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Aircraft Optimization for Minimal Environmental Impact

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The feasibility of integrating environmental considerations into aircraft conceptual design is explored. The approach involves designing aircraft to meet specific noise and emission constraints while minimizing cost. A detailed noise prediction code (NASA Langley Research Center's ANOPP) is coupled with an engine simulator (NASA John H. Glenn Research Center's NEPP) and in-house aircraft design, analysis, and optimization modules. The design tool and a case study involving a 280-passenger airliner are discussed. The study includes operational aspects, such as steeper approaches and takeoff thrust cutback for noise reduction. Low-emissions (CO_2 and NO_x) designs are also evaluated. Results show that optimized designs featuring cumulative noise reductions of up to 25-dB effective perceived noise level may be obtained with as little as a 3% increase in operating cost. The study also establishes a tradeoff between noise and emissions performance.

Introduction

NOISE and emissions have been of concern since the beginning of aviation, and continuous air traffic growth and increasing public awareness have made environmental performance one of the most critical aspects of commercial aviation today. It is generally recognized that significant improvements to the environmental acceptability of aircraft (whether through design, operations, or both) will be needed to sustain long-term growth.

Whereas considerable progress has been made to decrease aircraft noise at the source, the public's perception of noise continues to grow, as illustrated by the ever-increasing number of public complaints. This can be attributed to increasing air traffic, as well as the further encroachment of airport–neighboring communities. As a result, noise has become a major inhibitor of air traffic growth, with 60% of all airports considering it a major problem and the nation's 50 largest airport viewing it as their biggest issue.[1] The construction of new runways and airports raises massive issues due to public fears of increased air traffic and the associated louder, or more frequent, noise.

In response to these public concerns, airports have adopted operational restrictions on top of the International Civil Aviation Organization (ICAO) certification guidelines. A survey of the world's airports reveals a twofold increase in the number noise-related restrictions in the past 10 years.[2] These include curfews, fines, operating restrictions, and quotas (Fig. 1). In particular, night operations have been increasingly restricted. The quota count system at London Heathrow,[‡] for example, restricts the operations of aircraft through a points system. Each landing and takeoff costs points based on the certification noise of the airplane. By operating quieter aircraft, the airline can add more flights. In addition, at nighttime, only the quietest aircraft are allowed to operate. The result is that airlines, especially those likely to operate at night, face equipment and scheduling constraints. With the recognition of the importance of such restrictions, manufacturers have adopted the London system as a benchmark for the noise levels of their aircraft.

The historical trend in aircraft noise has shown a reduction of approximately 20 dB since the 1960s[3] largely due to the adoption of high-bypass turbofans and more effective lining materials. Reductions since the mid-1980s have not been as dramatic (Fig. 2), and future improvements will require further tradeoffs between operating costs and environmental performance, as shown notionally in Fig. 3: Reducing noise beyond a certain level will incur an operating cost penalty.

Environmental concerns have become driving forces in the design and operation of commercial aircraft. During a typical design process, the airplane is designed to meet performance and cost goals and then adjusted (usually through changes to the engine) to satisfy the environmental requirements of individual airports or airlines.

A good example is the Airbus A380, an airliner that explicitly trades fuel efficiency for lower noise[4]: The fan of the A380 engine has been sized larger than required for lowest fuel consumption, specifically to meet nighttime restrictions at Heathrow Airport. This modification was made well into the design phase at the request of the airlines. This trend is expected to continue as noise restrictions become increasingly stringent at airports around the world.

The ICAO Assembly has endorsed the concept of a balanced approach, which aims to address noise issues by working simultaneously on aircraft noise at the source (the main focus of past efforts), aircraft operational procedures, operating restrictions at airports, and land-use planning and management (Fig. 4). Although the focus of this paper is on the manufacturer contributions, significant reductions in acoustic nuisances around airports will also require contributions from airports, land planners, and local authorities.

The release of exhaust gasses in the atmosphere is the second major environmental issue associated with commercial airliners. The world fleet releases approximately 13% of CO_2 emissions from all transportation sources.[5] The expected doubling of the fleet in the next 20 years[§] will certainly exacerbate the issue, further increasing the contribution of aviation to anthropogenic emissions. Engine manufacturers have made low-emission combustors available as options and these have been adopted by airlines operating in airports with strict emissions controls.[¶]

Although modifications can be made to existing airliners to meet short-term noise and emissions requirements, further improvements in future aircraft will require a more systematic consideration of environmental constraints at the early design stage to ensure minimum

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‡Data available online at URL: http://www.aviation.dft.gov.uk/consult/night/index.htm, United Kingdom Department of the Environment, Transport, and Regions, January 1999 [cited 8 April 2003].

§Data available online at URL: http://www.boeing.com/commercial/cmo, The Boeing Company, 2002 [cited 8 April 2003].

¶Data available online at URL: http://www.lfv.se/lfv/environment/eng/emission_charges.asp, Swedish Civil Aviation Administration, October 2000 [cited 8 April 2003].

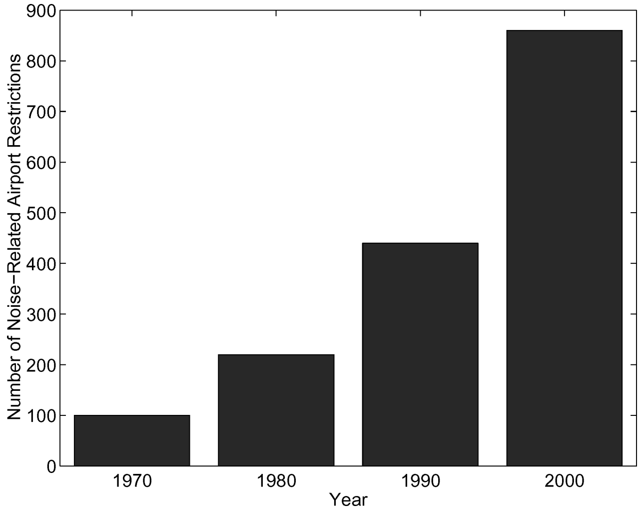


Fig. 1 Worldwide increase in airport-enforced noise restrictions.

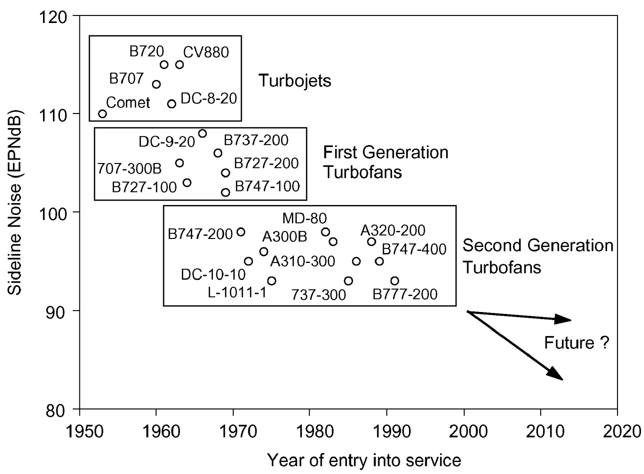


Fig. 2 Progress in noise reduction with use of select number of commercial aircraft of past 50 years (source: The Boeing Company)

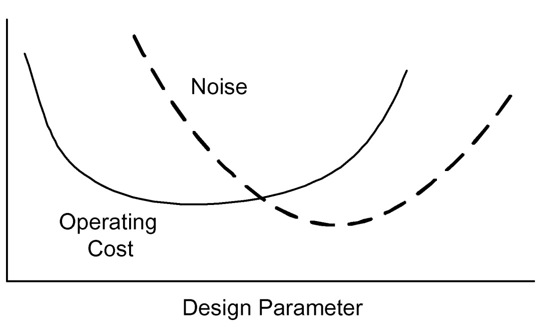


Fig. 3 Design challenge: estimating tradeoff between operating cost and environmental impact; what are costs involved in reducing noise and emissions of aircraft?

impact on operating costs. The advanced design tool described here explores the trade-off between operating costs and environmental performance, while optimizing the aircraft design.

The next segment is dedicated to the description of the design tool, including the aircraft design modules, noise and emissions modeling, and the database manager and optimizer. The focus of the results section is on case studies, including aircraft design for low noise, the impact of steeper approaches and takeoff thrust cutback on the objective, and finally a trade study of certification noise and operating cost.

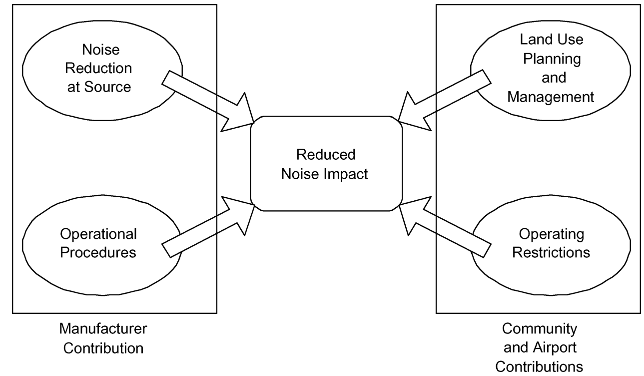


Fig. 4 ICAO balanced approach: successfully reducing noise impact of commercial aircraft on communities must include contributions from manufacturers and airports.

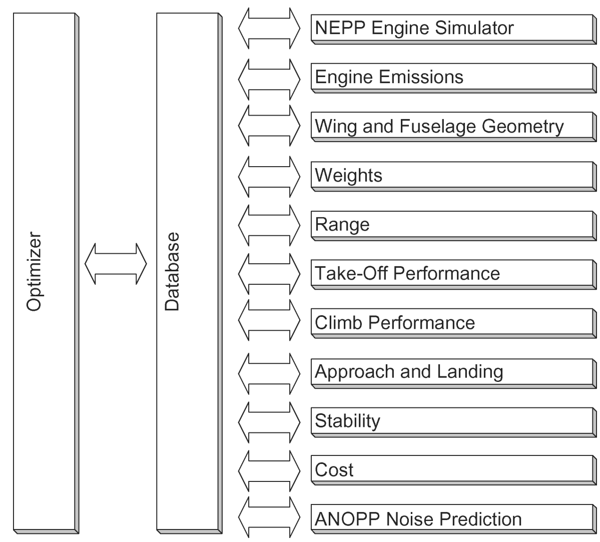


Fig. 5 Caffe design framework: aircraft design modules, noise prediction, and engine simulator coupled with an optimizer and database manager.

Methodology

The design tool is composed of a library of routines used to analyze key aspects of aircraft design and performance (Fig. 5). The integration of these multidisciplinary analyses and the optimization of the aircraft design are accomplished using the Caffe design framework (see Ref. 6) in conjunction with a nonlinear optimizer. Caffe allows the user to quickly reconfigure the design tool: Adding or removing design variables, objectives, and constraints is done via a simple graphical interface. The aircraft noise prediction program (ANOPP) developed by NASA Langley Research Center and the NASA John H. Glenn Research Center at Lewis Field engine performance program (NEPP) for predicting engine performance. The engine performance and noise estimation codes are coupled to programs that compute aircraft performance and operating cost.[7] These approximate methods are well suited for optimization due to their rapid execution and robustness.

Engine Performance

Developed at NASA John H. Glenn Research Center, NEPP is a one-dimensional steady thermodynamics analysis program. At the design point, NEPP automatically ensures continuity of mass, speed, and energy by varying the scale factors on the performance maps for the compressor and turbine components. Off-design operation is handled through the use of component performance tables and minimization of work, flow, and energy errors. The engine is then balanced by altering free variables of available components. Variable controls can also be used to obtain a certain performance. For

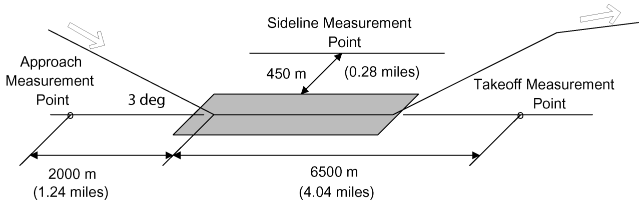


Fig. 6 ICAO certification noise measurement points.

example, airflow or combustion temperature can be varied to reach a desired thrust level. Controls are also used to limit and optimize engine parameters. Variables fed into NEPP include combustor exit temperature, overall pressure ratio, altitude, Mach number, sea-level static thrust, bypass ratio, and fan pressure ratio (the last four being supplied by the optimizer).

For the purpose of the design tool, the range of variables has been selected to accommodate technology that would be available by the end of the decade, including increased combustion temperatures and higher turbomachinery efficiencies, for instance, bypass ratios ranging from 4 to 13 are acceptable. (In this study, bypass ratio is calculated at sea-level static thrust conditions.)

Noise Estimation

The ICAO and the Federal Aviation Administration (FAA) issue noise certifications based on measurements made at three points during the takeoff and the landing procedures (Fig. 6). Noise is recorded at these locations continuously during takeoff and landing. The total time-integrated sideline, climb, and approach noise, known as effective perceived noise level (EPNL), must not exceed a set limit, itself based on the maximum takeoff weight of the airplane and the number of engines. Jet noise typically dominates in sideline and climb noise. On approach, high-bypass ratios diminish the noise contribution of the engine at low power, making aerodynamic noise a relevant component.

ANOPP is a semi-empirical code that incorporates publicly available noise prediction schemes and is continuously updated by NASA Langley Research Center. The relevant engine data are supplied to ANOPP from the engine performance code (NEPP), and the aircraft geometry and takeoff profile are supplied from other aircraft analysis routines. Sources modeled by ANOPP include fan noise, jet noise, and airframe noise.

Fan noise is predicted using a model developed by Heidman.[8] The components include inlet broadband noise, inlet rotor–stator interaction noise, discharge broadband noise, and discharge rotor–stator interaction noise. The method employs empirical correlations to predict the sound spectra as a function of frequency and directivity angle. The method of Stone et al.[9] is used to predict the coaxial circular jet noise. Because only high-bypass ratio subsonic engines are under consideration, shock turbulence interference is neglected, which leaves jet mixing noise as the only component. The airframe noise sources include the wings, tail, landing gear, flaps, and leading-edge slats. Broadband noise is computed using Fink's methodology,[10] which employs empirical functions to produce sound spectra as a function of frequency, polar directivity angle, and azimuth directivity angle. In some cases, the most significant source of airframe noise is the sound generated by the side edges of the flaps.[11,12] The version of ANOPP made available to the authors does not support flap side-edge noise. Flap–wing geometry is not modeled in the current design tool, however, and the contribution from side-edge vortex shedding may be assumed to be constant across all designs.

Once the near-field sound spectra is computed for each noise source, ANOPP runs a propagation module to determine the tone-corrected perceived noise levels as measured at the ICAO certification points. Finally, ANOPP computes the time-averaged EPNL values.

Acoustically absorbent materials in the nacelle typically account for about 5-EPNdB noise reduction for a modern high-bypass turbofan.[3] Although the effects of these liners are not included in the current study, nacelle surface area generally increases with bypass ratio and, hence, fan area. The result is additional space for more lining material. A model correlating liner surface area with noise attenuation could, in a future version of the design tool, be used to capture these effects.

Engine Emissions

Both particulate and gaseous pollutants are produced through the combustion of jet kerosene (products in italic stem from nonideal combustion):

Reactants	Air $N_2 + O_2$
	Fuel $C_nH_m + S$
Products	$CO_2 + H_2O + N_2 + O_2 + \mathit{NO_x} + \mathit{UHC}$
	$+\, \mathit{CO} + \mathit{C_{soot}} + \mathit{SO_x}$

ICAO regulations for the landing–takeoff (LTO) cycle cover NO_x, CO, unburned hydrocarbons (UHC), and smoke (soot) emissions. During the LTO cycle, about 80% of all commercial aircraft emissions are in the form of NO_x. They are computed based on engine fuel flow (expressed in kilograms per second) and the combustor emission index (EI), expressed in grams of NO_x formed per kilogram of jet fuel used, which is a strong function of power setting, during a takeoff and landing cycle involving four different throttle modes: 100% (takeoff), 85% (climb), 30% (approach), and 7% (idle). Time in mode is simulated as follows: 0.7 min for takeoff, 2.2 min for climb, 4 min for approach, and 26 min for taxi/ground idle. The sum of the emissions at these four conditions (expressed in kilograms) is used to determine the amount of NO_x emitted per LTO cycle. The calculation is

$$\text{LTO NO}_x = \sum \text{fuel flow} \times \text{EI} \times \text{time in mode} \qquad (1)$$

The two methods that allow a reduction in emissions include improving the combustor to yield a lower EI (that is, reduce the amount of pollutant emitted per kilogram of fuel burned) and choosing an engine cycle that yields lower fuel flow (to reduce the amount of fuel consumed during the takeoff–landing cycle). Increasing the combustor exit temperature and pressure promotes more complete combustion, resulting in reduced fuel flow. The trade-off is higher NO_x emissions due to the increased dissociation of nitrogen and, consequently, a higher EI.

During cruise, CO_2 emissions constitute 6% of the total mass flow emerging from the engine, vs 0.3% for NO_x and 0.04% for CO (Ref. 13). Jet fuel provides the carbon required for the formation of CO_2; therefore, emissions are directly proportional to the amount of fuel burnt over the duration of the flight (via the emissions index of 3.15 kg of CO_2 formed per kilogram of jet fuel used). As a result, aircraft can be configured to meet CO_2 emissions requirements in addition to the NO_x emissions, cost, and noise constraints already discussed by reducing the amount of fuel needed. CO_2 trip emissions (in kilograms) are computed as

$$\text{trip CO}_2 = \text{fuel flow} \times \text{EI} \times \text{trip time} \qquad (2)$$

Whereas improvements to the combustor could decrease the amount of NO_x or CO_2 released into the atmosphere, these are generally conflicting requirements. Typically, changing the operating conditions or combustor configuration to reduce NO_x emissions increases the quantity of CO_2 and unburned hydrocarbons.[14] This explicit modeling of engine performance could be refined further to also permit studies of other emissions, less commonly factored into the aircraft design process, allowing, for example, the design of optimal aircraft meeting specific constraints for contrail formation.[15]

Optimization

The design tool has been created to allow considerable flexibility in the selection of the objective, variables, and constraints. Common objective functions in aircraft design include takeoff weight, direct operating cost, and range. For the present paper, direct operating cost was selected because it allows trade studies of environmental and economic performance:

MINIMIZE:	Direct Operating Cost
CONSTRAINTS:	Noise
	Emissions
	Mission Performance
	Stability and Trim
VARIABLES:	Bypass Ratio
	Sea-level Static Thrust
	Maximum Take-Off Weight
	Cruise Parameters
	Wing Geometry
	Approach Angle
	Thrust Cutback

The optimization framework integrates codes such as NEPP and ANOPP with other modules that analyze parameters ranging from component weights to stability and control and mission performance. This is done by using a version of the Caffe design framework that facilitates the coupling of multidisciplinary analyses and optimization. The design tool in its present form includes approximately 20 modules grouped into 11 major components combined with a nonlinear optimizer and a database management system.

Maximum certification noise (EPNL) and allowable emission levels are included as constraints in the design tool, alongside traditional performance constraints such as range and field performance. This approach allows the user to specify explicitly the level of aircraft environmental acceptability: from slight improvements to "silent" and "clean" aircraft. Design variables include parameters pertaining to aircraft configuration, propulsion, and mission profile.

The engine simulator (NEPP) is run first because several engine characteristics are required early in the design process, in particular for range and takeoff calculations. The aircraft design programs, which are run next, include subroutines that compute other aspects of aircraft performance. Noise calculations (ANOPP) are run last. Several nonlinear programming methods are available to solve this type of optimization problem; due to the relatively small problem sizes addressed here, a constrained scheme based on a Nelder–Mead algorithm[16] was employed.

Results

The design tool produces the overall optimal configuration, performance, approach, and takeoff profiles for the aircraft, based on the specified noise and emissions constraints. It also enables the user to analyze separately the contributions to noise reduction made by, respectively, aircraft configuration, approach noise abatement procedures, and takeoff thrust cutback, as will be discussed. To further illustrate the effects of all three noise reduction components, a practical application of the design tool to a baseline 280-passenger airliner is also provided.

Designing Aircraft for Low Noise

As noted earlier, jet engines produce most of the sideline and takeoff noise measured during the certification process. It follows that engine design is critical to the noise performance of the aircraft. The particular importance of bypass ratios in this respect is well known: Increasing the bypass ratio can have a dramatic effect on fuel efficiency, noise and emissions. When the amount of airflow directed around the combustion chamber is increased relative to the amount of air passing through it, mixing between the flows on exit is increased and exhaust velocities reduced. The result is a considerable decrease in jet noise.

As part of the validation of the design tool, the effects of bypass ratio were studied. The aircraft was optimized to meet the mission requirements for various bypass ratios. Results are shown in Fig. 7a. As expected, the sideline EPNL emitted by the exhaust jets decreases (labeled jet noise) as the bypass ratio increases. Both fan noise and jet noise decrease, although at different rates. Fan noise does not decrease as rapidly because the turbomachinery noise emitted by the fan becomes significant in high-bypass ratios engines, which tend to require large fans. Notice that fan noise dominates at higher bypass ratios. Figure 7a shows that increasing bypass ratios from 5 to 14 results in a flyover noise reduction of about 15 dB, a 30-fold reduction in sound energy. These results match those published by Kennepohl et al.[17] Because Heidmann's fan noise prediction method[8] was developed before the advent of very-high-bypass ratio engines, it would be important to validate these results with more recent data.

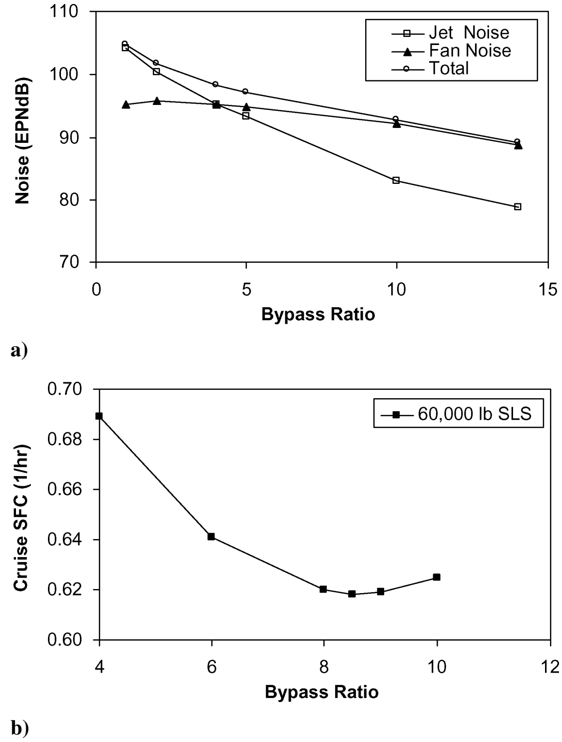


Fig. 7 Results obtained using the design tool; jet noise includes contributions from primary and secondary (bypass) flows: a) noise and b) SFC as function of bypass ratio.

The impact on emissions and operating costs of increasing bypass ratio is not as obvious. Figure 7b shows the variations in specific fuel consumption (SFC) (which largely determines both cost and emission performances) for optimal aircraft, as a function of the bypass ratio. Whereas SFC in Fig. 7b improves by about 10% when bypass ratio increases from 4 to 8, it increases again when the bypass ratio exceeds 9. The relative deterioration of the SFC for high-bypass engines is caused in part by the significant parasite drag associated with their large fans. In addition, for a given thrust requirement at cruise conditions, high-bypass-ratio engines will typically have excess sea-level static (SLS) thrust. For instance, an engine with a bypass ratio of 10 may produce about 20% less thrust at 31,000 ft than a engine with a bypass ratio of 6 having identical SLS thrust. As a result, although increasing bypass ratio reduces noise by decreasing exhaust velocities, the consequential higher installed thrust slightly degrades this advantage.

Steeper Approaches

The need to lower the impact of increasing air traffic noise on airport-neighboring populations has triggered considerable interest in noise-abatement procedures. While on approach, aircraft fly at low speed and descend at a shallow angle, in the process exposing a large ground area to noise for an extended amount of time. At the low throttle settings used during this regime, fan noise is the dominant component of engine noise, and aerodynamic noise is a factor as well. Some airports, such as London City, have adopted steeper landing profiles that reduce these effects. The applicability of these methods to current aircraft is limited by the descent velocity, which, for passenger comfort reasons, cannot exceed approximately 1100 ft/min. Modifications have been installed on some aircraft with only modest noise reduction. (A ventral airbrake is to be fitted to the Empresa Brasileira de Aeronáutia EMBRAER 170 for operations into London City, for example.[18]) However, these steeper

Table 1 Noise reduction due to steeper approach

Angle, deg	Throttle, %	Noise, EPNdB
3.0	25.9	91.6
3.5	22.2	89.1
4.0	18.4	86.5
4.5	14.7	83.9

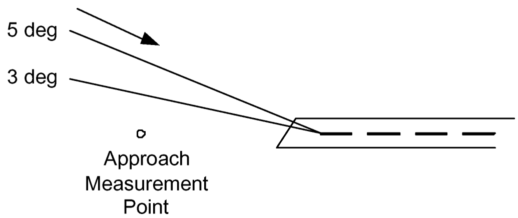


Fig. 8 Steeper approaches.

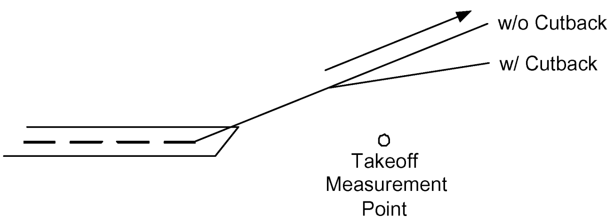


Fig. 9 Thrust cutback on TO.

approaches (Fig. 8) hold great promise for reducing noise[19,20] if applied to aircraft designed specifically to adopt such profiles without jeopardizing passenger comfort and safety. The design tool makes it possible to explore the potential gains of this approach because it includes approach angle as one of its variables and can produce conceptual designs offering the optimal combination of approach profile, engine characteristics, and aircraft performance.

Steeper approaches offer a twofold advantage: First, the steeper flight path increases the propagation distance between the aircraft and the ground; second, the engines can be throttled back because the amount of thrust required to maintain approach speed is reduced, which decreases engine noise. The combined advantages of reduced noise at the source and greater distance to the ground are shown in Table 1. These designs were optimized to adopt steeper approaches while still meeting the same mission constraints as the baseline aircraft. In this case, the approach certification point is used as the measurement point for comparison purposes to a standard 3-deg approach. The advantages are significant: Increasing the approach angle to 4.5 deg decreases predicted operational noise levels by 7.7 dB.

However, note that, just as configuring an aircraft for lower noise has a financial impact (higher operating cost), so do noise-abatement techniques, whose adoption would require substantial investment in crew training, onboard equipment modifications, and the development of appropriate safety guidelines and certification. This is especially true in the case of steeper approaches. These costs are beyond the scope of this study, but they may ultimately determine the feasibility of more aggressive noise-abatement procedures.

Takeoff Thrust Cutback

Thrust cutback on takeoff (Fig. 9) has been used since the early days of the turbojet as a method to minimize the noise exposure of adjacent communities. This method is still widely used, although it has lost some of its former importance following the development of high-bypass turbofans featuring noise emissions less affected by throttling than those of earlier engines. Because the amount of energy required to bring an aircraft to cruise altitude does not change, thrust cutback during the takeoff phase simply displaces the noise to a different location. Thrust cutbacks to lower noise in the immediate vicinity of airports are counterbalanced by a reduction in the aircraft climb angle, which increases the area exposed to takeoff noise, and an increase in noise when the engines are returned to full power, which may affect other, more distant communities. As a result, thrust cutback is ideal at airports located close to low-population density areas, such as seaside airports, for example, Orange County in California, where the procedure lowers noise substantially in the vicinity of the airport, but aircraft can resume full climb rapidly, without causing nuisance, once the ocean is reached.

Table 2 Noise reduction in decibels due to takeoff cutback for the baseline design (280-passenger, twin-engine, bypass ratio of 6)

	Cutback altitude, ft		
Thrust, %	800	1350	2000
80	−1.26	−1.69	−1.88
70	−2.21	−2.92	−3.06

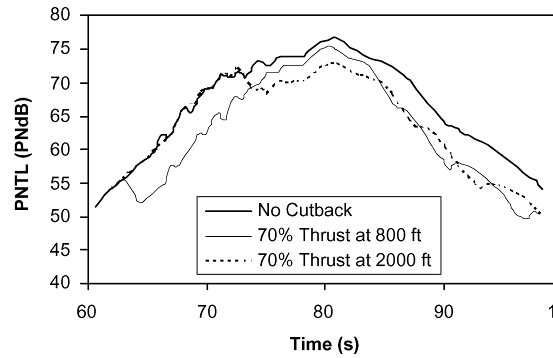


Fig. 10 Noise levels for three TO procedures as measured at the flyover certification point.

The ICAO and FAA allow pilots to execute thrust cutback between the altitudes of 800 (240) and 3000 ft (900 m). To determine the impact of thrust cutback during climb on noise measured at the certification points, the design tool was used to carry out a parametric study. Results, shown in Table 2, suggest a reduction potential estimated in the range of 2.2–3.1 dB for the baseline design. Because certification noise, which is measured close to airport, is the constraint used in the design tool, the optimization does not take into account possible acoustic nuisances experienced by more distant communities when full thrust is restored to complete the climb.

The modest potential of thrust cutbacks for reducing certification noise should not surprise: Very large changes in noise amplitudes would be required to impact the time-integrated noise measured for certification purposes. This phenomenon is well illustrated in Fig. 10, where the area under the curve represents time-integrated noise during takeoff. The areas corresponding to the thrust cutback cases are only slightly smaller than the one for takeoff without any noise-abating procedure. Nevertheless, the greatest gain involves cutting thrust as much as allowable to maintain the minimum climb gradient, which should be done close to but before the flyover noise measurement point for maximum beneficial effect. Cutbacks at lower altitudes, before reaching the measurement point, are not as effective: Although the source noise decreases, the shallower climb from a low altitude results in an increased time-integrated noise metric.

Trade Study

This section illustrates the optimization process performed by the design tool in the case of a 280-passenger, twin-engine airliner with a 6000-n mile range, and takeoff, cruise, and landing performances in line with industry standards for similarly sized aircraft.

Noise

The baseline design, representative of aircraft in service, features engines with a bypass ratio of 6 (a typical value for existing aircraft of this type).

The configuration leading to minimum operating cost was computed first by running the design tool without specifying any

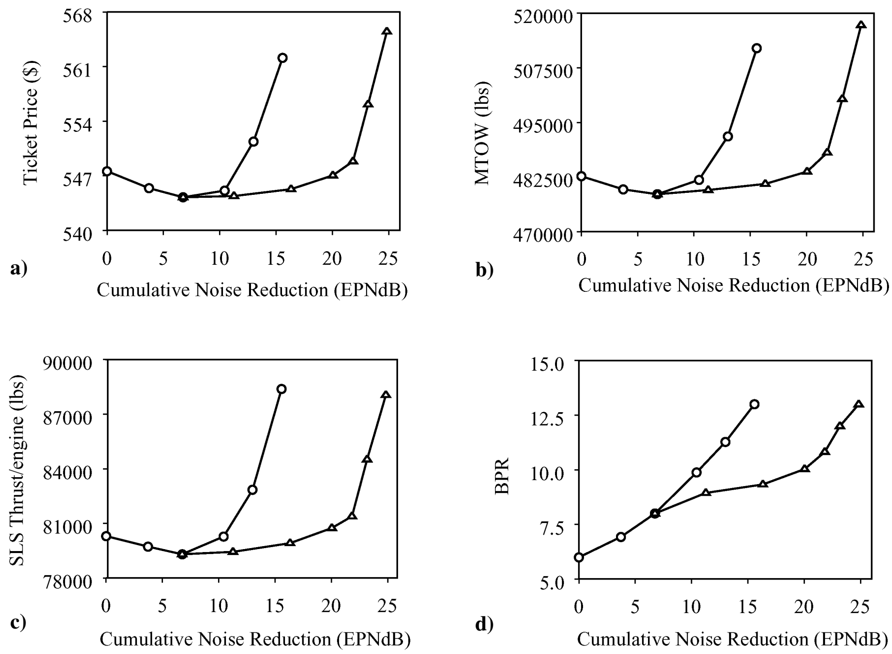


Fig. 11 Optimization results for designs with cumulative noise reduction relative to the baseline aircraft: ○, design only and △, design and operations.

noise constraint, nor noise-abatement procedures. This produced the minimum-cost aircraft. The cost metric corresponds to total operating costs based on the Air Transportation Association of America method[21] for direct operating cost and more recent data from Schaufele.[22]

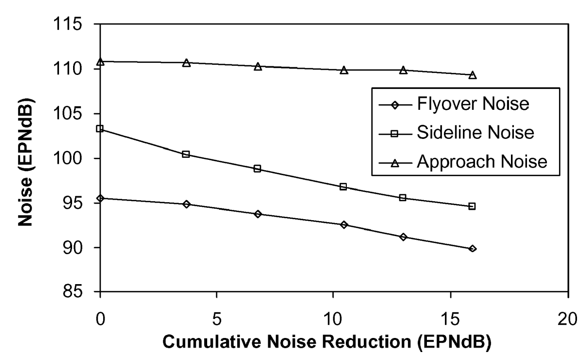
Next, noise reduction constraints were introduced, and the design tool produced the optimal aircraft configurations for specified noise reductions (Fig. 11a). The limit for noise reduction was attained when the engines of the optimized aircraft reached the maximum acceptable bypass ratio of 13. The low-noise configuration obtained at this point showed a noise reduction of about 16 dB and a cost increase of 3.0% compared to the reference aircraft.

Finally, noise-abatement procedures were specified in addition to noise-reduction constraints. Specifically, approach angles of up to 5 deg were allowed at landing (vs 3 deg in the reference case), as well as 20% thrust cutback at takeoff (none in the reference case). The design tool optimized configuration and noise-abatement procedures in producing the optimal aircraft. Results are shown in Fig. 11a. The low-noise design in this case is about 25 dB quieter than the reference plane, with a cost penalty of 3.3%.

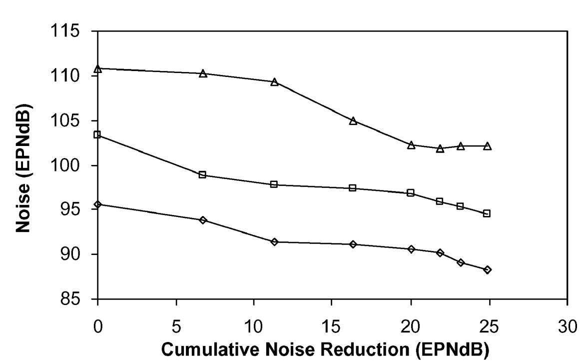
Figures 11b–11d show how selected design variables for the optimized aircraft vary in function of cumulative noise reductions relative to the baseline aircraft. As would be expected, the bypass ratio increases rapidly as noise constraints are tightened (Fig. 11d), reflecting that quiet engines are critical to better noise performance. The use of high-bypass engines results in the need to increase SLS thrust (Fig. 11c) to preserve performance at cruising altitude, and the larger engines in turn lead to heavier maximum takeoff weight (MTOW) (Fig. 11b).

Notice that increasing the bypass ratio from the reference value of 6 to approximately 8 decreases noise, emissions, and cost. This is expected; in this area of the design space, the reductions in fuel flow more than compensate for the cruise performance degradation associated with higher bypass ratios.

Dynamically, the optimizer recognizes that noise-abatement procedures are the most cost-effective way of reducing noise and, where permitted, achieves the initial 10 dB of noise reduction primarily through throttle cutback and steeper approach angles, with only a modest increase in bypass ratio (from 8 to 9). Further gains are made primarily by increasing the bypass ratio, with higher cost penalties. Technical limitations come into play at bypass ratios of about 13, when fan tip velocities of the engine simulated in the design tool are close to Mach 1, resulting in a substantial increase in noise. Engine manufacturers are addressing this problem by using geared fans to reduce fan tip velocities and by sweeping fan blades to delay the onset of shock waves.



a) Design only



b) Design and operations

Fig. 12 Noise at the ICAO certification points as a function of desired cumulative noise reduction.

Figure 12 shows how flyover, sideline, and approach noise each contribute to the cumulative noise reductions that are achieved. Figure 12a relates to optimal configuration aircraft, whereas Fig. 12b factors in noise abatement as well. The most notable feature is the steep decrease in approach noise when noise abatement is used and the bypass ratio increases up to cumulative noise reductions of about 20 dB. Beyond that point, fan noise on approach increases again due to higher turbomachinery noise. However, this is more than offset by lower sideline and flyover noise, so that additional cumulative

Table 3 Comparison of optimized designs: design only (1) and design and operations (2)

Design variable	Minimum cost	Minimum noise (1)	Minimum noise (2)	Minimum LTO NO_x	Minimum trip CO_2
MTOW, lb	478,610	511,964	517,277	482,346	481,748
Wing area, ft^2	4,757	5,177	5,267	4,888	4,873
SLS thrust/engine, lb	79,303	88,387	88,053	79,738	79,863
Wing sweep, deg	33.45	34.85	33.81	33.67	33.67
Wing thickness/chord	0.129	0.141	0.130	0.129	0.131
Bypass ratio	8.00	13.00	13.00	9.86	9.80
Approach angle, deg	3.00	3.00	4.68	3.00	3.00
TO thrust cutback, %	0.0	0.0	20.0	0.0	0.0
Noise margin, EPNdB[a]	6.76	15.59	24.85	11.00	11.02
NO_x, kg/LTO	28.60	27.76	27.67	27.01	27.10
CO_2, kg/trip	252,718	267,769	270,783	246,501	245,956
Ticket price, $	544.3	562.9	565.5	545.3	545.0

[a]Cumulative noise margin is relative to baseline.

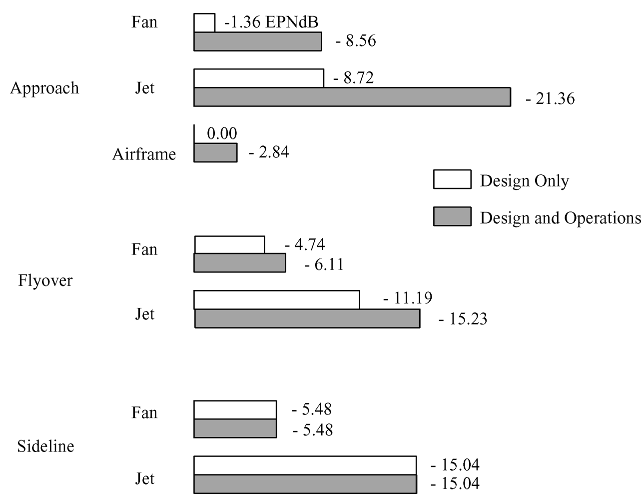


Fig. 13 Noise reduction by source for minimum-noise designs relative to the baseline aircraft.

noise reductions are possible, up to the maximum 25 dB at which maximum allowable bypass ratio is reached.

Additional insight into noise reductions achieved in the optimized aircraft can be gained by looking at the three sources (airframe, engine fan, and jet) that are the major contributors of noise at the approach, flyover, and sideline measurement points. Figure 13 presents such an analysis for the low-noise aircraft, again for the two cases of optimal configuration only (in white on the bar charts) and optimal configuration plus noise abatement procedures (in grey). The low-noise aircraft yielded by the design tool have engines with maximum allowed bypass ratios, in which the turbomachinery component of fan noise is increasingly difficult to manage and becomes an issue. Unsurprisingly then, the analysis shows that the fan contributes only modest noise reductions. Jet noise reductions are significant at all three points of measurement, as would be expected given the increase in bypass ratio from 6 in the reference airplane to 13 in the low-noise designs, which lowers jet velocities considerably. This beneficial effects of this large decrease in jet noise on overall noise performance is limited because of the dominance of other sources (especially the fan) at these high-bypass ratios. Finally, aircraft configured for low noise show no measured airframe noise reduction on approach unless noise abatement procedures, that is, steeper descent, are used. Takeoff (TO) thrust cutback only reduces noise measured at the flyover because the procedure is carried out too far from the sideline measurement point to have any impact.

As illustrated by the case study, compliance with noise constraints introduced at the preliminary design stage requires extensive changes in aircraft configuration and in operating procedures as well. Although significant cumulative noise reductions can be achieved by optimizing aircraft configuration alone, taking a systems approach and optimizing the aircraft simultaneously for configuration and noise-abatement techniques produce greater benefits.

Emissions

Two types of minimum emissions optimal designs are computed: minimum NO_x during the LTO cycle (during which NO_x emissions dominate) and minimum CO_2 for the entire trip.

Table 3 summarizes the key parameters for comparison purposes of the extreme designs. Minimizing trip emissions generates a configuration with a more modest bypass ratio than designs for low noise. Whereas higher bypass ratios reduce the fuel flow during the simulated LTO cycle (and, therefore, improves NO_x emissions), the poor performance at altitude of these designs necessitates a greater fuel load, in the process increasing emissions during cruise. Results show that LTO NO_x can be reduced, for a given combustor, by approximately 5.6% for a cost increase of 0.2%. This is done by increasing the bypass ratio relative to the baseline: The higher NO_x emission index is more than compensated by the reduction in SFC. Further bypass ratio growth, however, would result in an increase in LTO NO_x. Further gains could be achieved through detailed design of the combustor. As already discussed, reducing CO_2 emissions amounts to reducing fuel flow; the designs for minimum cost and minimum CO_2, for example, minimum fuel, a dominating parameter in the cost calculation, are very similar.

The differences in designs based on the type of emissions to be reduced has led to increasing pressure for the ICAO to supplement LTO emissions regulations with constraints during the cruise portion of the flight. These results show that between 245,000 and 270,000 kg of CO_2 are released into the upper atmosphere during each 6000-n mile segment. Whereas air quality in the vicinity of the airport is of importance, the long-term effects of unregulated emissions at cruise are worrying. In response to these demands for quantifying emissions generated during cruise, the FAA is developing a system for assessing aviation's global emissions** that permits the computation of the total emissions generated by an aircraft fleet over the entire mission, based on published engine emissions data.

Essentially, the design of an aircraft for low environmental impact results in a tradeoff between conflicting objectives: NO_x emissions during the LTO cycle and CO_2 emissions during cruise, noise, and cost. This tradeoff will be resolved depending on the particular emissions and noise regulations applying in the market to be served by the aircraft.

Conclusions

The objective of this research was to determine the feasibility of including explicit environmental constraints during the initial phase of aircraft design. A design tool was developed using multidisciplinary optimization to quantify the tradeoffs between noise performance, direct operating cost, and emissions performance. High-fidelity engine and noise models available from NASA were integrated into the optimization framework. In addition to the physical

**Locke, M., and Morales, A., System for Assesing Aviation's Global Emissions data available online at URL: http://www.aee.faa.gov/emissions/global/sage.htm [cited 8 April 2003] aircraft and engine configurations, the design tool can take into account the effect of noise abatement procedures (thrust cutbacks and steeper approaches) in optimizing the entire aircraft and mission. The application of this design approach was successful in producing optimal solutions.

Conclusions that emerge are that modifying aircraft configuration to achieve compliance with environmental requirements can only go so far and that environmental performance can be enhanced significantly by using noise-abatement techniques in conjunction with improved physical configurations. High engine bypass ratios, which reduce jet velocity and noise, were found to be the most important factor in reducing noise. The manufacturers' ability to develop engines with ever-increasing bypass ratios seems likely to remain a key factor for further progress in this area, at least in the short term. The study also established a tradeoff between noise performance and emissions performance, the resolution of which will largely depend on the environmental regulations applying in the markets served by the aircraft. The ability of a conceptual tool to predict the consequences of design changes is heavily dependent on validation: Because of the uncertainty in modeling noise and emissions, it is crucial that the design tool be compared to experimental results and existing, usually proprietary, databases. Finally, note that the results presented here fully support the balanced approach adopted by the ICAO, which deems that reductions in the environmental nuisances associated with commercial aviation will be achieved most effectively by a combination of quieter and cleaner aircraft, appropriate flight procedures, suitable government regulations, and, for the long-term, adequate land-use planning.

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