levels

Fan diameter is the physical measurement, from blade tip to blade tip, across an engine's fan face. By Pass Ratio (BPR) is the ratio of secondary and primary airflows. For a given core size, the engine bypass ratio increases in concert with increases to the fan diameter. Alternatively, and for a given fan diameter, engine bypass ratio increases by reducing the core flow size. A further consequence of the higher BPR engines is that effective jet velocities tend to be lower. Figure 4.1.4 shows the fan diameter and bypass ratio characteristics of the UEET engines. Large increases in BPR were achieved with nominal increases, or in some cases no increases, to the fan diameter.

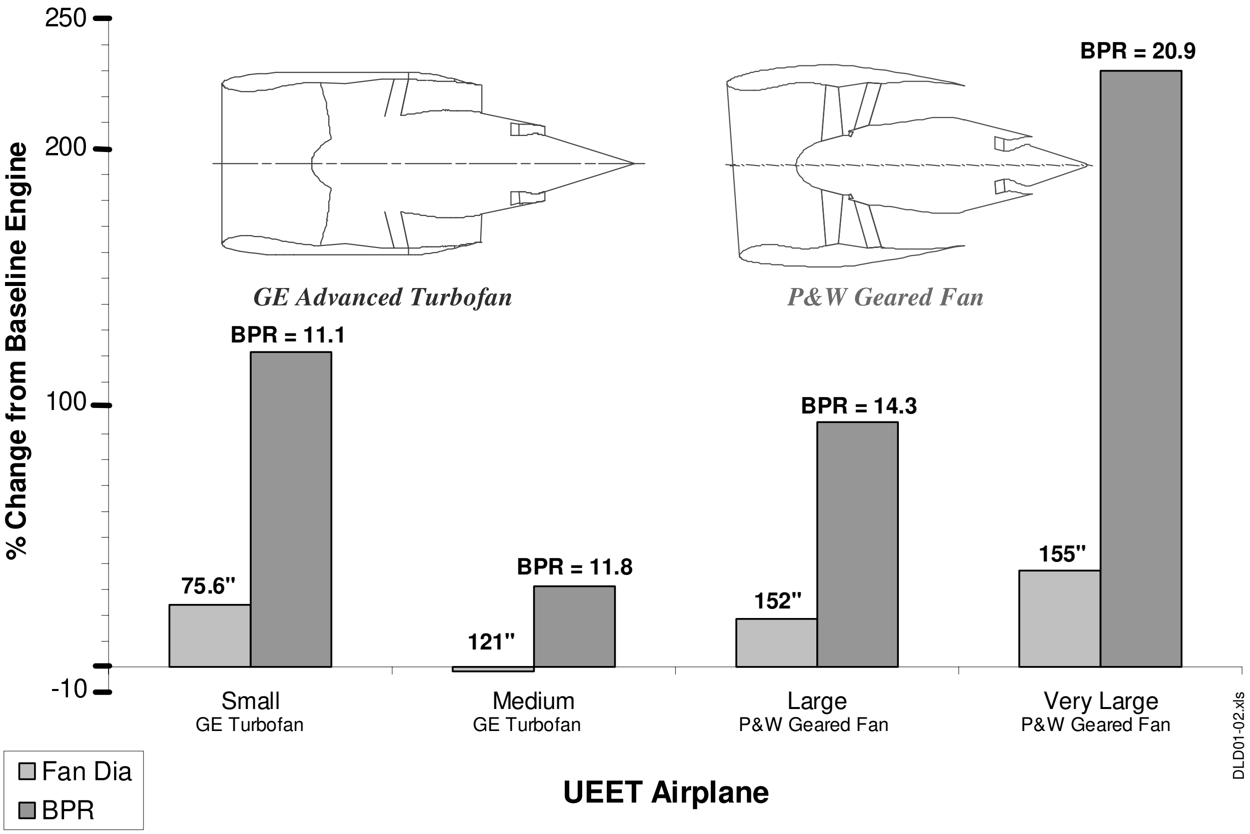


Figure 4.1.4, Engine Fan Diameter and Bypass Ratio Comparison

The very large airplane uses an extremely high BPR of 21. Although higher BPR engines are quieter and efficient by themselves, there can be performance tradeoffs due to weight increases for the larger fan and also resulting drag increases due to the larger nacelles as illustrated in figure 4.1.5. It is not clear if the very large airplane's engine fell into "the bucket" for these tradeoffs and was optimized.

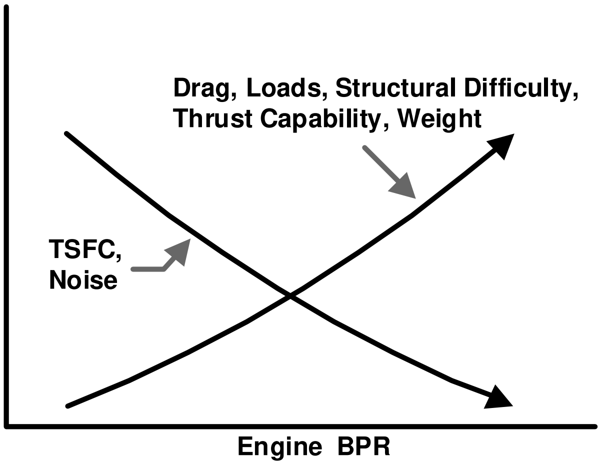


Figure 4.1.5, Engine BPR trades

The engine Overall Pressure Ratio (OPR) is defined as the ratio of the compressor exit and engine inlet total pressures . Engines with high OPRs compress the inlet air more in preparation for mixing with fuel and burning in the engine's combustion chamber. Burning fuel at high pressure levels enables the release of more heat per unit area and ultimately results in higher engine thermal efficiencies (3). Figure 4.1.6 illustrates that all of UEET engines exhibited large increases in OPR as compared to the baseline engines.

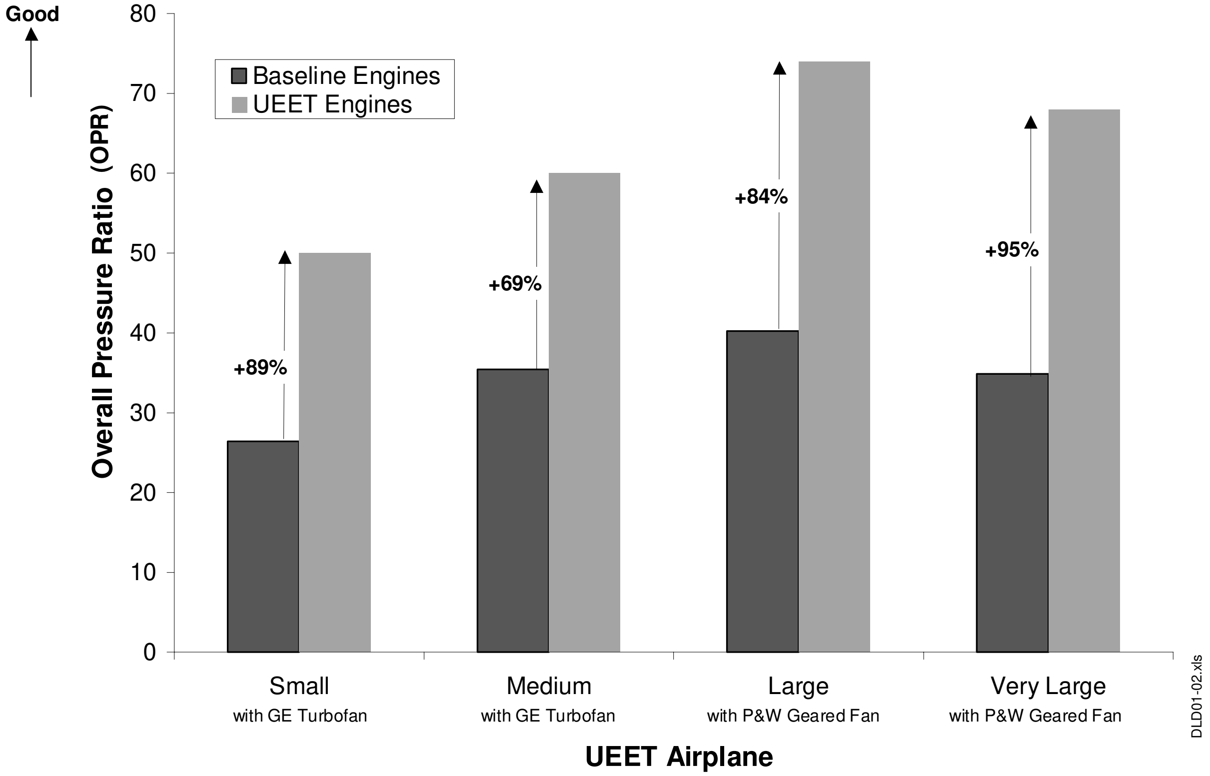


Figure 4.1.6, Engine Overall Pressure Ratio Comparison

Although increasing the OPR typically leads to increases in engine efficiency, it must be evaluated against the increased weight of the larger compressor. In addition, the increase in engine weight due to the large fan diameter, as previously discussed, should be evaluated (4). A typical evaluation performance metric is an engine's Thrust to Weight ratio (T/W). For each of the study engines, Figure 4.1.7 shows the SLS thrust level versus the engine weight, as compared to the baseline engine (in percent improvement). The engines for the small, medium and large airplanes show an improvement in the 20-30% range. However, the very large engine experienced an 18% decrease in the T/W ratio, due to the larger fan diameter and associated weight increases of the fan blades, hub, fan frame, containment shield, nacelle and gear reduction system.

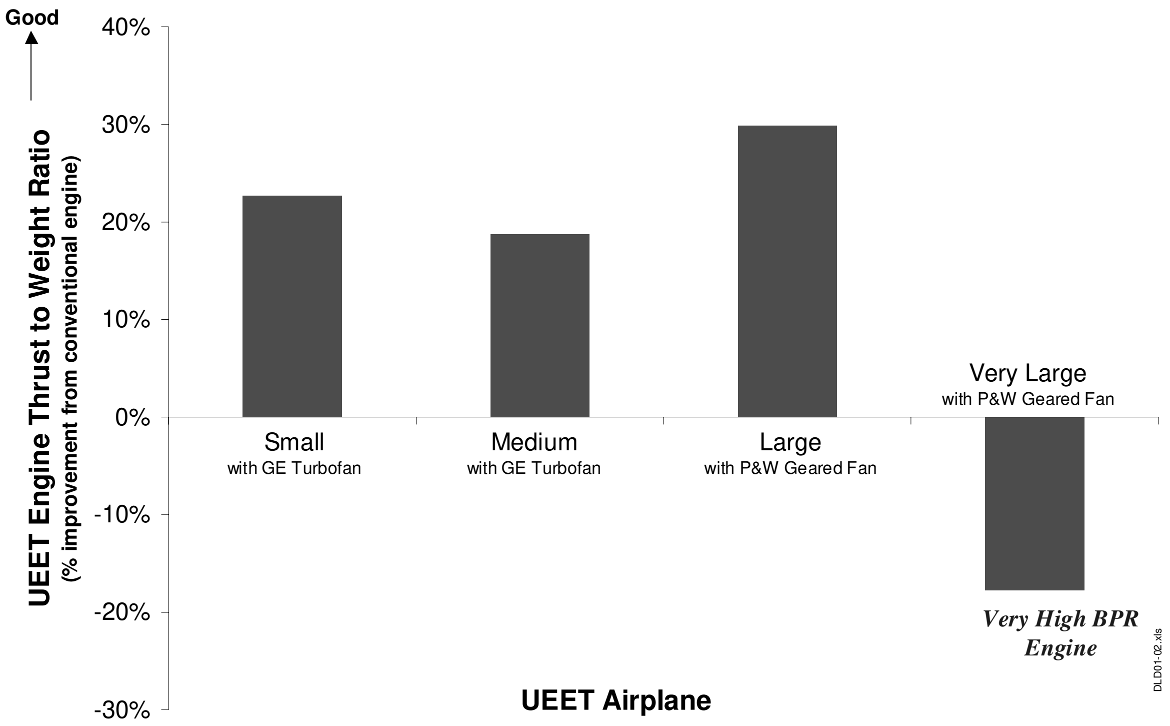


Figure 4.1.7, Engine Thrust to Weight Ratio

Another consideration of larger fan diameter engines is the increase in nacelle drag. Depending on the size of the nacelle, (long or short duct), fan duct noise treatment, and nacelle thickness, increases in nacelle drag can rise precipitously with increases in fan diameter. Figure 4.1.8 illustrates the percent increase in nacelle drag versus the percent increase in fan diameter for the 4 engines. The P&W engines have a slightly different drag slope as compared to the GE engines due to nacelle shape. The engine for the very large airplane experienced an 87% increase in nacelle drag as compared to the baseline engine due to the very high bypass ratio design and resulting large nacelle area.

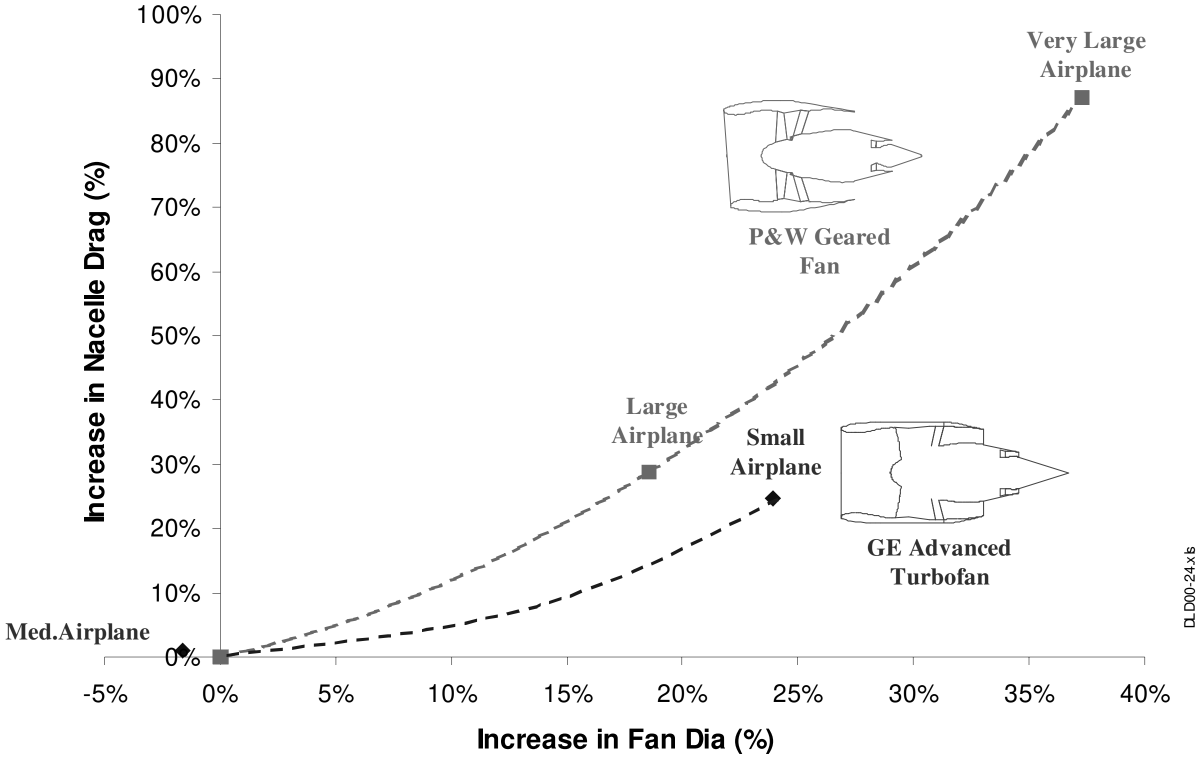
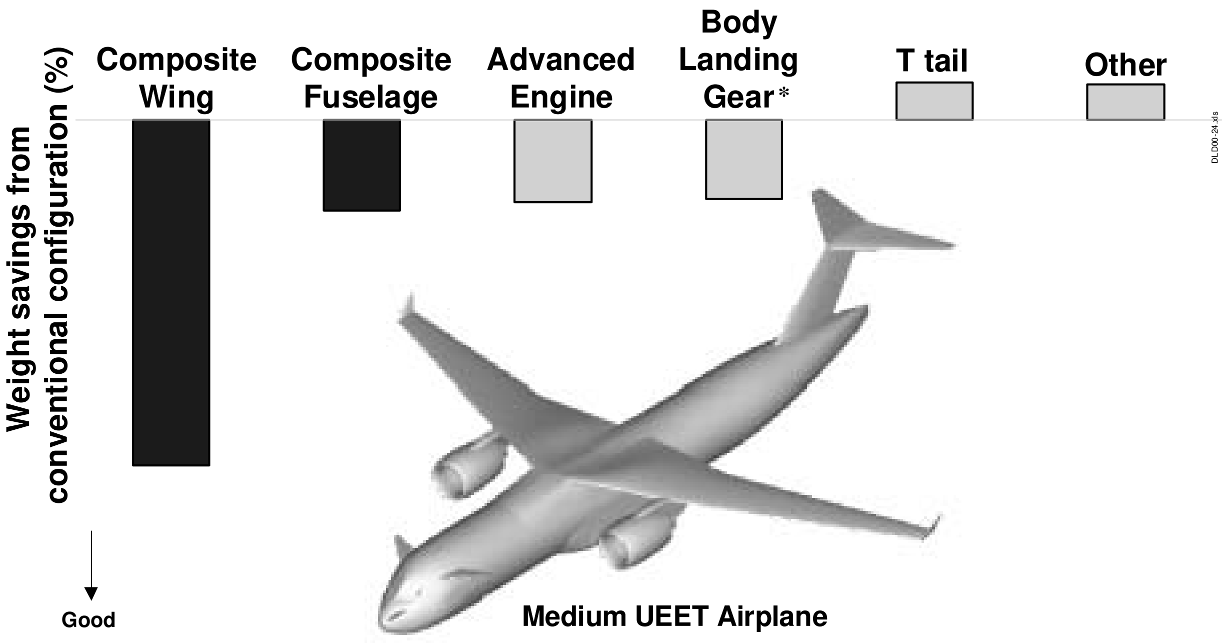


Figure 4.1.8, Engine Nacelle Drag Comparison

4.2 Airframe

Weight is a crucial factor in evaluating an airplane's performance. As the weight of an aircraft increases, increased lift must be generated which results in increases to induced drag which must be overcome with increased thrust and associated fuel burn (5). The UEET airplane used composite materials in the engine and airframe to reduce weight. Figure 4.2.1 shows that the greatest percentage weight reduction (as compared to a baseline airplane) was obtained by the use of composites in the wing construction. The fuselage played a lesser role. Figure 4.1.7 showed an improvement in the thrust to weight ratio and is also reflected in Figure 4.2.1. A body-mounted landing gear is normally heavier than a wing-mounted landing gear on a low-wing airplane(6). However, the use of metal matrix composites resulted in a net decrease in landing gear weight. The use of a "T" tail configuration resulted in weight increases in all of the wing and tube UEET airplanes. Increased passenger amenities (e.g. entertainment systems) slightly increased the weight of all the airplanes from the baseline.



≈15% OEW Weight Reduction

* Due to material and OEW improvements only

Figure 4.2.1, Relative Aircraft Weight Savings

Figure 4.2.2 shows the operating empty weight savings for each of the wing and tube UEET airplanes as compared to the baseline aircraft.

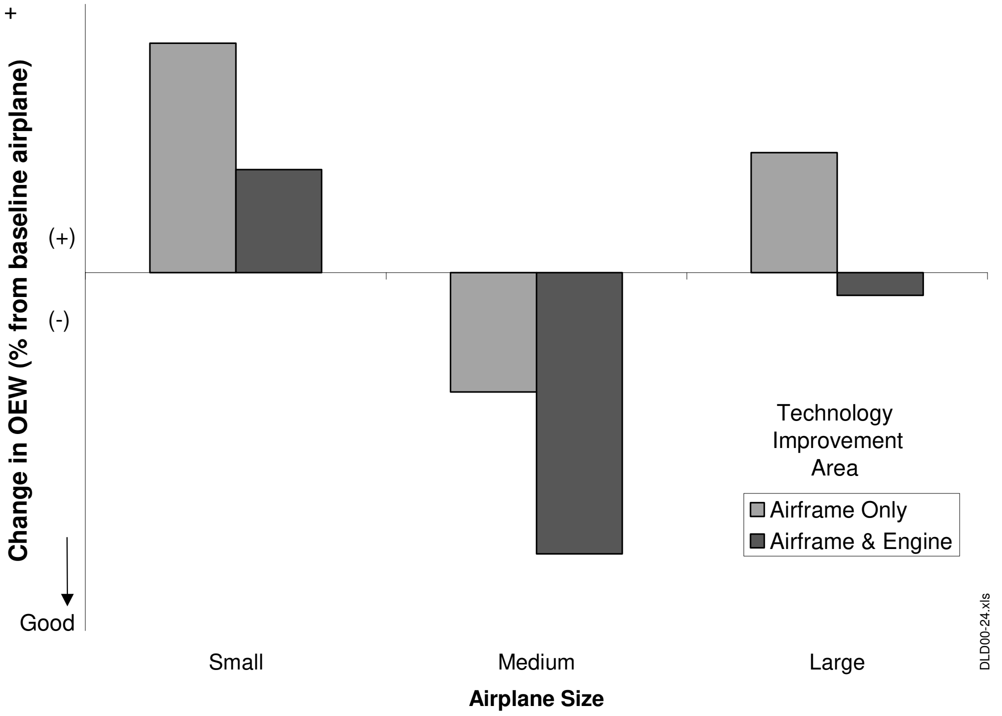


Figure 4.2.2, Absolute Weight Comparisons

Generally, larger aircraft are less fuel sensitive (on a % increase basis) to a given increase in weight than smaller aircraft. Thus, for a 1,000 pound increase in OEW, a 747 would exhibit less of a block fuel efficiency penalty (% increase) than a 737. This is due to the fact that the larger aircraft has a higher block fuel usage rate than the smaller aircraft, so the increased fuel use is comparatively small. The general trend in % block fuel increase per 1,000 pound added OEW is shown in Figure 4.2.3.

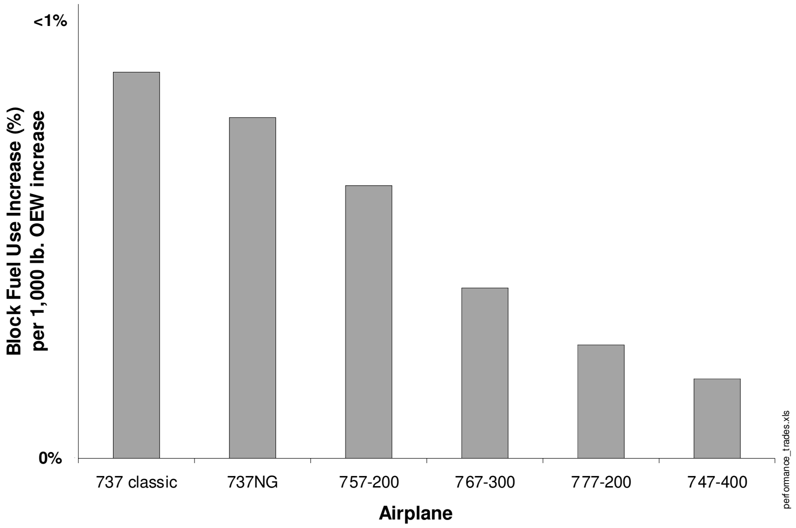


Figure 4.2.3, Airplane Fuel Use Sensitivity to Weight Increases

Percent increases to airplane drag versus percent increases to block fuel burn are relatively flat. All studied aircraft exhibit about an 0.8% increase in fuel burn for a 1.0% increase in drag as shown in Figure 4.2.4

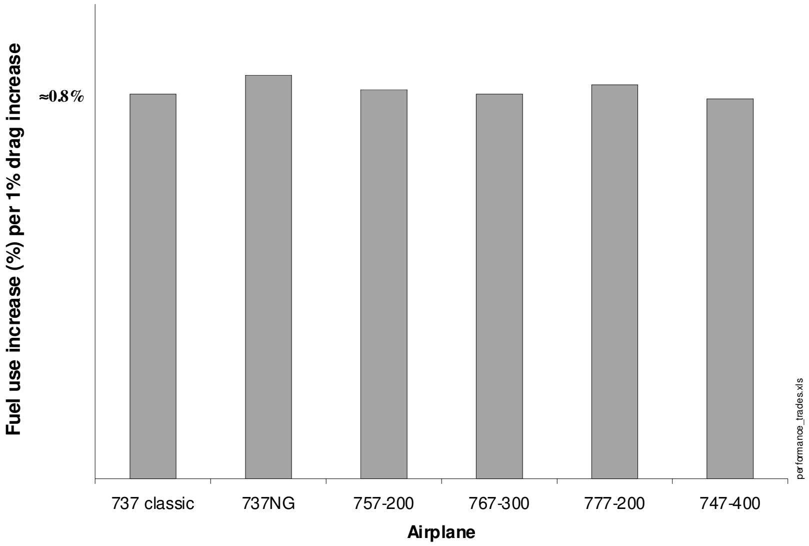


Figure 4.2.4, Airplane Fuel Use Sensitivity to Drag Increases

As the UEET aircraft were designed to meet realistic anticipated future customer requirements, the speed of some aircraft were increased. To account for the benefit of this variable, an aerodynamic metric titled "Cruise Range Factor" is shown in Figure 4.2.5 wherein cruise velocity (V), engine SFC and L/D are accounted for. Improvements in airplane speed and L/D illustrate that these factors make for large productivity gains between the baseline airplanes and the UEET airplanes with current technology engines. The effect of improved engine SFC on cruise range factor is illustrated between the UEET airplane with conventional engines (i.e. "airframe") and the UEET airplane with UEET engines (i.e. "+ engine").

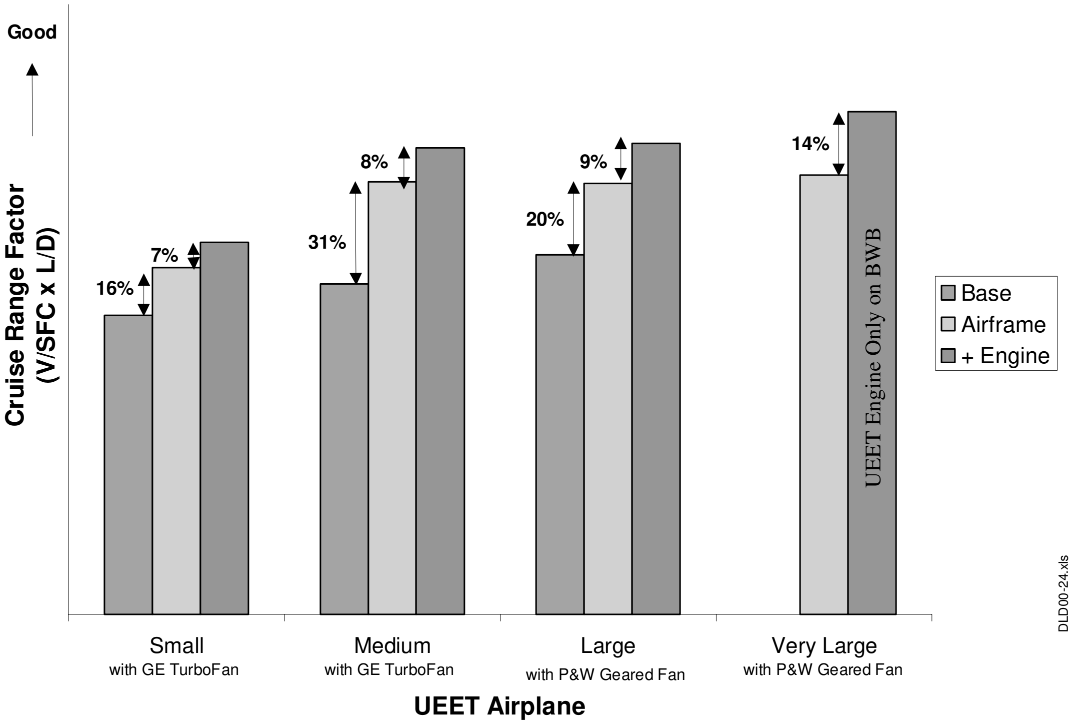
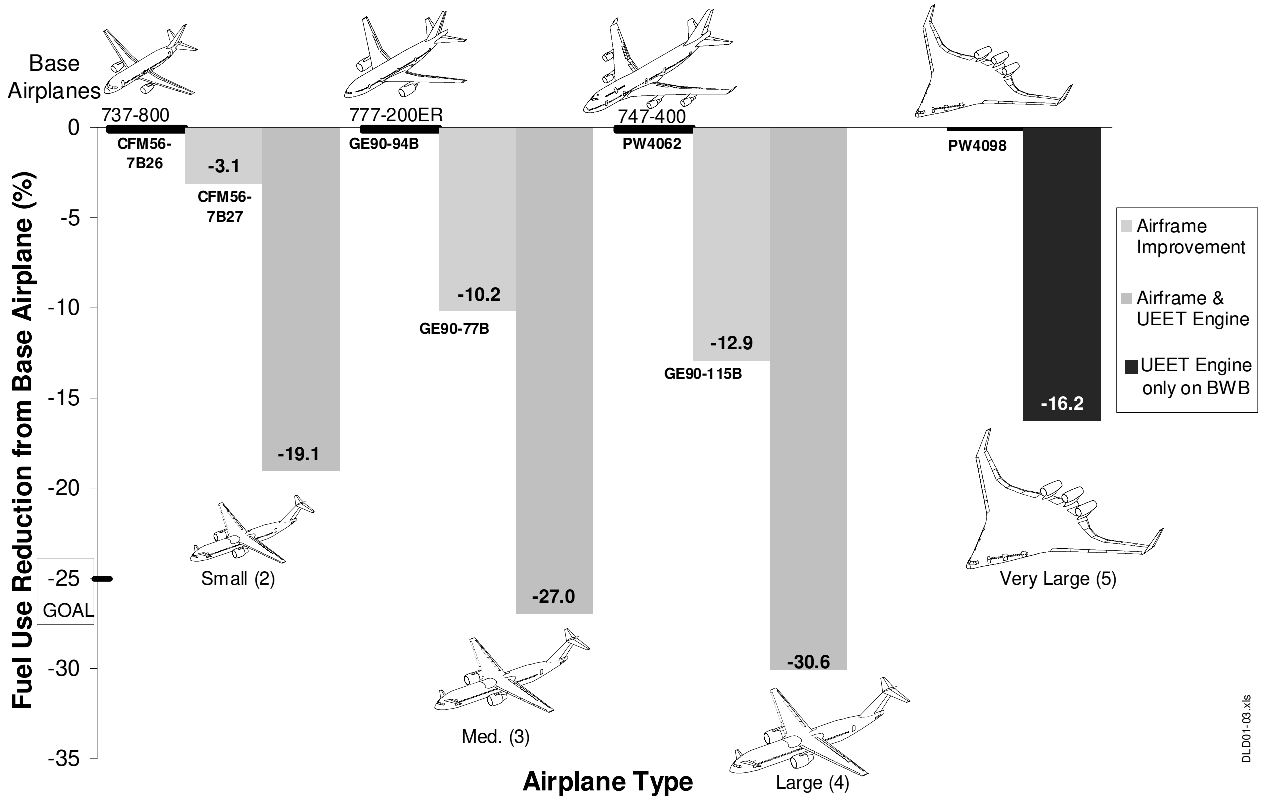


Figure 4.2.5, Comparison of Airframe and Engine Technology on Aerodynamic Productivity

4.3 Block Fuel Use

The amount of block fuel the aircraft uses on a mission includes standard allowances for the particular model (e.g. 737-800/CFM56-7B27) during taxi out, approach and taxi in. Block fuel use also includes calculated values for takeoff, climb-out, climb, cruise and descent.

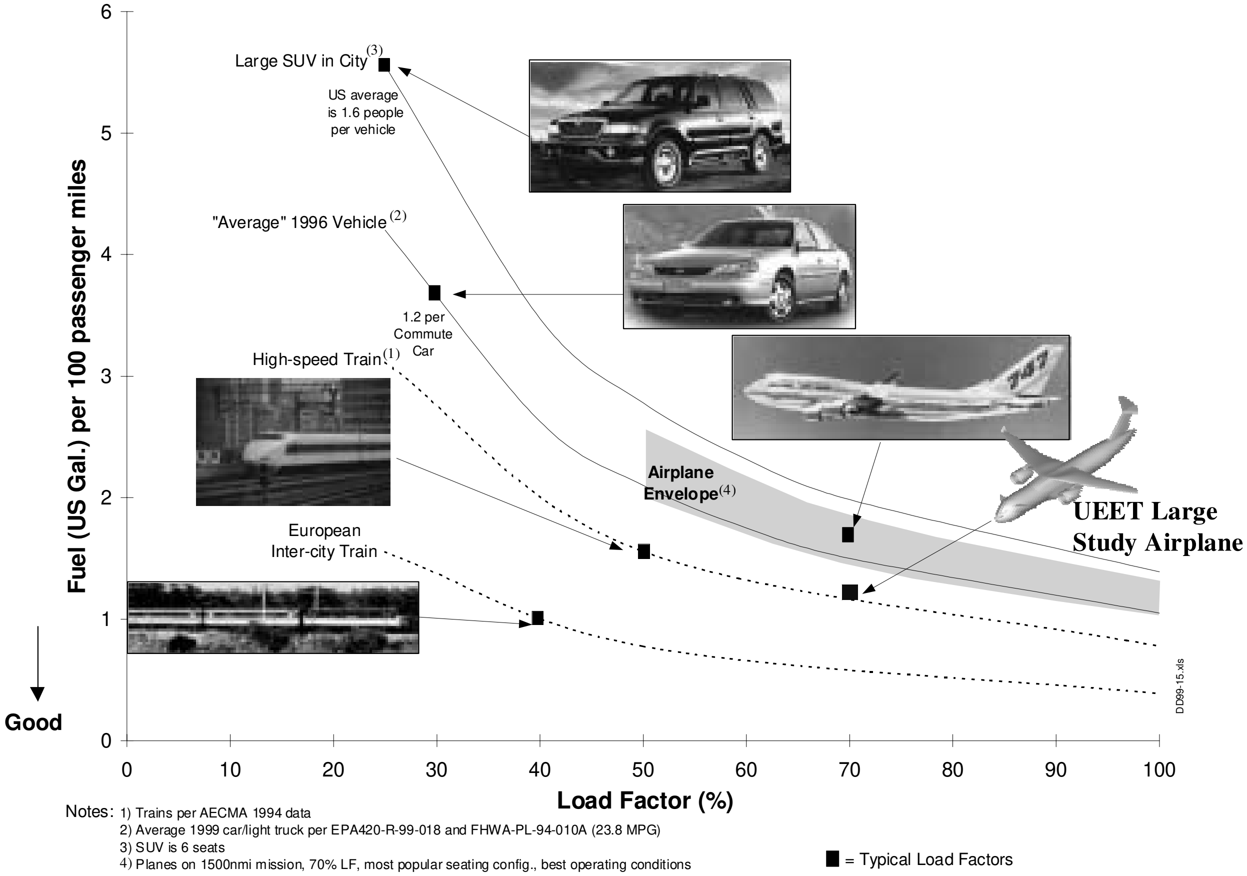
Figure 4.3.1 illustrates a block fuel use comparison (% change) between the baseline airplane, and advanced airframe with current technology engines and advanced airframe with UEET engines. The small airplane with advanced technology airframe and conventional engines only achieved a 3.1% fuel use improvement due to the penalties associated with the increased passenger comfort levels of that airframe. Using an UEET engine on that airplane further reduced the fuel use, but failed to bring the airplane to the -25% Boeing goal level. However, the medium and large airplanes more than met the airplane goal level. Since there was no conventional baseline very large airplane for comparison with, the BWB aircraft only shows the block fuel reduction that is associated with the use of UEET engines. All of the airplane engines met the –15% NASA block fuel use reduction goal.



Notes: 1. All airplanes loaded at 70% pax. LF
2. 1,000 nmi, 0.8 Mach, 162 seats
3. 3,000 nm , 0.85 Mach, 305 seats
4. 3,000 nmi, 0.85 Mach, 420 seats
5. 3,000 nmi, 0.855 Mach, 571 seats

Figure 4.3.1, Airplane Block Fuel Use

When comparing the fuel efficiency of aircraft with other modes of transportation, it is important to consider average passenger load factors as this can dramatically impact the “per passenger fuel mileage” results. Figure 4.3.2 shows the fuel used per passenger and average load factors for current automobiles, current production commercial aircraft, and European trains. When considering that aircraft have an average passenger load of 70% of seating capacity(7), commercial aircraft are quite competitive. The application of advanced airframe technology and UEET engines makes a large airplane as fuel efficient as a high-speed train on a 1,500 NMI mission. However, shorter mission lengths will result in poorer aircraft fuel efficiency.

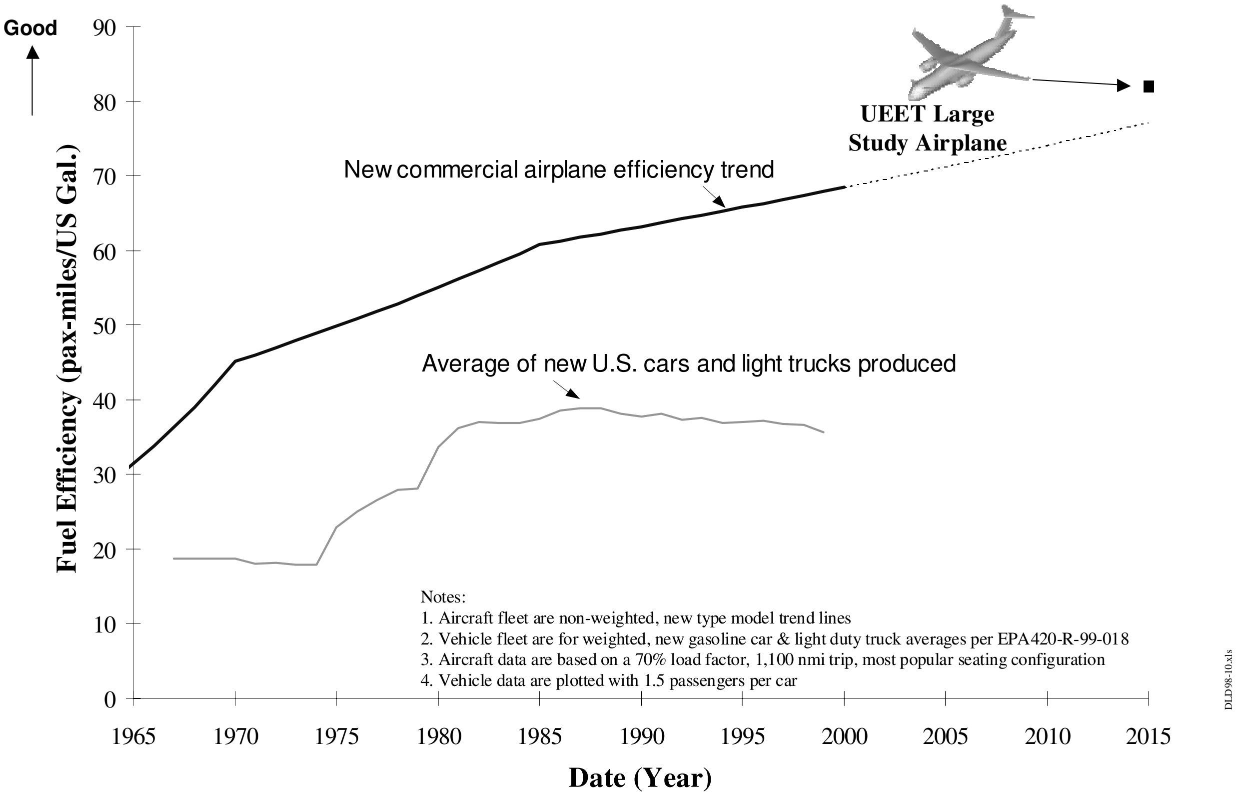


Notes: 1) Trains per AECMA 1994 data
2) Average 1999 car/light truck per EPA420-R-99-018 and FHWA-PL-94-010A (23.8 MPG)
3) SUV is 6 seats
4) Planes on 1500nmi mission, 70% LF, most popular seating config., best operating conditions

Figure 4.3.2, UEET enables one of most efficient transportation modes

Figure 4.3.3 shows the historical fuel efficiency trend for combined new automobile and light truck fleets as well as the trend of newly certified commercial aircraft. The automobile trend line represents the average new fleet's measured fuel efficiency accounting for make and number of models sold (i.e. weighted) over time for combined city/highway fuel mileage. The aircraft trend line represents the calculated average fuel efficiency of each newly certified aircraft (i.e. non-weighted) over time assuming a 1,100 NMI mission length at 70% passenger load factor for the aircraft's most popular seating configuration (e.g. 305 seats in a 777-200ER tri-class configuration).

The figure shows that since 1965, average Boeing aircraft have had higher "per passenger" fuel efficiencies than cars and have shown continuous improvement while the US car and light truck fleet has actually experienced declines in recent years. This is primarily due to the recent popularity of light trucks and sport utility vehicles that are bringing the average US fleet fuel efficiency down. In the last 15 years, newly certified commercial aircraft have experienced roughly a 1% per year improvement in fuel efficiency when compared to their predecessor aircraft. If this trend were to continue to the year 2015, the UEET airplane is seen to achieve better fuel efficiency gains than would otherwise be experienced.



Notes:
1. Aircraft fleet are non-weighted, new type model trend lines
2. Vehicle fleet are for weighted, new gasoline car & light duty truck averages per EPA420-R-99-018
3. Aircraft data are based on a 70% load factor, 1,100 nmi trip, most popular seating configuration
4. Vehicle data are plotted with 1.5 passengers per car

Figure 4.3.3, UEET provides for a leap in fuel efficiency gains

4.4 Noise

There has been continued interest in reduction of aircraft community noise levels as increasing restrictions take place (Figure 4.4.1). Thus, one performance metric of interest in this study was for community noise level.

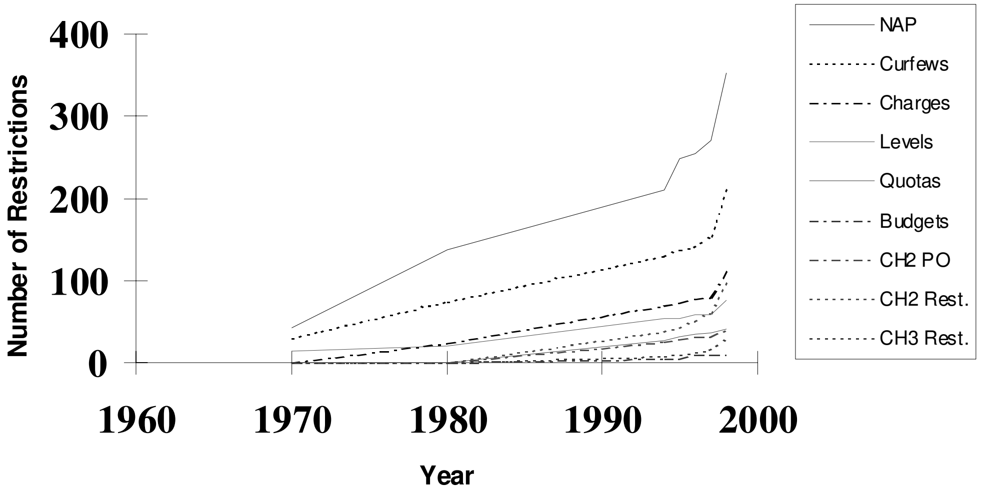
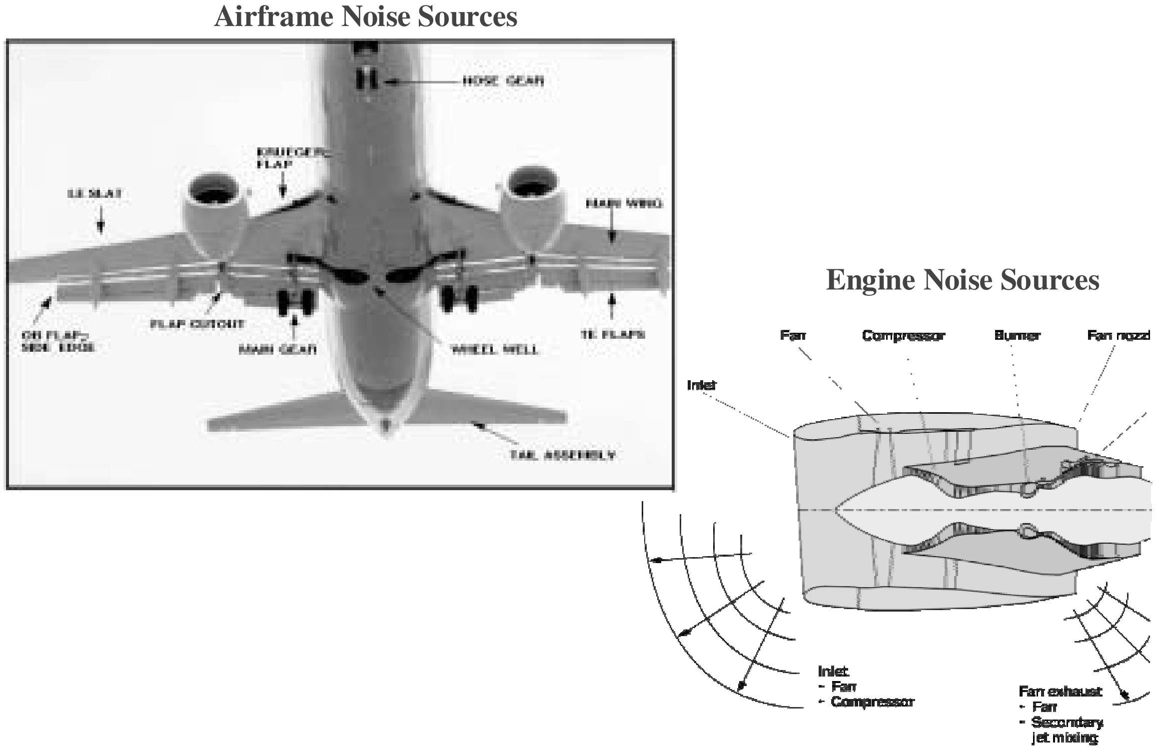


Figure 4.4.1, Improved noise levels are required due to increasing restrictions

Noise is generated from both airframe and powerplant sources as illustrated in Figure 4.4.2. The study airframe noise sources and levels were taken from traditional technology airplanes. The UEET engines used some noise reduction technologies, but the bulk of the noise reduction was from the use of high by pass ratio engines. Namely high BPR engines move large quantities of air through the engine more slowly than low BPR engines. This results in less shearing action between the ambient air and fan duct air as well as the engine core exhaust which generates less noise.


Airframe Noise Sources

Engine Noise Sources

Figure 4.4.2, Conventional airframe with advanced engine used for noise estimates

Figure 4.4.3 shows the standard definitions for measurement of noise during takeoff and approach as well as a sideline measurement. These definitions are used in the noise certification process of an aircraft and are also used to describe the noise levels that are calculated in this study and shown in Figures 4.4.4 through 4.4.7.

Thrust rating influences sideline noise most. Cutback flyover levels depend on good airplane performance for altitude over centerline microphone locations. Airframe noise can be as important as engine noise on approach. Noise improvement of the UEET airplanes includes lower thrust ratings and improved performance as well as noise beneficial engine cycles.

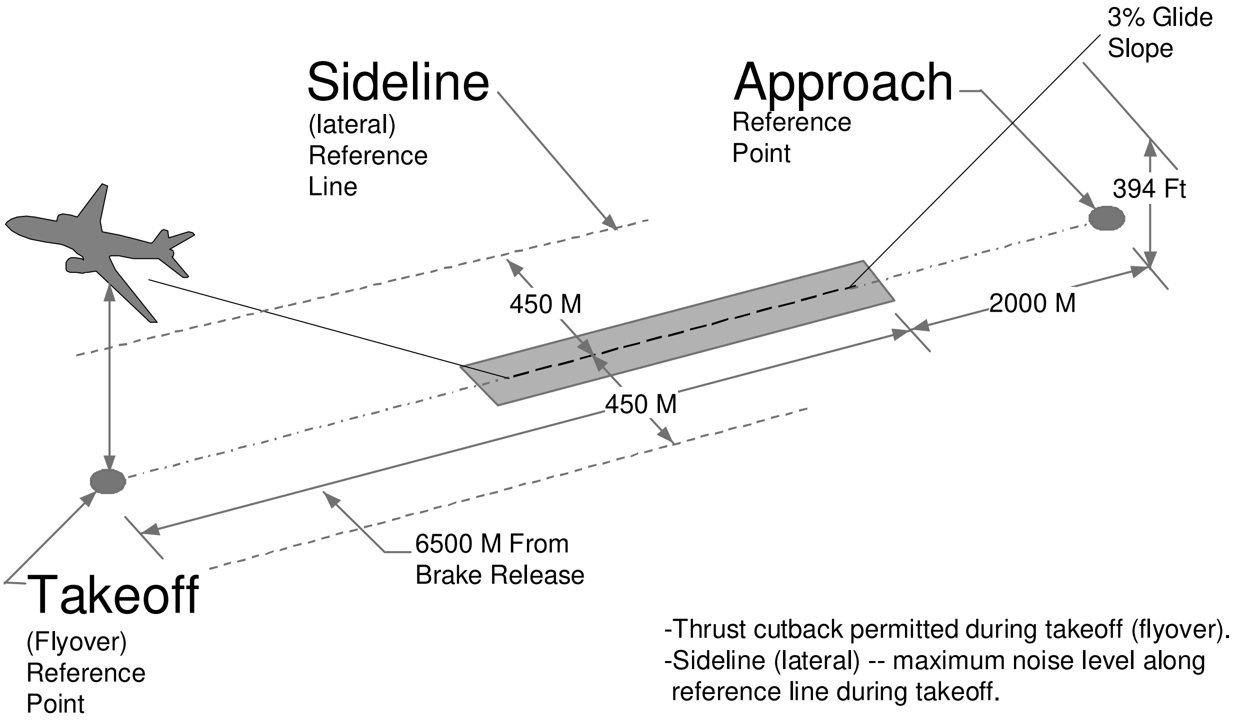


Figure 4.4.3, Noise Definitions

Three sets of community noise metrics are shown for each airplane and engine comparison in Figures 4.4.4 through 4.4.7. The certification noise estimates at approach, takeoff with cutback, and sideline are given in Effective Perceived Noise Level, (EPNL), in terms of EPNdB. This metric involves the time integration of the tone corrected perceived noise levels in the flyover time history.

Cumulative measures of the three certification points are shown in the center plot of each figure. A cumulative margin of ten (10) EPNdB below Stage 3 has been recommended to the International Civil Aviation Organization (ICAO) for the next noise certification requirement. A goal of Stage 3 minus 20 was used for this UEET study. Because of the unknowns in extrapolating noise data bases, and the likely variations in ultimate airplane performance, these UEET predictions must reserve appropriate tolerances for whatever levels might be assured.

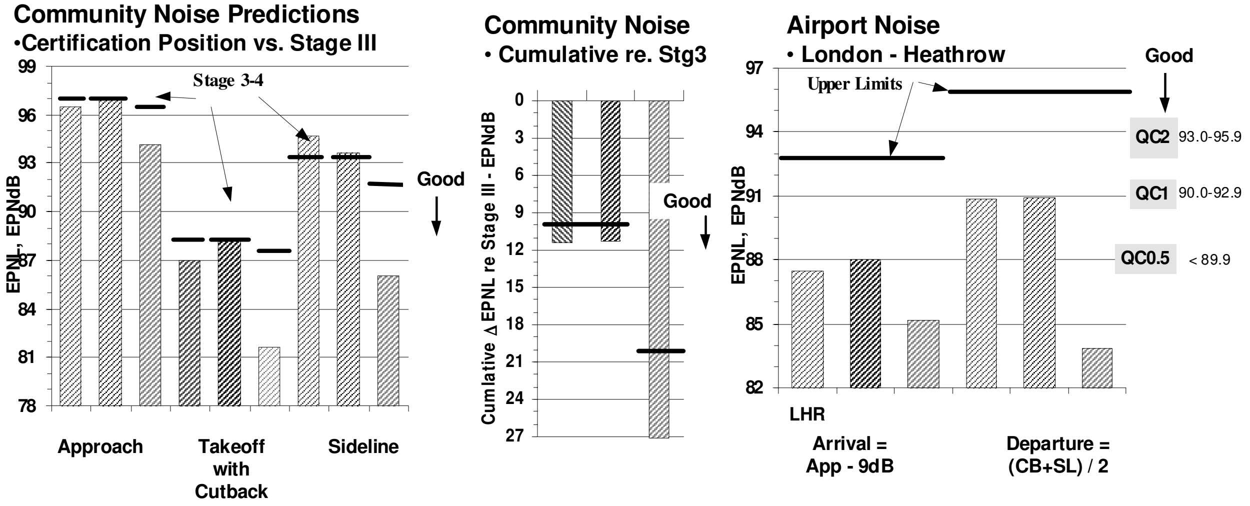
Night restrictions at London-Heathrow airport (LHR) are the "QC" categories shown in the right hand part of each figure. Certification levels are used in the calculation. The departure metric uses the average of cutback and sideline values, and the arrival metric subtracts "9" from the approach value. Today, achieving departure "QC2", less than 95.9 EPNdB is considered necessary.

▨ ***737-800***
MTOW = 174,200 lbs, MLW = 146,300 lbs
SLS = 27.3 klbs

▨ ***Conv Cycle***
MTOW = 181,385 lbs, MLW = 167,441 lbs,
SLS = 26.5 klbs

▨ ***UEET Cycle***
MTOW = 165,338 lbs, MLW = 151,433 lbs,
SLS = 26.5 klbs

Nominal Predictions: Certification or Guarantee Confidence Requires Appropriate Tolerances



UEET: GE Advanced Turbofan, BPR 11.0, Fan Diameter = 76.0"

Figure 4.4.4, Small UEET airplane met noise goals

▨ ***777-200ER***
MTOW = 656,000 lbs, MLW = 460,000 lbs
SLS = 94.0 klbs

▨ ***Conv Cycle***
MTOW = 594,000 lbs, MLW = 476,891 lbs,
SLS = 79.7 klbs

▨ ***UEET cycle***
MTOW = 524,618 lbs, MLW = 416,041 lbs,
SLS = 72.3 klbs

Nominal Predictions: Certification or Guarantee Confidence Requires Appropriate Tolerances

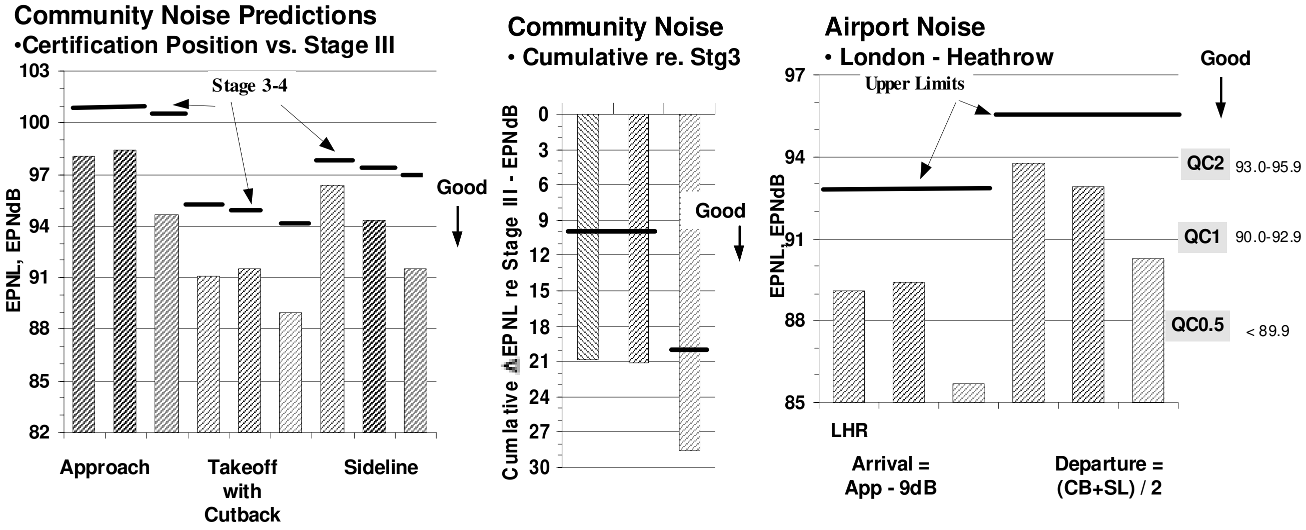


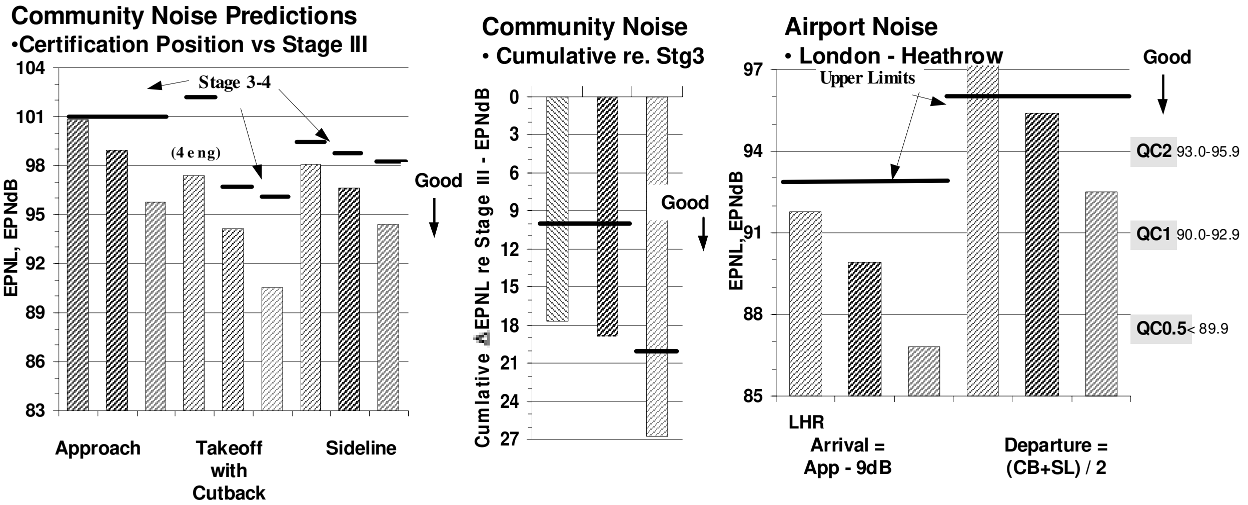
Figure 4.4.5, Medium UEET airplane met noise goals

▨ ***747-400***
MTOW = 875,000 lbs, MLW = 564,000 lbs
4 engines @ SLS = 63.3 klbs

▨ ***Conv Cycle***
MTOW = 824,140 lbs, MLW = 609,650 lbs,
2 engines @ SLS = 112.8 klbs

▨ ***UEET Cycle***
MTOW = 736,800 lbs, MLW = 575,058 lbs,
2 engines @ SLS= 108.3 klbs

Nominal Predictions: Certification or Guarantee Confidence Requires Appropriate Tolerances



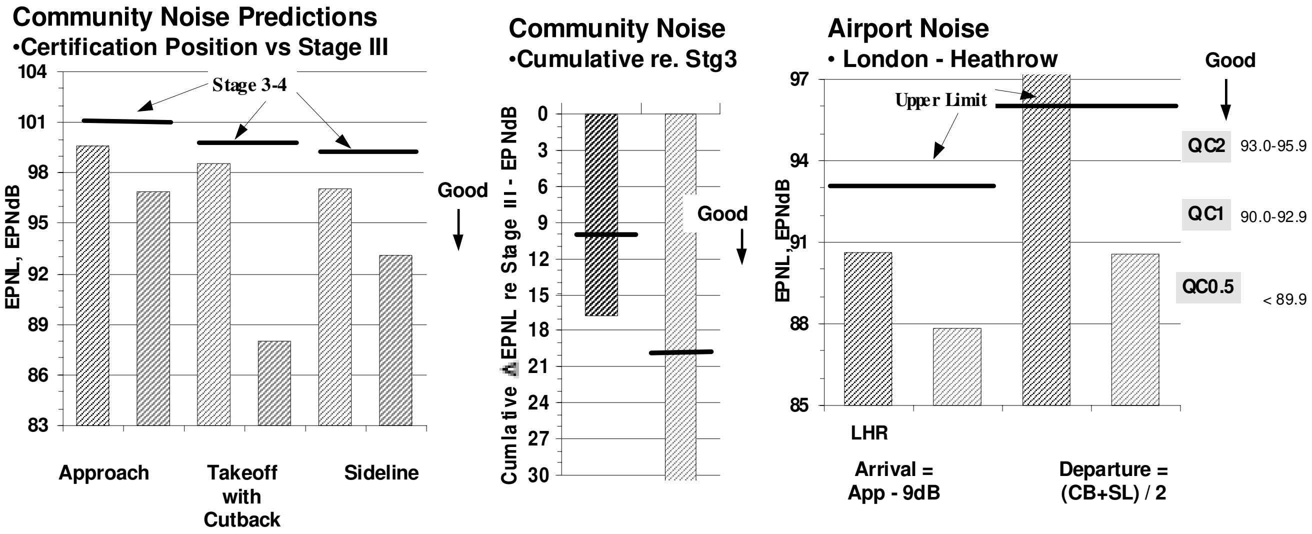
UEET: PW Geared Fan, BPR 14, Fan Diameter = 152"

Figure 4.4.6, Large UEET airplane met noise goals

▨ ***Conv Cycle***
MTOW = 1,076,000 lbs, MLW = 780,869 lbs,
SLS = 96.0 klbs

▨ ***UEET Cycle***
MTOW = 983,000 lbs, MLW = 775,000 lbs,
SLS = 102.9 klbs

Nominal Predictions: Certification or Guarantee Confidence Requires Appropriate Tolerances



UEET: PW Geared Fan, BPR 20.9, Fan Diameter = 155"

Figure 4.4.7, Very Large UEET airplane met noise goals

Only general aspects of the engine and nacelle configuration and design were considered for community noise estimates in this phase. The very high bypass ratio and some unique turbomachinery operating points are outside the conventional engine noise database. As major noise sources such as jet noise is reduced, the acoustic design features for secondary noise sources become more important.

4.5 Emissions

One of the objectives of the study was to achieve lower NOx emissions while also decreasing fuel use. The burning of fossil fuels produces CO_2, which is also a gaseous emission. For jet fuel, a direct relationship exists between the amount of fuel burned and the amount of CO_2 and water vapor generated. For every pound of jet A fuel burned, 3.16 pounds of CO_2 and 1.24 pounds of water are generated as illustrated in Figure 4.5.1. Thus, the amount of CO_2 generated is a function of the amount of fuel consumed and the amount of carbon atoms in the fuel's molecular makeup. Low emissions combustor designs exhibit nearly 100% combustion efficiency and are able to reduce other emissions, but they are unable to reduce CO_2 because this is a fuel phenomenon.

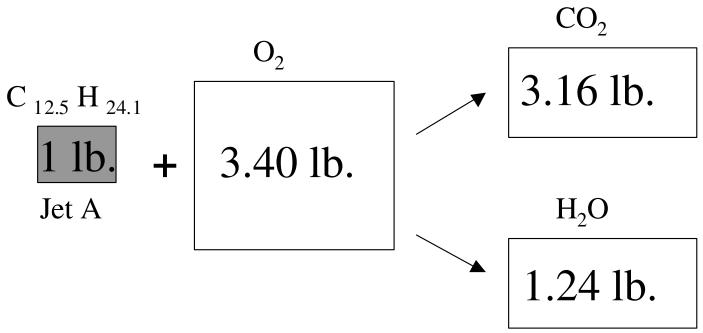


Figure 4.5.1, CO_2 is an efficient byproduct of combustion

Recently, there has been increasing emphasis on reducing CO_2 emissions because they have been suggested to be responsible for an increase in global warming. Thus, part of this study emphasizes the reduction in CO_2 emissions (fuel use).

In order to evaluate the absolute amount of CO_2 emissions reduction, some airplane performance guidelines need to be understood. The absolute amount of CO_2 generated increases with the aircraft mission length; it also increases with the amount of payload carried. Thus, when considering payload and mission length, it can be seen in Figure 4.5.2 that the study aircraft have a similar efficiency trend wherein mission lengths in the 1,500-3,000 NMI range are the most efficient. A 1,500 NMI mission length was used as the standard comparison point. In the past, this has allowed comparison of aircraft with shorter ranges.

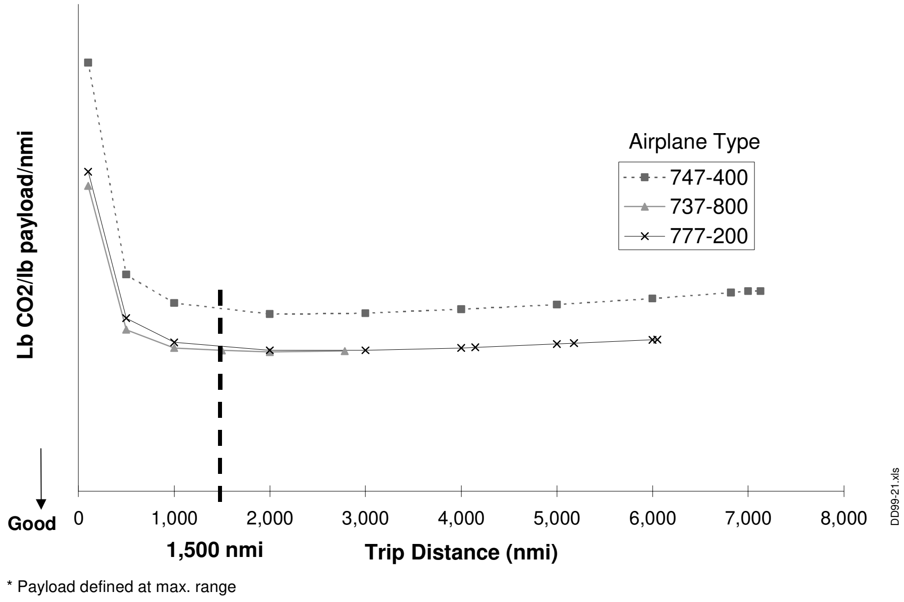


Figure 4.5.2, 1,500 NMI used as the CO_2 baseline mission length for commonality

Seating configuration can also impact the efficiency of an aircraft. The more fully an aircraft is loaded, the less CO_2 emissions will be generated per pound of payload carried. For instance, changing a 777-200 aircraft's seating configuration from a tri-class configuration (1st, 2nd and coach) to a single class (all coach) configuration will change the seat count from 305 to 440. This will increase the available payload and reduce the amount of CO_2 generated by 26%.

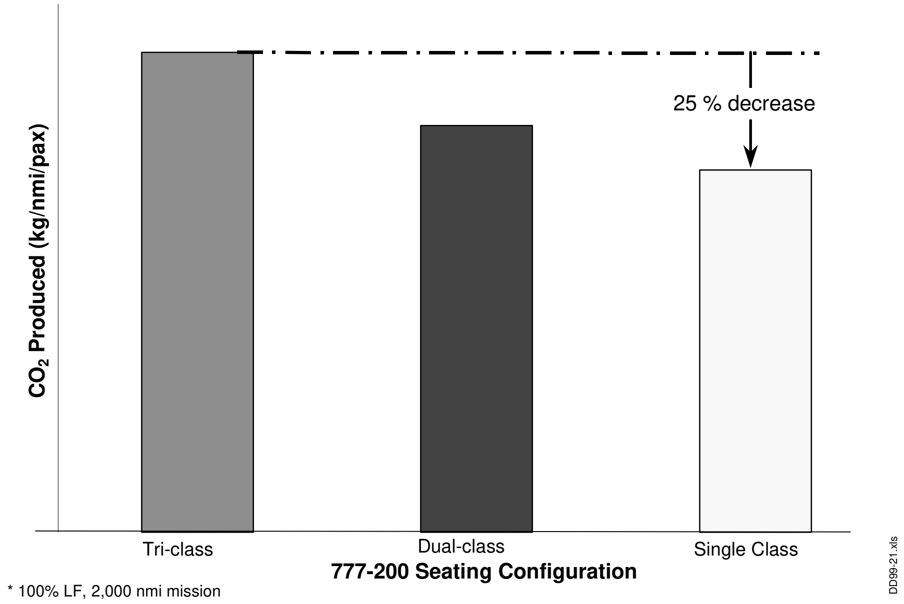


Figure 4.5.3, Number of seats affects per passenger efficiency matrix

For the studied aircraft, the most often airliner ordered seating configuration for each model was chosen. Thus, the small aircraft utilized a dual-class configuration while the medium, large and very large airplanes used a tri-class configuration. This resulted in the small aircraft having a higher seating density, which resulted in a more efficient mission having the lowest CO_2 emissions of any airplane (Figure 4.5.4).

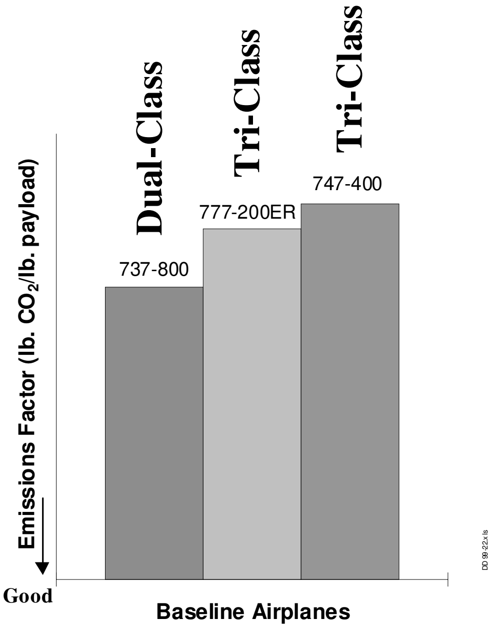
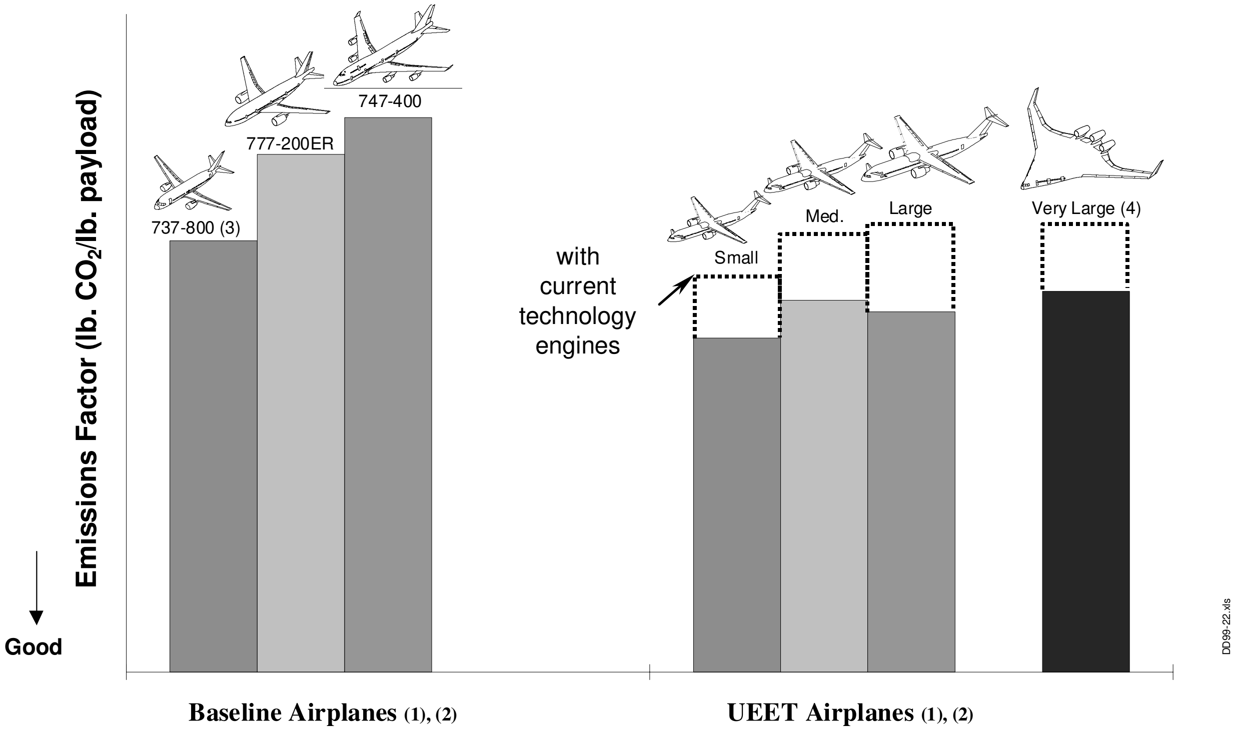


Figure 4.5.4, Seating configuration affects per passenger emissions

Similarly, the amount of actual enplaned passengers, or load factor, on an aircraft affects the results, empty airplanes being the least efficient when measuring emissions on a per pound of payload carried basis. For this study, a common 70% passenger load factor was used.

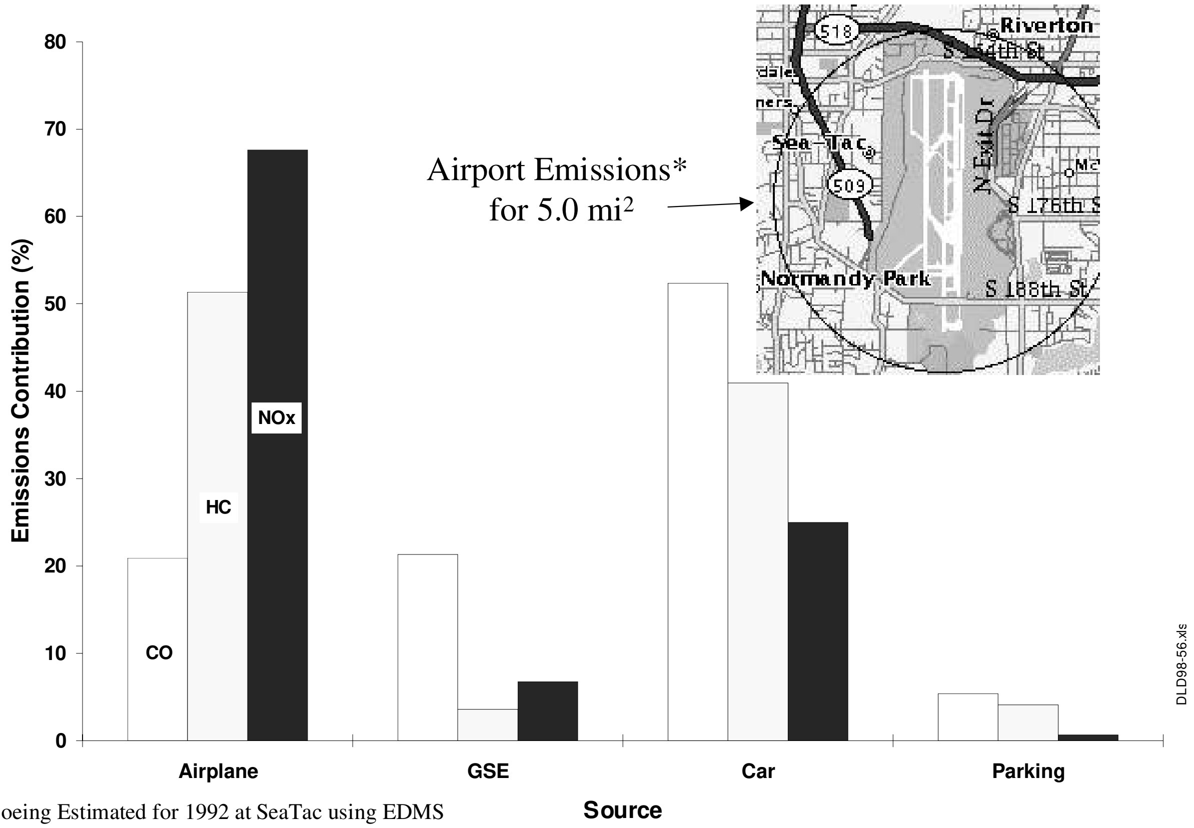
Figure 4.5.5 shows the absolute CO_2 emissions for each aircraft, normalized for mission length and passenger load factor, but retaining the seating configuration effects. Thus, the 737 and small UEET airplanes show the least amount of CO_2 emissions due their dual-class seating arrangement. The advanced technology airframes and UEET engines show that they are able to drastically reduce CO_2 emissions when compared to the baseline airplanes. For the very large airplane (BWB), the comparative efficiency is similar to the UEET airplanes. Its efficiency would improve when including all of the same airframe technologies as were used on the wing and tube airplanes.



Notes:1. Loaded at 70% passenger load factor at each airplane's most popular seating configuration
2. Flown at optimum profile for 1,500 nmi Mission
3. Lower emissions factor is due to dual class seating vs. tri-class on other 3 airplanes
4. Current configuration (does not include many UEET airframe technologies)

Figure 4.5.5, UEET enables large reductions in CO_2 emissions

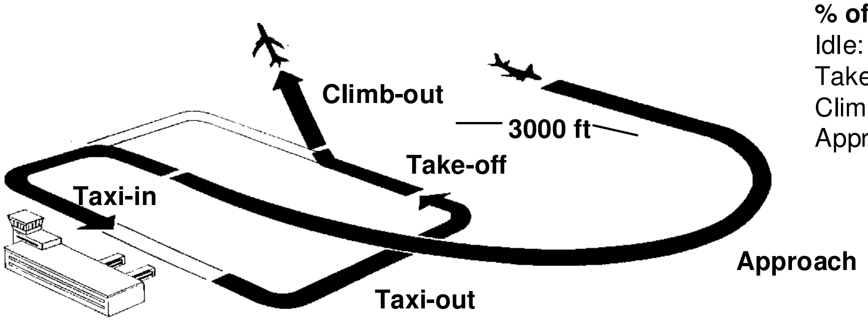
Although aircraft are calculated to typically produce less total emissions than cars at airports, airplane Oxides of Nitrogen (NOx) emissions are under scrutiny due to their relative contribution amount (Figure 4.5.6). Aircraft produce larger amounts of NOx than Hydrocarbon (HC) or Carbon Monoxide (CO) emissions due to their high power operation during takeoff. Surface vehicles (e.g. cars) are calculated to produce larger amounts of CO and HC because of the many idling automobiles waiting to drop off or pick up passengers at the airport.



* Boeing Estimated for 1992 at SeaTac using EDMS

Figure 4.5.6, NOx is the Airplane Emission of Focus at Airports

The standard method of calculating airport emissions for aircraft is the Landing Take Off (LTO) cycle (8). Established times in modes are set for each operating condition (idle, taxi, takeoff and approach). The fuel flow (kg. /min.) and emissions index (grams of emission per kg of fuel consumed) at each operating condition is measured during the certification process of the engine model. Summing up these values and dividing by the engine's SLS takeoff thrust produces a result titled "Dp/Foo". This is used in evaluating the UEET emissions result.



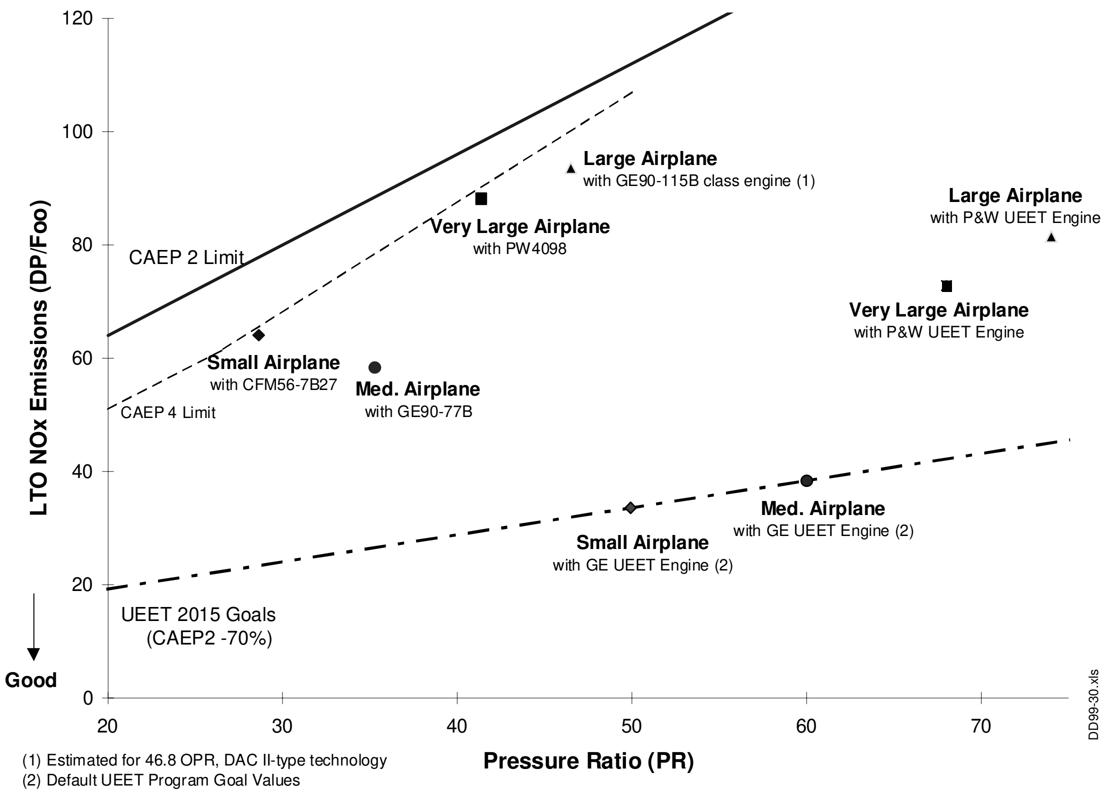
Power setting
% of std. day take-off (T/O) thrust
Idle: 7%
Take-off: 100%
Climb: 85%
Approach: 30%

Operating mode	Time		*Fuel Flow*		*EI*		Dp/Foo
1. Taxi / idle	26.0 minutes	•	*x.x kg/min*	•	*x.x g/kg fuel*	=	x.x g/kN
2. Take-off	0.7 minutes	•	*x.x kg/min*	•	*x.x g/kg fuel*	=	x.x g/kN
3. Climb	2.2 minutes	•	*x.x kg/min*	•	*x.x g/kg fuel*	=	x.x g/kN
4. Approach	4.0 minutes	•	*x.x kg/min*	•	*x.x g/kg fuel*	=	x.x g/kN
							Sum ÷ *T/O Thrust* = **Ave. Dp/Foo**

Figure 4.5.7, Landing Take Off (LTO) is used to measure airport emissions

Figure 4.5.8 shows the LTO Dp/Foo NOx emissions for each of the baseline and UEET engines as well as their overall pressure ratio. All of the current technology engines meet the current CAEP 2 limit as well as the CAEP 4 limit that will go into effect in 2004.

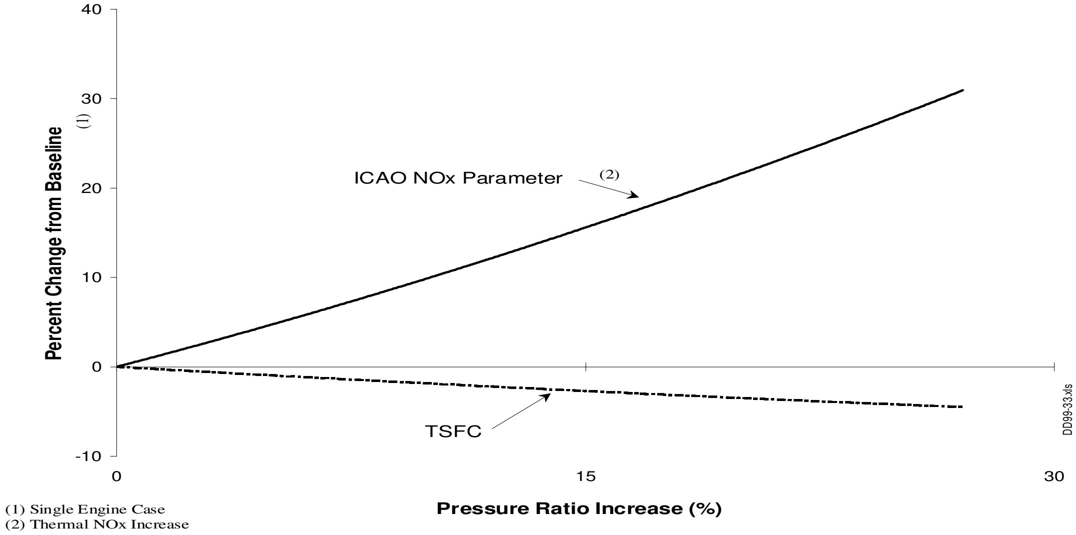
No emissions values were supplied by GEAE for the engines used on the small and medium airplanes. However, it was suggested by GEAE that they would be able to meet the CAEP2 –70% UEET goal levels, and so are thereby illustrated at this level. The P&W engines did not meet the UEET goal.



(1) Estimated for 46.8 OPR, DAC II-type technology
(2) Default UEET Program Goal Values

Figure 4.5.8, UEET offers improved NOx emissions

As discussed in section 4.1, the UEET engines increased fuel efficiency partly by increasing OPR. This has an adverse affect on NOx emissions; that is, high OPR engines generate increased levels of NOx. Figure 4.5.9 illustrates that for a significant percentage increase in OPR, a slight percentage decrease in fuel consumption will be realized, but at the expense of a large increase in NOx emissions.



(1) Single Engine Case
(2) Thermal NOx Increase

Figure 4.5.9, NOx rises precipitously for small increases in pressure ratio

When the NOx/OPR relationship is considered, an evaluation of the relative improvement of the P&W UEET engine shows a substantial decrease in NOx emissions. Figure 4.5.10 shows that when OPR is set to a common value of 30:1 (assuming a 91% compressor efficiency), the normalized (via NOx severity parameter) takeoff NOx emissions index for the P&W UEET engines compares favorably to older technology combustors from P&W(9). 1980's and 90's technology combustors from Rolls-Royce and CFMI are also shown (9).

If lower NOx emissions were to be required, the engine cycle could be adjusted to lower the OPR in order to more easily achieve the desired level. The optimum NOx/OPR/SFC/CO_2 tradeoffs have yet to be determined.

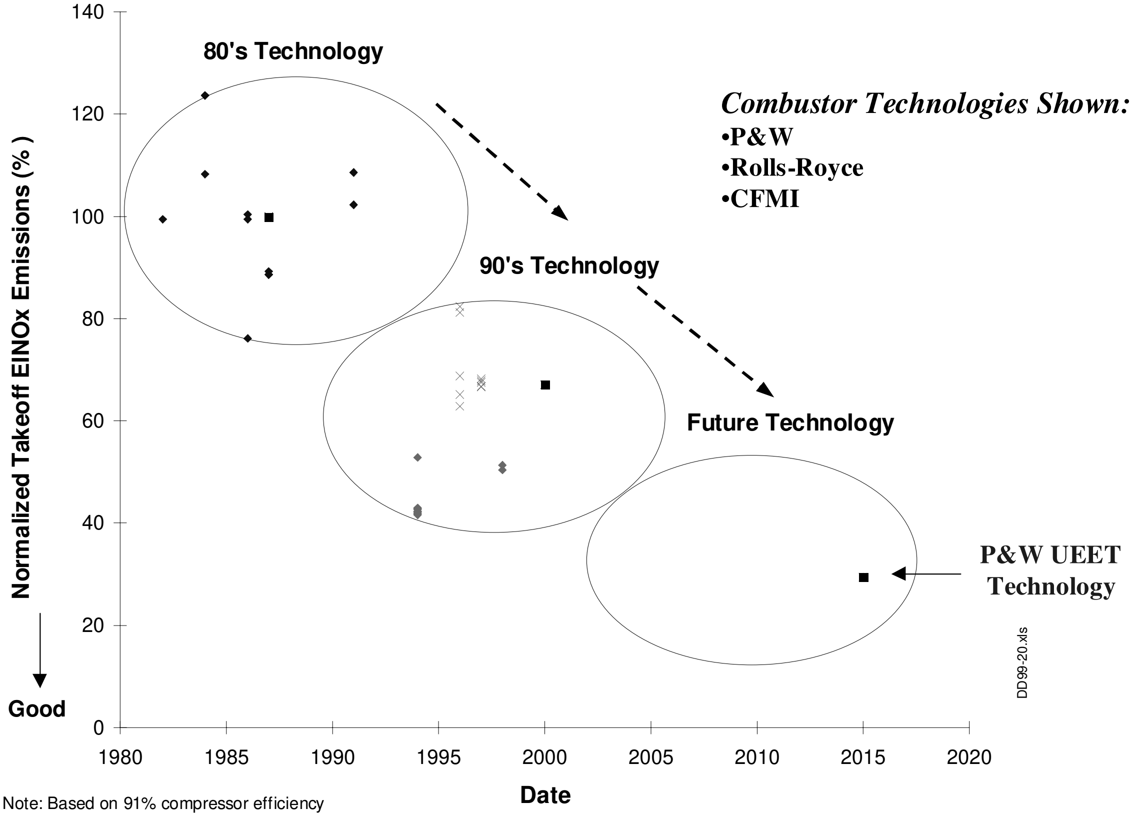


Figure 4.5.10, P&W combustor shows significant NOx improvement when normalized

Figure 4.5.11 shows that the P&W engine meets the HC and CO emissions goal with ease. Due to unavailability of data, the GEAE engines are again illustrated at the default UEET goal levels.

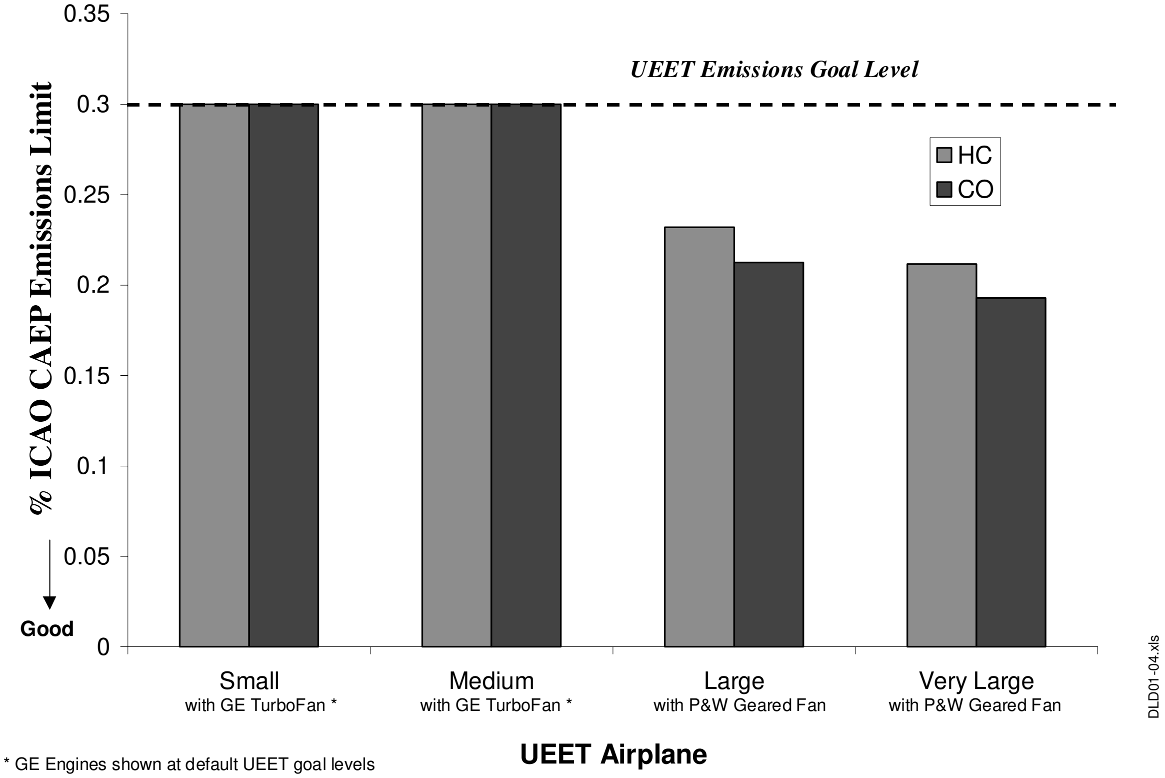


Figure 4.5.11, HC and CO emissions met goal levels

5.0 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the small, medium and large aircraft with advanced airframe technology and UEET powerplants achieved better block fuel burn reductions than the Boeing goal (-25% from baseline airplanes). The small aircraft did not meet the goal due to increases in aircraft speed and passenger comfort levels. All engines achieved the NASA goal of –15% block fuel improvement.

All of the aircraft met the Boeing airplane Noise goals of Chapter 3 minus 20dB cumulative.

The Pratt & Whitney engines met the HC and CO emissions goals, but did not meet the NOx goals. This is partly due to the tradeoffs associated with very high-pressure ratio engines. An emissions assessment was not possible for the GEAE engines due to unavailability of data.

Commercialization of UEET powerplants will enable the production of more fuel-efficient future commercial aircraft than would otherwise occur.

It is recommended to conduct an engine sizing tradeoff study to find the optimal design conditions for each of the two UEET architectures that are employed by Pratt and Whitney and GEAE. This will enable airframe manufacturers, and engine companies, to focus on the development of optimally sized engines and appropriate airframe configurations. Once engine sizing tradeoff studies are concluded, the benefits of engine installation on low-wing versus high-wing aircraft can be evaluated. Thus, an optimally designed engine may drive airframe configuration.

Efficient engines are only half the fuel efficiency solution. Airframe technology must also be developed. It is recommended to select the best engine and airframe configuration(s) for further development of high-risk, high-payoff technologies.

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13. ABSTRACT ***(Maximum 200 words)***

This study documents the design and analysis of four types of advanced technology commercial transport airplane configurations (small, medium, large and very large) with an assumed technology readiness date of 2010. These airplane configurations were used as a platform to evaluate the design concept and installed performance of advanced technology engines being developed under the NASA Ultra Efficient Engine Technology (UEET) program. Upon installation of the UEET engines onto the UEET advanced technology airframes, the small and medium airplanes both achieved an additional 16% increase in fuel efficiency when using GE advanced turbofan engines. The large airplane achieved an 18% increase in fuel efficiency when using the P&W geared fan engine. The very large airplane (i.e. BWB), also using P&W geared fan engines, only achieved an additional 16% that was attributed to a non-optimized airplane/engine combination.

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