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18 Quiet Aircraft Design and Operational Characteristics

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Scope

In contrast to the preceding chapters, which have dealt largely with the physics of the generation and suppression of specific noise sources, this chapter deals with the application of aircraft noise technology to the design and operation of aircraft. Areas of discussion include the setting of target airplane noise levels, major design considerations in achieving these levels, operational considerations and their effect on noise, and the sequencing and timing of the design and development process. Primary emphasis is placed on commercial transport aircraft of the type operated by major airlines. The final sections of the chapter include brief comments regarding the noise control engineering of other types of aircraft.

Airplane Noise Level Design Requirements and Objectives

The adoption of the target levels for the community, interior, and ramp noise of an airplane includes consideration of regulatory requirements, customer guarantees, risk assessment, and design margins.

Regulatory Requirements for Community Noise

Regulatory requirements for commercial aircraft include national regulations, international standards, and local airport requirements.

FAA Regulations

In the United States, the Federal Aviation Administration (FAA) requires transport aircraft to comply with the noise requirements of Federal Aviation Regulations

(FAR) Part 36 (ref. 1) as one condition for the issuance of a type certificate (for a model) or an airworthiness certificate (for an individual airplane). Maximum noise levels for individual flights are specified under standardized test conditions at three locations: (1) during takeoff, directly under the flight path at a distance of 6500 meters (approximately 4.0 statute miles) from brake release; (2) at the point of maximum noise during takeoff along a sideline 450 meters (approximately 0.28 mile) from and parallel to the (extended) runway centerline; and (3) during approach, directly under the flight path at a distance of 2000 meters (approximately 1.25 miles) from the runway threshold. These locations are illustrated in figure 1.

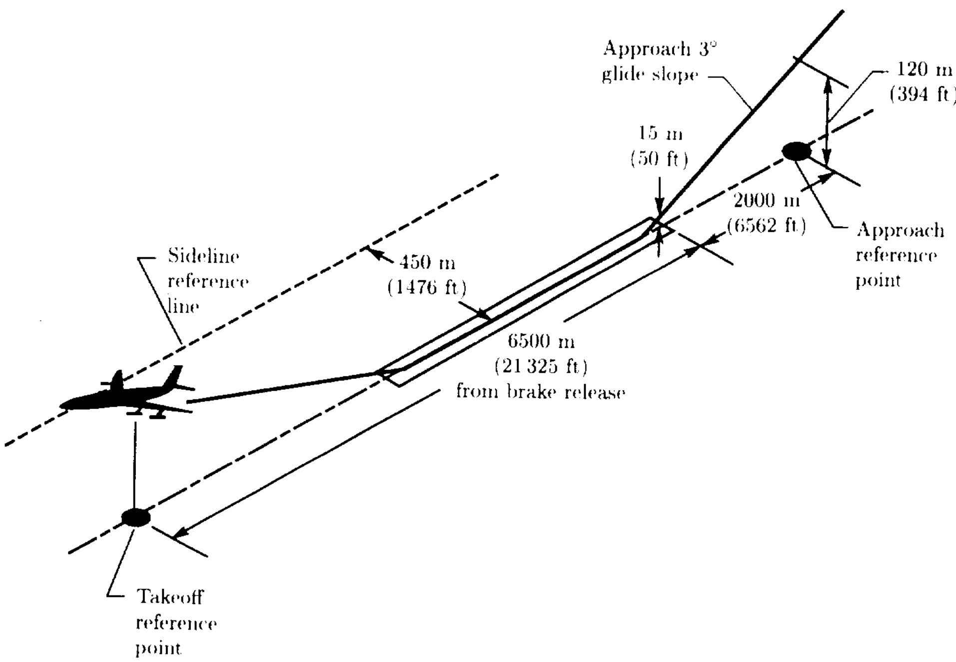


Figure 1. FAR Part 36 noise certification conditions.

The allowable noise levels are specified in terms of effective perceived noise level (EPNL) in decibels and depend on the maximum certificated takeoff gross weight of the airplane. These limits are illustrated in figure 2. The more stringent limits are known as the stage 3 requirements and apply to airplanes for which applications for type certifications were made on or after November 5, 1975 (which roughly corresponds to commercial transports certified after 1978). Between December 1, 1969, and November 5, 1975, the applicable requirements were the stage 2 limits, which were not as stringent as the current stage 3 rules. Airplanes for which application for type certificates were made prior to December 1, 1969, are defined as stage 1 airplanes and were not required to meet noise regulations. In issuing aircraft noise standards and regulations, the FAA must consider whether such requirements are "economically reasonable, technologically practicable, and appropriate for the particular type of aircraft" (ref. 1). Thus as noise reduction technology has developed, requirements have become more stringent.

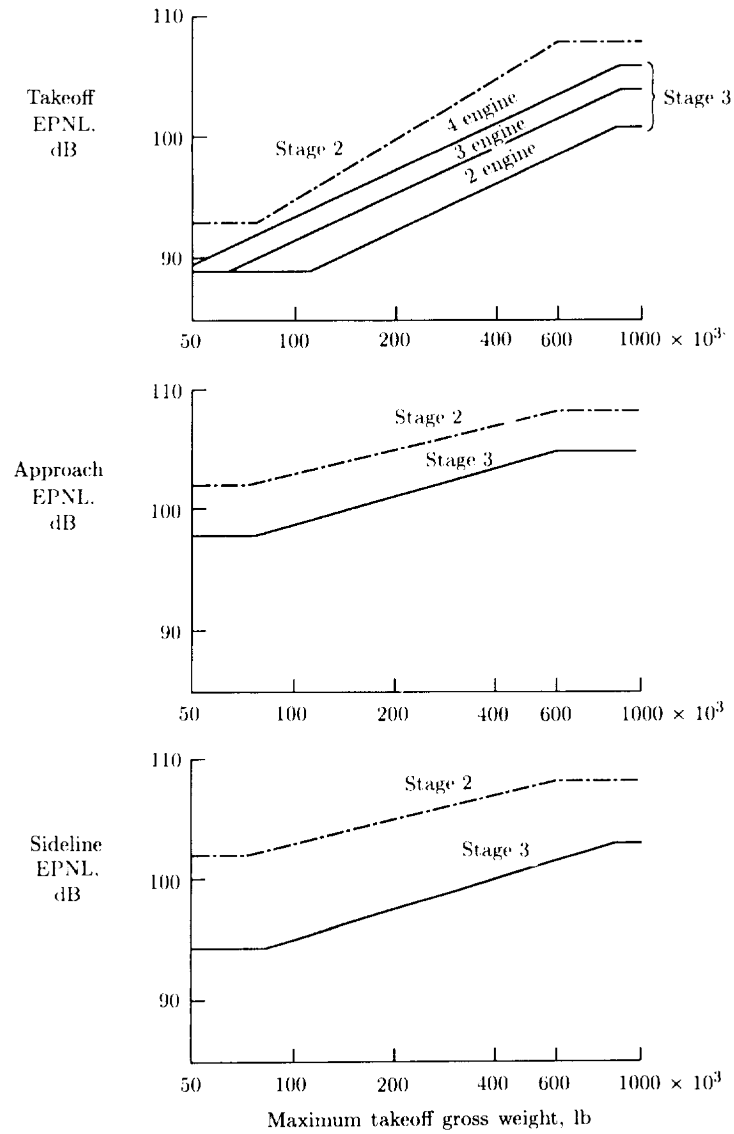


Figure 2. FAR Part 36 certification noise rules.

Unlike the approach and sideline requirements, the stage 3 takeoff limits depend on the number of engines, for the following reasons. Safety considerations require that an airplane have enough thrust to meet its critical takeoff performance requirement with one engine inoperative. Consequently, during normal takeoff with all engines operating, a two-engine airplane is 100 percent overpowered, a three-engine airplane 50 percent overpowered, and a four-engine airplane 33.3 percent overpowered. Therefore, with all engines operating, an airplane with fewer engines can take off from a shorter field length at a steeper climb angle and thus achieve a higher altitude over the takeoff measurement point under the flight path. The noise regulations, which invoke a policy of equal stringency (i.e., demanding the same noise control technology irrespective of the number of engines on the aircraft), require the airplane with fewer engines to meet a lower noise requirement. In this manner, the regulations recognize the noise implications of the engine-out safety requirement and the need to be technologically practicable and appropriate for the particular type of aircraft.

An additional important feature of the FAR Part 36 noise requirement is the trade-off provision: an aircraft may exceed the nominal EPNL limit by a maximum of 2 dB at a single point and by a maximum of 3 dB collectively at two points provided that there are compensating margins at the other point(s). That is, the sum of the exceedances over the respective nominal requirements at the three points does not exceed zero. This "3-2 trade" provision is illustrated graphically in figure 3, in which the region inside the geometric figure corresponds to compliance with FAR Part 36.

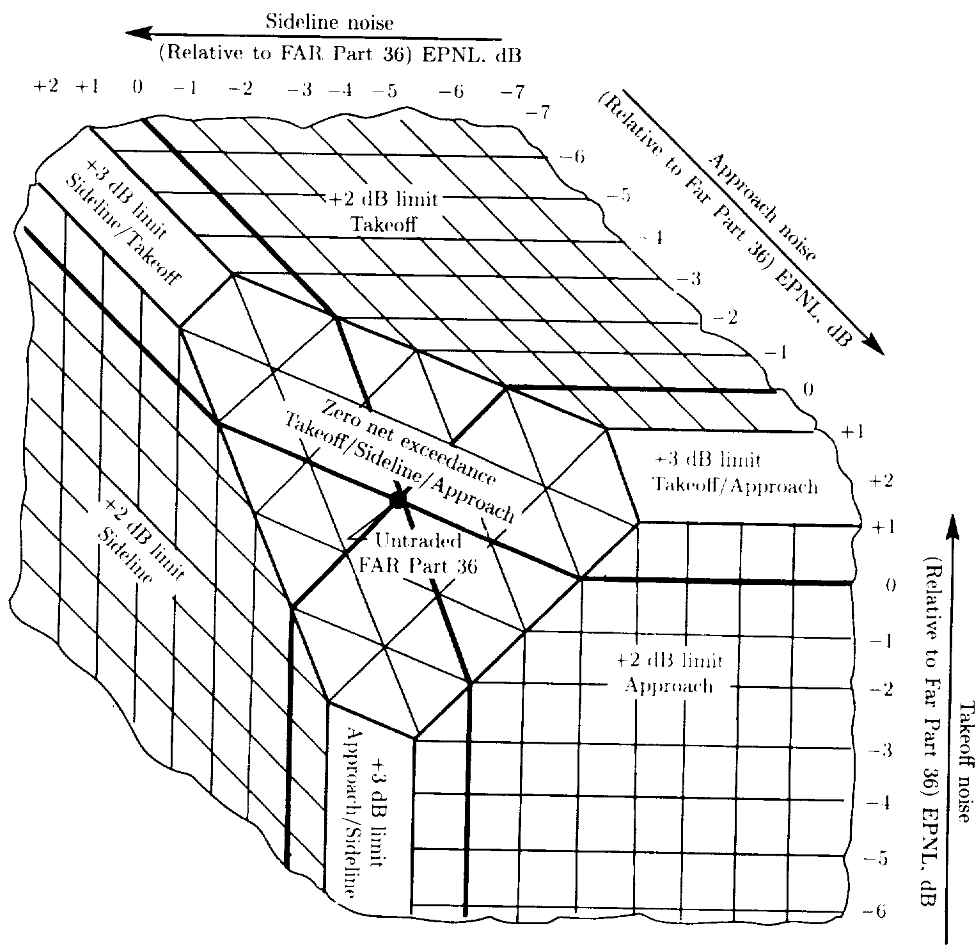


Figure 3. Three-dimensional illustration of possible combinations that ensure compliance with FAR Part 36 requirements.

In addition to requirements for new type designs, there are also noise limitations on both continuing production (FAR Part 36) and operation of previously certified aircraft (FAR Part 91, ref. 2). These rules are designed to phase out the operation of older, noisier airplanes in the United States. Figure 4 shows the effective dates of each of the three types of requirements.

ICAO Requirements

Similar to the FAA requirements, the International Civil Aviation Organization (ICAO), consisting of representatives of most governments throughout the world, makes recommendations to its member countries for noise requirements for aircraft to operate in these countries. The requirements are recommended for both domestically registered aircraft and for those aircraft from other countries. Most countries, including the European countries, Japan, and Australia, require compliance with the ICAO guidelines, known as Annex 16 (ref. 3), which have evolved to the point of being essentially equivalent to the FAA requirements. There has typically been a time lag between the adoption of the FAA stage 2 and stage 3 requirements and the corresponding ICAO Chapter 2 and Chapter 3 guidelines, as illustrated in figure 4.

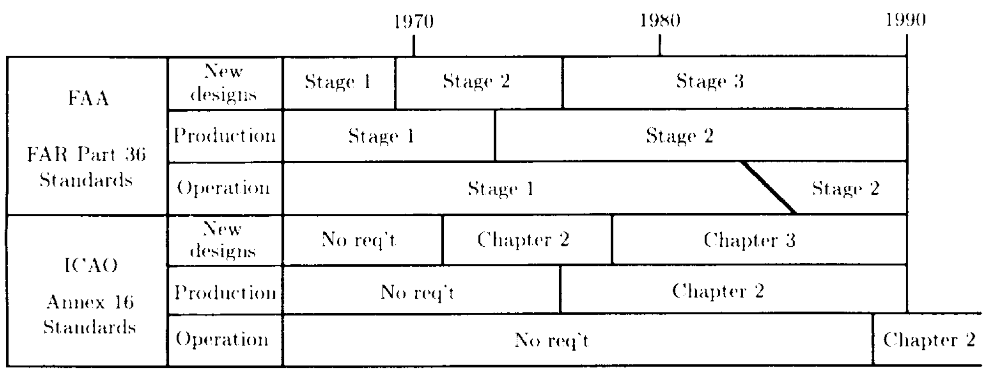


Figure 4. Noise rule progression.

Local Airport Regulations

In addition to the FAR Part 36 and ICAO Annex 16 requirements, commercial aircraft are often required to meet local noise restrictions at specific noise-sensitive airports. These restrictions may take the form of curfews, noise-dependent usage fees, noise level requirements based on various noise metrics, integrated fleet noise level restrictions on individual operators, etc. They include a multitude of noise units. The most prominent and restrictive of these local regulations are at Washington National Airport, John Wayne Airport (Orange County) and other California airports, and European airports. The widespread nature of these local regulations in the United States is illustrated in figure 5, from an FAA document (ref. 4). Each black dot represents an airport which has local noise regulations. These requirements significantly influence airplane sales competitions for individual customers and increase the complexity of design-goal development.

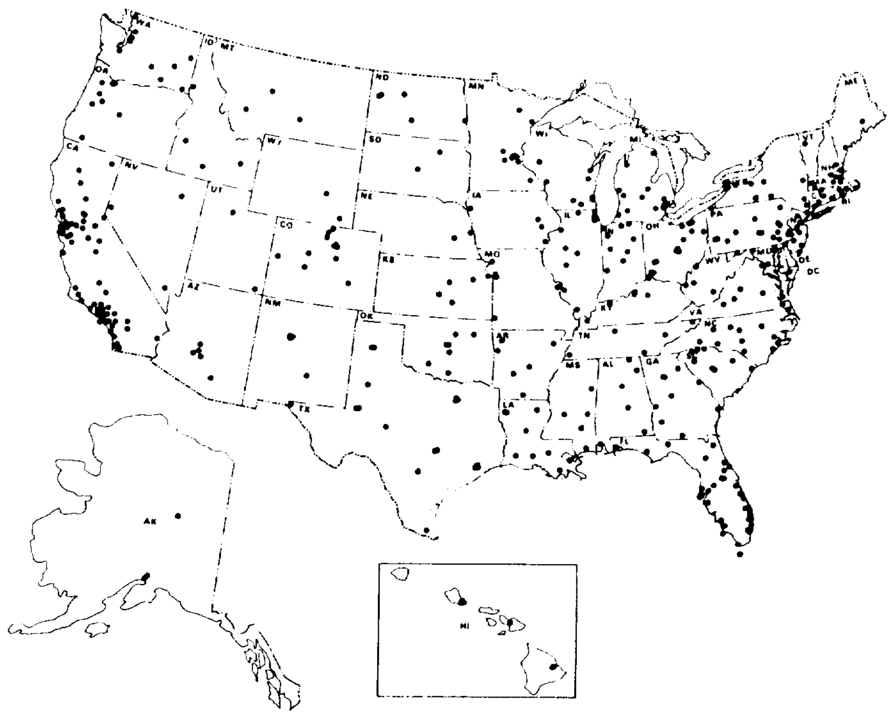


Figure 5. Extent of local actions to control airport noise. (From ref. 4.)

Compliance Demonstration

Initial compliance of an airplane model with an FAA (or ICAO) certification requirement is demonstrated by flight test and is described in detail in a previous chapter of this book. The history of a given airplane model, however, is typified by numerous design changes, some of which may affect community noise. Common examples of major changes are (1) changes in maximum takeoff or landing weight associated with airplane growth or (2) alternative engine offerings on the same airplane, in which the noise may differ from that with the parent engine. In this latter certification, what has become known as the "family plan" is often invoked. In a family plan certification, the effect of the engine change is based on comparative ground tests of the original and the new engine designs. First the noise increment δ between flight and ground tests of the parent aircraft (aircraft 1) is determined:

$$\delta = \mathrm{EPNL}_{\mathrm{flight},1} - \mathrm{EPNL}_{\mathrm{ground},1}$$

This noise increment is then superimposed on the ground test results for the new engine to determine the flight noise of this follow-on aircraft (aircraft 2):

$$\mathrm{EPNL}_{\mathrm{flight},2} = \mathrm{EPNL}_{\mathrm{ground},2} + \delta$$

Use of the family plan method can greatly reduce the cost and time of the certification program and has been shown to provide adequate technical accuracy. Smaller design changes, for example, modification of a small area of acoustic treatment of an engine duct, can sometimes be certificated by analysis alone, without additional testing.

Local airport compliance is typically monitored in service by the airport authorities themselves.

Airline Customer Guarantees

As part of the business arrangement in which an airline purchases a commercial airliner, the airframe manufacturer is typically required to guarantee that the airplane will meet certain maximum allowable community, interior, and ramp noise levels.

Community Noise

As a minimum, the manufacturer will be required to comply with the appropriate noise certification standards for the airplane in the countries in which the airline will operate it. For a domestic airline, this requirement would be the appropriate stage of FAR Part 36; for an international airline, the appropriate chapter of the ICAO guidelines is typical.

In addition to the certification requirements, an airline may request or demand compliance with the requirements at one or more specific local airports at which the airline expects to operate the airplane. Such guarantees are often very important in the competition among airplane (and engine) manufacturers for an airline order.

Interior Noise

Although there are currently no certification requirements on interior (passenger cabin or flight deck) noise, airlines still require that the manufacturer guarantee noise levels in the passenger cabin. As a minimum, the guarantee is specified at the passenger seats. Often, flight deck, galley, and/or lavatory noise levels are also specified. Typical guarantees are written for the cruise condition in terms of both overall sound pressure level (OASPL) and speech interference level (SIL). OASPL includes the entire audible spectrum and is typically dominated by low-frequency fuselage-boundary-layer noise; SIL includes the three octave bands centered on 500, 1000, and 2000 Hz and typically includes contributions from both the boundary layer and the cabin air-conditioning system.

Ramp Noise

In addition to airport community and interior noise guarantees, the manufacturer typically also guarantees that ramp noise—that is, the noise exposure to the airline maintenance crew when servicing the airplane or to passengers when boarding or deplaning via outdoor stairways—will not exceed certain limits. The most important sources of ramp noise are usually the auxiliary power unit (APU) and the air cycle machines (ACM's).

Contractual Arrangements

Standard noise guarantees that are offered to all customers are typically cited in the airplane specification document, which describes the airplane and the various aspects of its performance. Exceptions to these standard guarantees may be included in jointly signed side letters. The airplane contract cites the specification and/or the appropriate side letters.

Guarantee levels and tolerances: Noise guarantees are often expressed as a nominal value, together with an allowable demonstration tolerance to cover measurement uncertainties during compliance demonstration. In some cases, however, the guarantee is written simply as a not-to-exceed value, which exceeds the nominal value by the demonstration tolerance. These concepts are illustrated in figure 6.

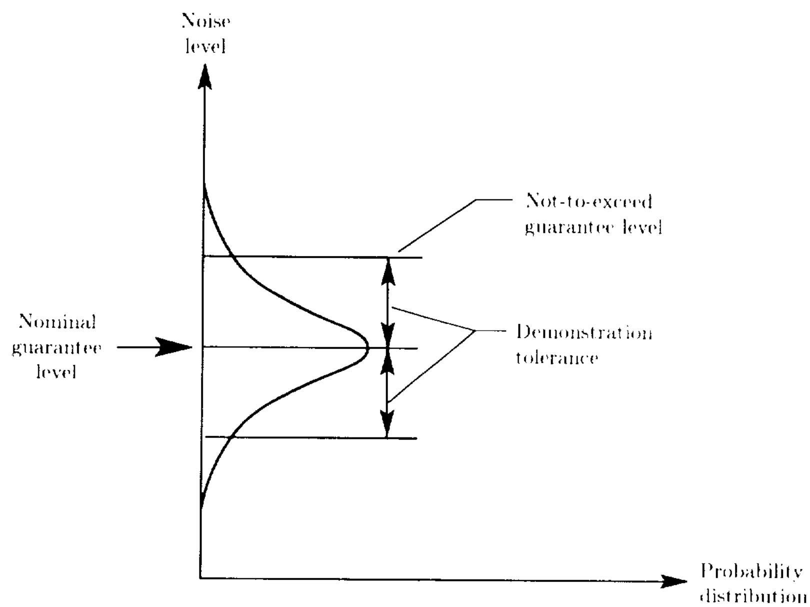


Figure 6. Airline customer guarantee nomenclature.

Compliance demonstration: As part of the contractual arrangement between the airplane manufacturer and airline customer, compliance with noise guarantees is normally demonstrated by tests performed by the manufacturer. When the guarantee is identical to a certification requirement, the certification test itself suffices. Compliance with local airport rules is demonstrated by different means sometimes by testing at the airport itself, sometimes by analysis based on the certification test data. Interior noise guarantee compliance tests are typically performed on the customer's airplane sometimes for the first airplane of a group of airplanes of a given design, sometimes on each airplane delivered.

Nominal Noise Estimates, Uncertainty Analysis, and Risk Assessment

During the design of an airplane, expected noise levels are estimated for community, interior, and ramp noise. These estimates are made for various configuration options during the preliminary design of the airplane; they are then refined as test data are obtained, design details frozen, and estimating methods improved as a result of ongoing noise research. Closely related to these estimates is the uncertainty in the estimates themselves and the resulting confidence level of compliance with various requirements.

Nominal Noise Level Estimates

The nominal noise level estimates are the noise engineer's most accurate estimates of the airplane noise, for example, a FAR Part 36 approach EPNL of 97.3 dB or an OASPL in the last aisle seat in the first-class cabin of 85 dB. The engineer does not inject any deliberate conservatism or optimism into these estimates. These estimates are, therefore, those levels which the airplane has a 50-percent chance of achieving. For community noise, they are typically based on a 1/3-octave band synthesis of the expected contributions from each (suppressed) noise source at each directivity angle, as explained previously in this book.

Uncertainty Analysis

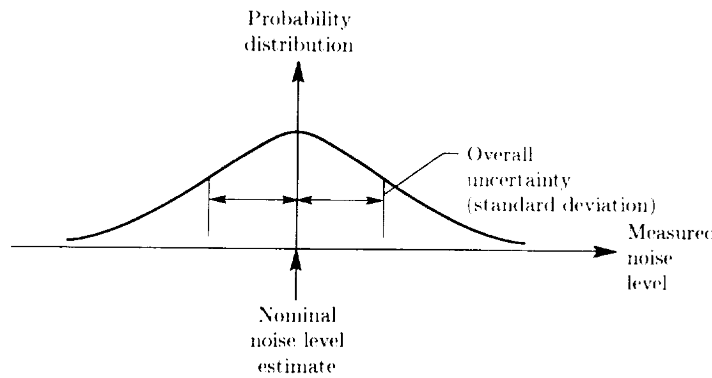
The process of noise level assessment also includes an uncertainty analysis—that is, a determination of the degree of uncertainty in the nominal estimates, or determination of the probability that the actual levels will deviate from the estimates by a particular amount when the compliance demonstrations are performed. The possible range of noise levels is typically assumed to be normally distributed about the nominal estimate, with the distribution characterized by its standard deviation, as illustrated by figure 7(a). The standard deviation itself is an engineer's best estimate, aided by a comparison of estimated and realized noise levels for similar circumstances in the past. The standard deviation representing the uncertainty in a noise estimate is comprised of two parts: the prediction uncertainty and the measurement uncertainty. Several definitions are helpful in understanding this concept:

True noise level: The true noise level is defined as that level that would be measured by a (hypothetical) perfect experiment or the average level that would be obtained from a large number of repeated measurements of the airplane noise level.

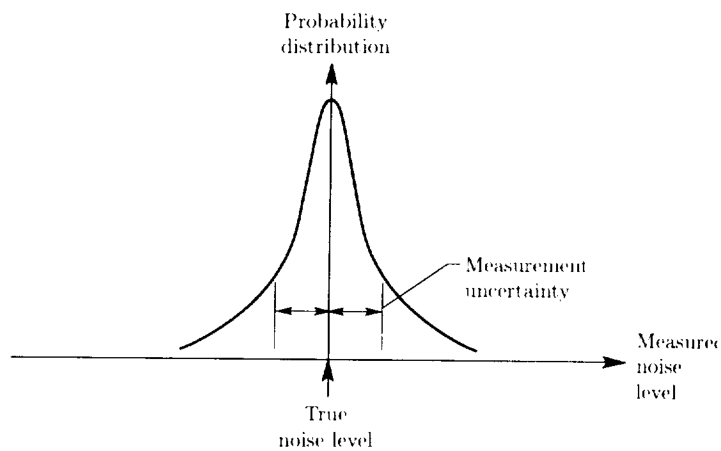
Measurement uncertainty: The measurement uncertainty is the uncertainty in the ability of an individual test (e.g., the compliance demonstration test) to represent the true value of the noise level, as illustrated in figure 7(b). Factors that contribute to the measurement uncertainty include test site variations, variations in atmospheric conditions (together with imperfect correction methods), instrumentation inaccuracies and imprecision, truncation (or round-off) errors, pilot or instrumentation operator variability, and variations (among airplanes of the same design) associated with manufacturing variability.

Prediction uncertainty: The prediction uncertainty is the uncertainty in the ability of the nominal estimate to represent the true noise level, as shown in figure 7(c). It includes any imperfections in analytical or empirical methods (based on other similar airplanes or engines) used to predict source noise levels, together with the measurement uncertainties in any "anchor point" measurements on which the predicted nominal estimate is based.

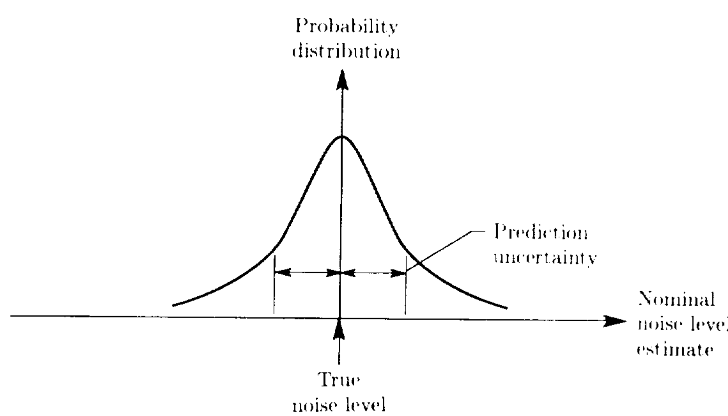
Overall uncertainty: The relevant uncertainty in the noise-estimating process is the uncertainty in the future measurement relative to the predicted value. Simplified



(a) Overall uncertainty.



(b) Measurement uncertainty.



(c) Prediction uncertainty.

Figure 7. Uncertainty analysis.

statistical theory shows that this overall uncertainty, depicted in figure 7(a), is the root sum square of the measurement and prediction uncertainties. This total uncertainty in EPNL typically corresponds to a standard deviation of 1 to 4 dB at a specific flight condition, depending on the basis for the predictions and measurements. As an aircraft program proceeds from the preliminary design, through developmental testing, to the certification flight-test phase, this uncertainty is reduced. For a small design change that can be demonstrated using carefully controlled incremental testing anchored to an existing flight-test data base, the uncertainty may be quite low. However, for a completely new engine and new airplane design, decisions on airplane go-ahead and customer guarantee offerings typically must be made when uncertainties are reasonably high.

Risk Assessment

The confidence of complying with a certification requirement or customer guarantee level—or, alternately, the risk of not complying—is calculated from the nominal noise level estimate, the overall uncertainty, and the compliance requirement, as shown in figure 8. For a single point guarantee, if the nominal estimate is equal to the compliance requirement, the compliance risk is 50 percent, characteristically an unacceptable situation. If the nominal estimate is one standard deviation (sigma) below the requirement, the risk of noncompliance is approximately 16 percent—or, alternately, the compliance confidence is about 84 percent.

For assessments involving more than one compliance point, the risk assessment calculation is more complicated. For example, in a FAR Part 36 certification, there are compliance requirements at three different flight conditions—approach, takeoff, and sideline—and limited exceedances are permitted at one or two points provided that there are compensating margins at the other conditions(s). (This situation is pictured graphically in figure 3, in which the three axes represent the noise at the three flight conditions, and the region inside the beveled geometric figure represents situations of compliance, and that outside the figure noncompliance.) The risk assessment calculation involves calculating the probability that the result will comply with the requirement (i.e., it will lie within the beveled geometric figure). The result depends on the relationship between the three nominal noise level estimates and their respective certification requirements, together with the overall uncertainties at the three conditions and the assumed degree of dependence of these uncertainties on one another.

Design Requirements, Objectives, Margins, and Risk

As can be deduced from the previous discussion, the imperfections in noise prediction and measurement processes make it imperative that the design targets for an airplane's noise levels be below the levels that the airplane is expected to meet. During the initial stages of a preliminary design, the design requirements and objectives are established, resulting in tolerances appropriate to the situation.

Design Requirements and Objectives

A design requirement is just that—a criterion that an airplane design must satisfy prior to go-ahead. Examples of design requirements are that the airplane be designed

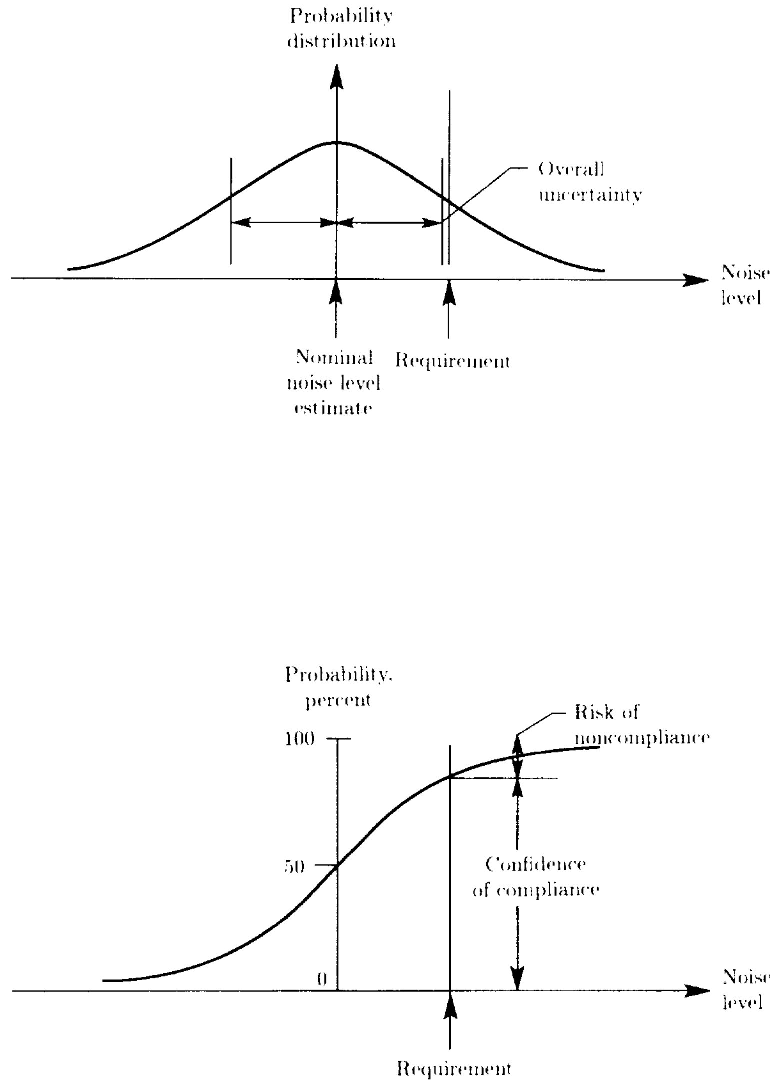


Figure 8. Risk assessment.

to meet FAR Part 36 with 90-percent confidence, that the airplane be designed to be nominally quieter than a competitor's airplane at a certain airport for a certain critical mission, or that the speech interference level in the first-class cabin not exceed a certain value with 80-percent confidence. If the airplane does not meet a requirement, it is unacceptable and must be redesigned, and the redesigned airplane must be re-evaluated.

A design objective is a less stringent goal than a design requirement. An objective is expected to be met, but does not constitute an absolute requirement for the design to proceed to production go-ahead. Design objectives, nevertheless, are intended to make the airplane more marketable and more profitable for the airline customer.

Design Margins

As can be seen from the above discussion, for an airplane to meet a requirement with greater than 50-percent confidence (or equivalently a risk below 50 percent), it must be designed to have nominal noise level estimates below the nominal requirement. These required margins, as depicted in figure 9, are derived from the uncertainty analysis described above. The larger the uncertainty and/or the lower the acceptable design risk, the larger the margins must be. The prediction and measurement uncertainties give rise to design and demonstration tolerances, respectively.

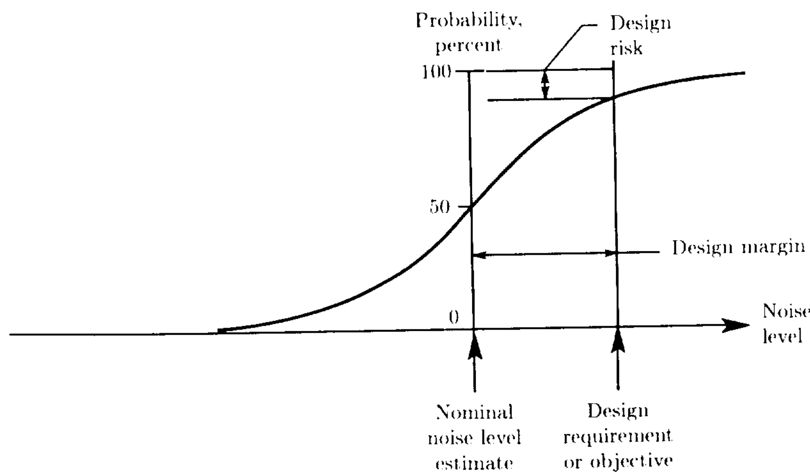


Figure 9. Design margin and risk.

Design Risk

From the concepts of uncertainty analysis, it is not difficult to see that a finite risk is associated with any finite design margin. A key element of airplane (and engine) design, therefore, is determination of the appropriate risk for a given situation. A number of factors affect this choice: the marketability of the airplane; the feasibility and cost of a redesign, retrofit, and other consequences in the event of noncompliance; the performance and cost penalties associated with designing for lower noise; the profit potential of the program; the development cost of the program; and others. For example, if the development costs of an airplane (or engine) are very high and the possibility of subsequent successful redesign and retrofit very remote, the program manager would require a very low risk of noncompliance (high confidence of compliance) with a certification requirement and therefore a relatively high design margin. If, on the other hand, the development costs are low, subsequent redesign and retrofit quite feasible, and the goal applicable to very few customers for very limited situations, a reasonably high risk would be appropriate. Certification risk typically ranges from 5 percent to an absolute maximum of 20 percent.

Major Design Considerations

Having discussed the adoption of airplane design requirements, we now discuss the major aspects of an airplane design which affect the ability to meet these objectives, the penalties associated with a low-noise design, and the engineering of derivative airplanes.

Engine Acquisition

The major source of community noise, and often a significant contributor to the interior noise of an airplane, is the propulsion system, exemplified by figure 10. The propulsion system includes both the basic gas generator which includes the fan (or propeller), the compressor, combustor, and turbine and the nacelle which includes the inlet, exhaust nozzles, and thrust reverser. The basic gas generator and (in recent years) often the nacelle are supplied by an engine company. The engineering of the installed propulsion system is a cooperative effort among the engine company, the airplane manufacturer, and (in some cases) a nacelle manufacturer. This engineering effort is very critical to the airplane noise and warrants special discussion.

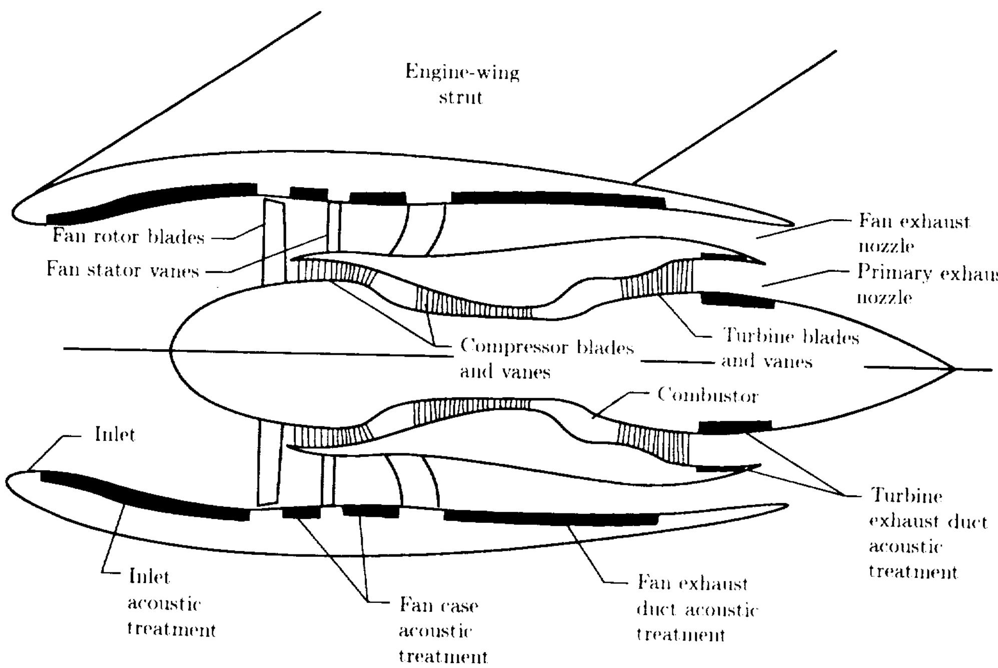


Figure 10. High-bypass-ratio engine and nacelle.

Engine Specification and Guaranteed Noise Levels

An engine specification is a description of the engine and other parts of the propulsion system that the engine company supplies. It normally includes noise guarantees, that is, noise levels that the engine is required to meet. As in the airplane specification, these may be expressed in terms of nominal levels and tolerances, not-to-exceed levels (that have the tolerance already incorporated), or merely the guarantee to comply with certain regulatory levels. Typically, the engine company must guarantee the flight noise levels.

The engine company is frequently required to meet certain noise levels during ground static operation. The engine company also may commit to provide ground static test data during the development program and to carry out a recovery program if certain noise levels are exceeded. The purpose of these ground test requirements is to obtain an early assessment and resolution of any potential noise problems and therefore avoid an unsatisfactory airplane and/or an expensive retrofit.

Compliance Demonstration

An engine noise compliance demonstration can be of different forms. Usually it is tied to the method by which the airplane is certified; if possible, the engine compliance demonstration and the airplane compliance demonstration are accomplished with the same test and the same basic data. This philosophy avoids the necessity to compound demonstration tolerances for two different tests and motivates the engine and airplane manufacturers to work together toward a common goal: a quiet airplane that meets its noise requirements and objectives. In effect, the airplane certification risk is shared by the engine company and the airplane manufacturer.

If the engine is the first to be introduced on a model, the engine and airplane compliance test is usually the FAR Part 36 certification flight test. In addition to the primary test, the airplane is flown at very low power to demonstrate the airframe noise levels and at various power settings and altitudes in level flight to provide a comprehensive data base for future interpolation and family plan analyses.

If the engine is not the first to be introduced on a model and the family plan concept is used to certify the airplane, then the engine noise compliance test is often a ground static test of a single representative engine on a test stand with a turbulence inflow control structure, shown in figure 11. The turbulence inflow control structure reduces the inflow turbulence to the fan, which is typically much higher statically than in flight, so that the resulting fan noise generation is representative of the flight situation. As explained previously, the results of this test, together with results of a previous engine ground test and airplane flight test with the original engine, are used to calculate the certified noise levels of the airplane.

Major Design Parameters for Community Noise

During the preliminary design of an airplane, a number of key decisions are made which significantly affect the community noise of an airplane. In addition to their noise implications, these decisions affect safety, performance, manufacturing cost, and maintainability of the airplane and/or engine.

Number of Engines

The number of engines on an airplane can significantly affect the airplane noise, particularly at takeoff. As explained previously, for a given total (engine-out) thrust requirement, an airplane with fewer engines tends to have (with all engines operating) higher total takeoff thrust, and hence higher maximum sideline noise levels. On the

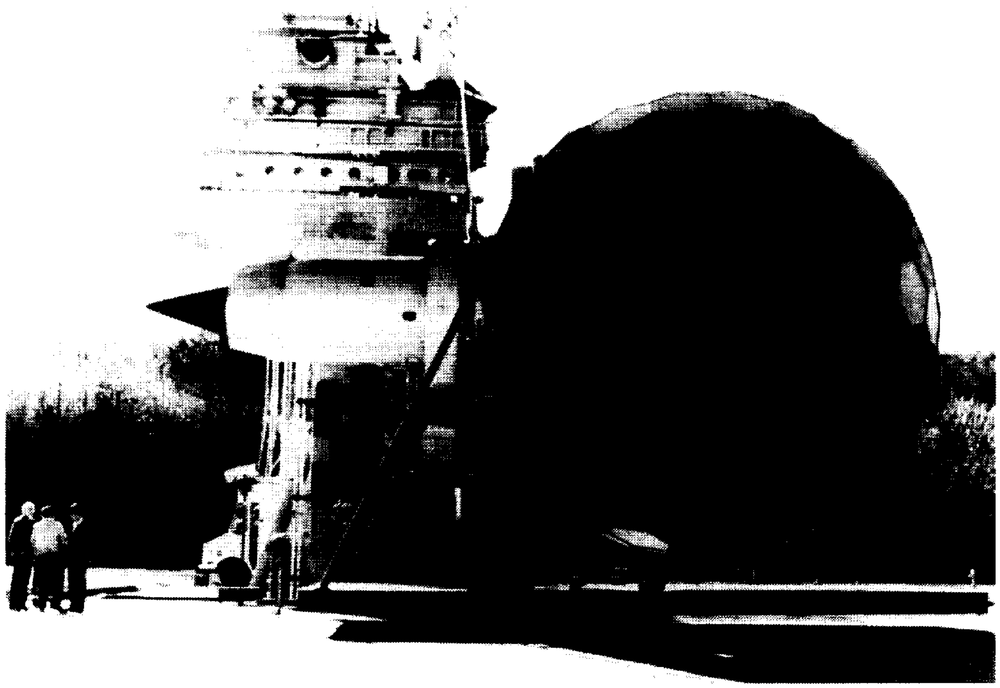


Figure 11. Fan flight noise simulation full-scale testing.

other hand, the same airplane has superior climbout performance and lower noise at the takeoff certification point and other points beneath the flight track. The effect of higher altitude is usually stronger than the effect of higher thrust. Thus, on balance, for the same takeoff gross weight, an airplane with fewer engines tends to have lower noise on takeoff.

Engine Design

The power plant type and performance cycle have a major influence on the community noise of an airplane. The evolution of the turbojet and turbofan engine has significantly affected noise. There has been a continuing trend toward higher engine bypass ratios, starting with the turbojet (with no bypass flow), to the low-bypass-ratio engine, to the high-bypass-ratio engine. Engine cycle analysis studies show that turbine materials and cooling improvements, coupled with improved fan aerodynamics, make possible significant fuel consumption advantages with higher bypass ratios. A higher bypass ratio results in a larger mass flow of air being accelerated to a lower exhaust velocity (to develop a given amount of thrust) and/or greater power extraction from the turbine reducing the primary jet velocity. A major community noise implication of this trend is reduced jet noise associated with the reduced turbulence intensity of the jet efflux. This historical trend is illustrated in figure 12.

This trend toward higher bypass ratios, larger diameter engines, and reduced jet noise has resulted in greater relative importance of fan noise and other internal

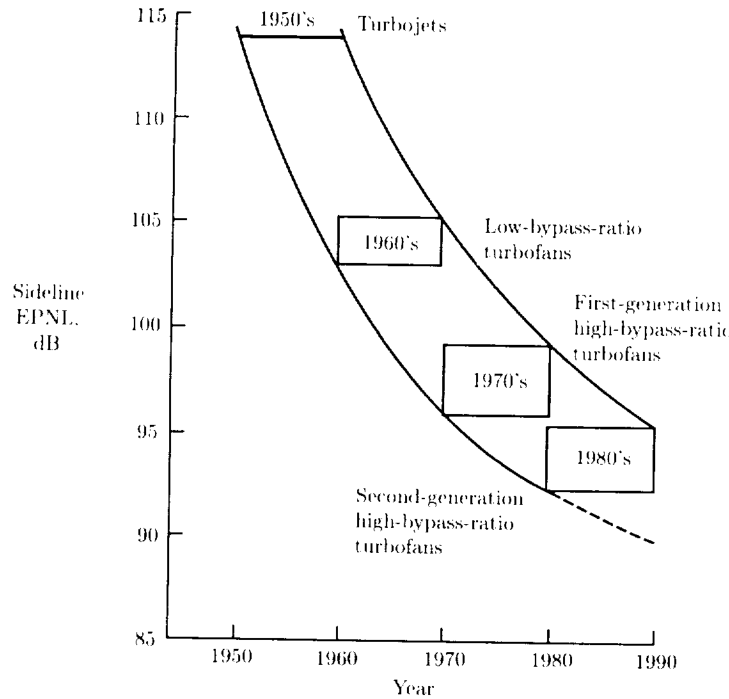


Figure 12. Noise reduction with engine evolution. Total airplane sea level static thrust is 100 000 lb. (From ref. 5.)

sources, which stimulated the development of sound-absorbing duct lining and low-noise fan blade design techniques. The noise from airplanes powered by high-bypass-ratio engines is typically quite well balanced between fan and jet noise.

Power Plant Location

The engines on a subsonic commercial airliner are typically either mounted on struts attached near the leading edge of the wing or closely coupled to the fuselage at the rear of the airplane. Three-engine airplanes have the center engine integrated into the tail cone and/or empennage. The community noise is affected by this configuration choice. Exhaust flows from wing-mounted engines often interact with the wing flaps to cause jet-flap interaction noise. Improvements in engine installation aerodynamics have made possible more closely coupled engines, resulting in a greater need to consider not only this jet-flap interaction noise, but also jet-wing interaction noise. Rear-mounted engines can benefit from shielding of fan noise by the fuselage, wings, flaps, and wing wake.

Thrust-to-Weight Ratio

Another parameter that affects community noise is the thrust-to-weight ratio of the airplane. A higher thrust-to-weight ratio results not only from selection of fewer engines but also from selection of a larger engine to obtain greater cruise thrust, greater climb thrust, or shorter takeoff field length. Again the sideline noise tends to be controlled by the thrust level, while the takeoff noise is strongly affected by the climbout performance.

Flap Systems

The design of the flap system of an airplane has several noise implications. A more sophisticated flap system can mean a more efficient airplane on takeoff, resulting in higher altitudes and lower noise on the ground under the flight path. The design of the approach flap system can significantly affect not only the thrust required on approach but also the airframe noise and jet-flap interaction noise.

Engine Nacelle

The design of the engine nacelle, particularly the quality and extent of the acoustic treatment in the inlet and fan exhaust, can significantly affect fan noise (and other internal noise sources).

Penalties for Noise Reduction

The previous chapters of this book have dealt in considerable depth with the physics of noise generation and suppression; and the initial impression of the reader might be that noise reduction technology is readily available to achieve low noise levels without serious penalties to the airplane. This is not the case. To the contrary, each noise reduction feature of an airplane must be assessed carefully to determine the impact on airplane thrust, installed thrust-specific fuel consumption, weight and balance, drag, manufacturing cost, maintenance cost, safety, and dispatch reliability.

Cost-Benefit Law of Diminishing Returns

Noise reduction, like many other environmental benefits, can often be represented by a cost-benefit curve of a typical qualitative shape, as represented in figure 13. The cost axis may represent a parameter such as block fuel or direct operating cost for a given payload and range. The benefit axis may be noise reduction at one of the FAR Part 36 certification locations, average design margin at the three flight points, certification confidence level, reduction in footprint contour area, reduction in speech interference level or OASPL in the passenger cabin, or any other noise benefit.

Each point on the curve represents a point design, in particular, that design which results in the minimum penalty for that particular noise level. All other designs corresponding to that noise level lie above the cost-benefit curve. In other words, optimum designs for a given noise level or for a given amount of penalty lie on the curve, and all other designs lie to the left and above the curve.

It is important to observe the shape of the cost-benefit curve. Initial increments of noise reduction have a relatively low cost compared with further increments of benefit. Eventually, the curve has a vertical slope, which represents the maximum possible noise reduction, in most cases at a prohibitive penalty. If the noise reduction is expressed in terms of a FAR Part 36 noise level, the term "technologically practicable" refers to the limit imposed by the vertical asymptote of the line, and the term "economically reasonable" is related to the slope of the line at the required level of noise reduction.

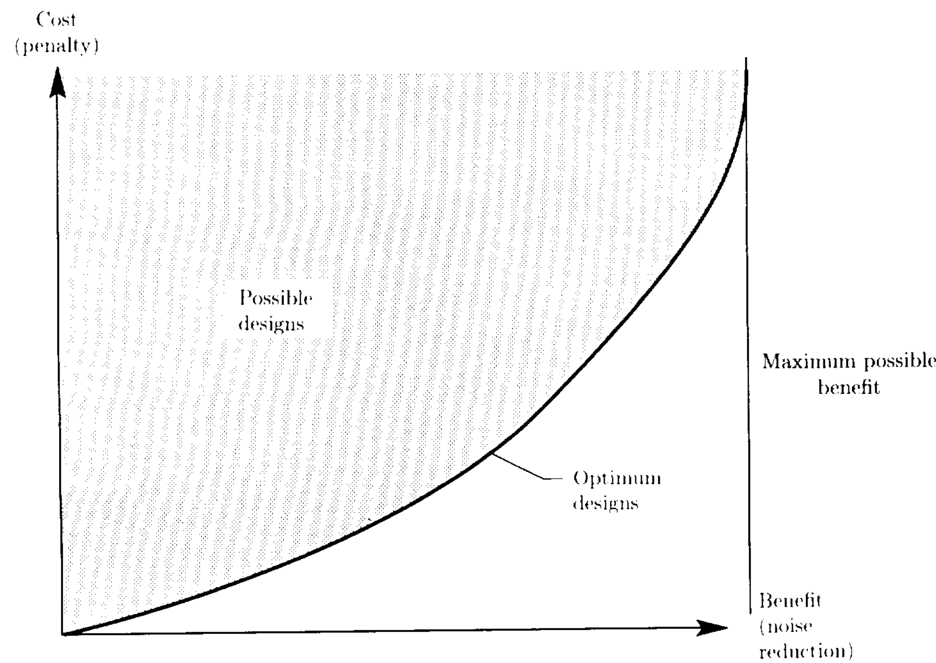


Figure 13. Cost-benefit law of diminishing returns.

Community Noise Example

An example of a cost-benefit curve is represented by figure 14, from reference 5. The curve was actually developed to assess the penalties associated with various hypothetical requirements during the Boeing evaluation of the FAR Part 36 stage 3 noise levels when they were first proposed. Each point on the line corresponds to a different degree of acoustic treatment. The penalty is the additional fuel consumption of the airplane corresponding to the additional weight and drag of the heavier and larger nacelles. The benefit is the reduction in the noise level (relative to the stage 2 requirement that was applicable at the time of the evaluation). It can be seen that, for this particular airplane and mission, the requirement to satisfy the FAR Part 36 stage 3 EPNL (which is 3.5 dB below the stage 2 EPNL) resulted in a penalty of approximately 3 percent in fuel consumption when design margins are included in the assessment.

Interior Noise Example

A second example of a cost-benefit curve is illustrated by figure 15. In this particular case, a number of sidewall treatment options were evaluated, and the weight penalty associated with each option was estimated by the designers. This display enabled the designers to eliminate some designs as being heavier than others for the same noise reduction, or less effective, from a noise reduction standpoint than others at the same weight.

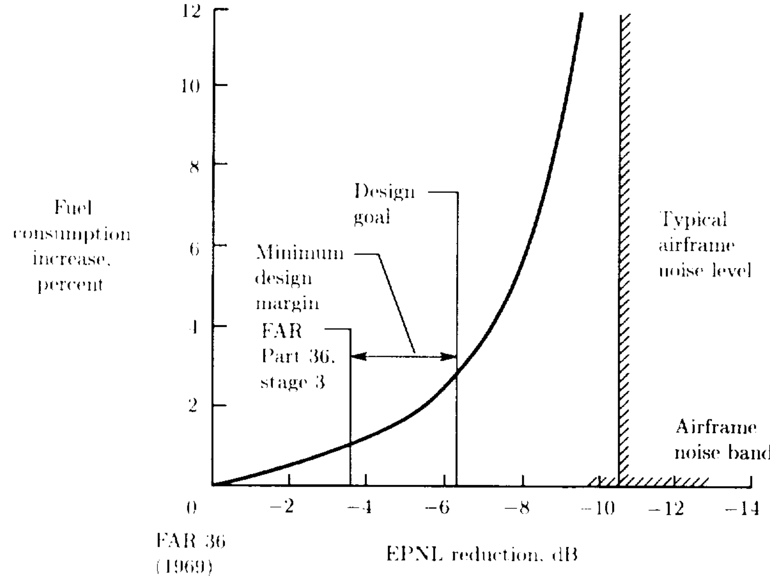


Figure 14. Noise reduction penalties. Approach power; engine treatment only. (From ref. 5.)

Effect of Technology Improvement

The effect of technology improvements on the cost-benefit curve is worthy of some discussion. The cost-benefit curve represents a given level of technology or state of the art in designing airplanes. Technology improvements resulting from research programs in noise (and in other technologies) can shift the cost-benefit curve down and to the right, as indicated in figure 16. In other words, additional noise reduction can be obtained at the same penalty, and/or the same noise reduction can be obtained at a less severe penalty.

Returning to the example of figure 14, an improvement in the acoustic technology involved in treatment design would result in additional noise reduction within a given nacelle and hence shift the line to the right. On the other hand, an improvement in materials technology that would make possible a lighter nacelle of the same shape and size would shift the curve downward.

It is seen from the above example that improvements in noise technology and in technologies that affect the penalties associated with the noise reduction together make lower noise levels more economically reasonable and more technologically practicable.

Derivative Airplanes

The previous section discussed the typical steps in developing the first design of a particular model, for example, a Boeing 747-100. A derivative airplane, for example, a Boeing 747-200, is based on a design derived from the first of the model or parent airplane. The noise engineering relies as much as possible on knowledge of the noise

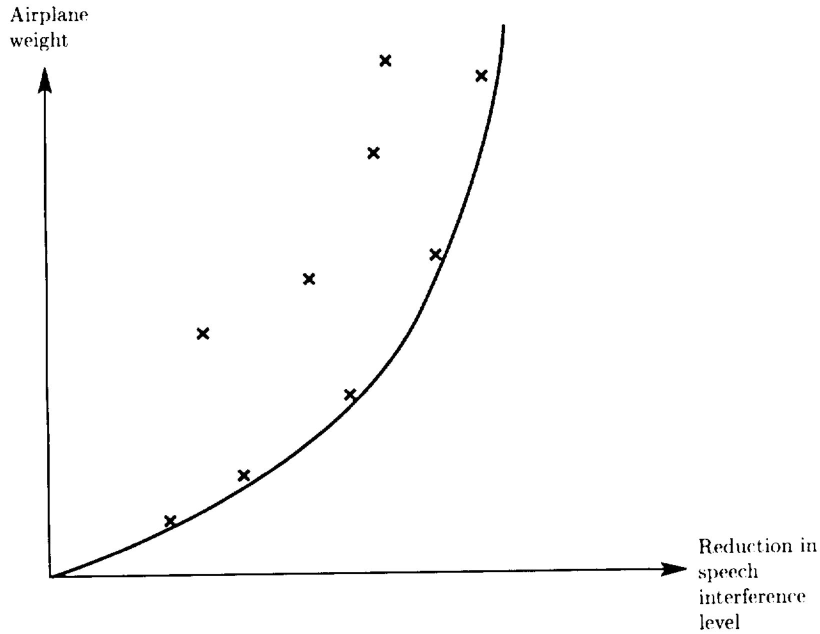


Figure 15. Weight penalty for interior noise reduction.

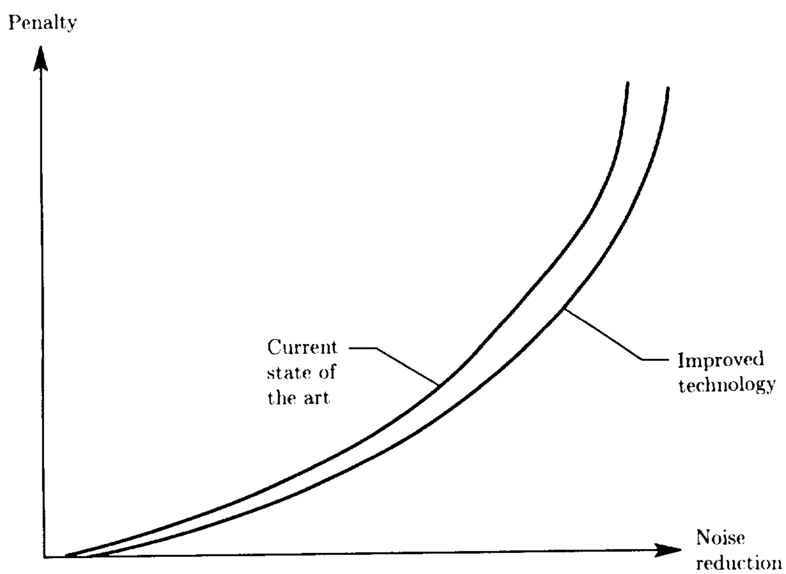


Figure 16. Effect of technology improvement on cost-benefit curve.

aspects of the parent airplane. Analyses are performed incrementally relative to the established noise levels of the parent airplane.

Growth Airplanes

Many derivative airplanes simply represent growth versions of the parent airplane. There are two typical types of growth: (1) growth in payload, usually accompanied by a lengthening of the fuselage, and (2) growth in range, usually accompanied by higher takeoff thrust and gross weight, together with an increase in fuel capacity, and perhaps a reduction in fuselage length and passenger capacity. Growth airplanes are the natural evolution that results from (1) improvements in technology, (2) engineering development and refinement based on operating experience with the airplane, and (3) the requirements of the air transportation system for airplanes with a variety of payload and range characteristics—without incurring the incremental maintenance, training, and engineering costs associated with introducing a completely new model into the operating fleet. The potential for growth must be preserved during the design of the parent airplane, including the provision for adequate noise design margins to accommodate the typical increases in noise with growth.

Alternative Engines

In some cases, derivative airplanes result from alternative engines becoming available and being installed. For example, the airplane manufacturer may wish to generate a more competitive supplier situation by means of introducing a second engine supplier with a very similar engine. Another situation comes from installing a significantly improved engine from a fuel and/or noise standpoint, for example, the introduction of the high-bypass-ratio SNECMA/GE CFM56 on the Boeing 737-300 airplane and the refanned Pratt & Whitney JT8D engine on the McDonnell-Douglas MD-80.

Major Operational Considerations

The previous sections of this chapter have dealt with design considerations of an airplane. This section deals with the effects on noise levels of the manner in which an airplane is operated. These operational considerations are closely related to the design itself and are considered during the design process.

The major determinant of the noise level of an airplane is the design of the airplane itself. There is some ability, however, to vary operational procedures to affect the certification noise levels of the airplane, its ability to meet local airport requirements, or its environmental impact in certain communities.

Takeoff Operational Procedures

For a given airplane design, the noise under the flight path (and to the sideline) during takeoff is determined by the thrust, flap, rotation, and landing gear schedules. These factors, in turn, control the altitude and flight speed, which, together with the power setting itself, determine the noise for a given (flap and landing gear) configuration. An example of the wide variety of noise signatures associated with different schedules is shown in figure 17 (from ref. 6) which describes different operational procedures and the resulting noise under the flight path. Comparison of the noise aspects of different takeoff flight procedures usually results in lower noise levels for one procedure at some points in the community, accompanied by higher noise levels at other points.

When noise in proximity to an airport is not important, the normal procedure is to maintain full takeoff thrust rating until reaching a given altitude, after which the thrust is reduced to climb thrust.

Noise-Abatement Cutback

A takeoff procedure that is sometimes used over noise-sensitive communities involves reducing the power to a lower, but safe, level to reduce the noise exposure to the community near the airport. This results in a shallower climbout and tends to increase the noise over parts of the community farther from the airport, as seen from figure 17. A particular special case of a noise-abatement thrust cutback is that permitted by FAR Part 36 (ref. 1) and ICAO Annex 16 (ref. 3) for noise certification under the takeoff flight path.

The safety of thrust cutback during in-service operations is, of course, paramount and can be enhanced by automated features in the flight guidance and control system which provide for automatic rapid thrust increases in the remaining engines in the event of an engine failure.

Reduced-Power Takeoff

When the takeoff field length is not critical, an airplane is sometimes operated at takeoff thrust below the maximum rating; this option tends to extend engine life and lower maintenance costs. In this case, the sideline noise is lower than with full takeoff power; however the liftoff point is delayed, initial climb rate is reduced, and thus the noise benefits under the flight path are reduced or eliminated.

Rotation Point and Overspeed

Another flight procedure that can be invoked when takeoff field length is not critical is to delay rotation, resulting in overspeeding the airplane compared with its typical rotation velocity. This tends to reduce sideline noise, increase noise under the flight path at liftoff, but permit lower takeoff flap settings, more favorable lift-to-drag ratio, and higher climb rates—resulting in lower noise farther from liftoff.

Flight Track Selection and Variation

In addition to variations in thrust, flaps, landing gear, and rotation schedules, the takeoff noise in the community can be affected by the choice of flight tracks. Routing airplanes over large bodies of water, industrial areas, or sparsely populated areas instead of over densely populated residential areas can significantly reduce complaints. An example of such a strategy is that developed in the 1970's for the Seattle-Tacoma International Airport; eastbound flights taking off to the north were routed over the industrial area and Puget Sound before turning east over the residential areas of Seattle and its eastern suburbs. As a result, the airplanes were at much higher altitude over these residential areas, and community exposure was reduced.

Consistency Versus Special Procedures

The many possibilities of flight procedures might be misconstrued to imply that a given airline should fly the same airplane in a different manner at each different

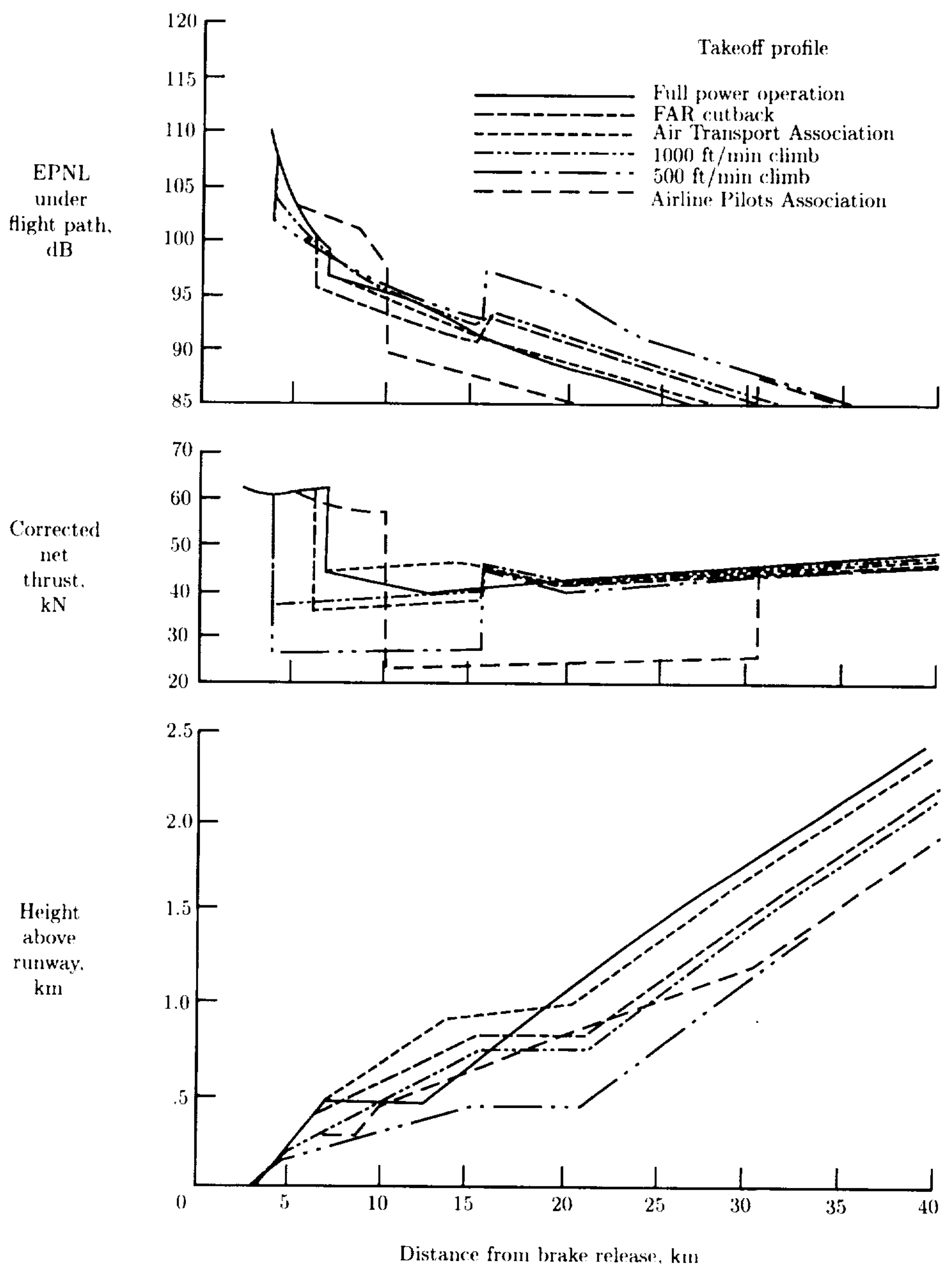


Figure 17. Takeoff noise variations with flight procedures. Airplane is 727 refan with flaps deflected 5°; temperature, 77°F; relative humidity, 70 percent. (From ref. 6.)

airport or that each airplane at a given airport can fly an optimum procedure independent of the procedure being used by other airplanes taking off and landing in the same community. Either of these hypothetical situations can cause confusion and/or increase workload on the part of the pilot, which can have safety implications. Therefore special procedures are not used as extensively as if noise abatement were the predominant objective. Safety remains the first priority in selecting takeoff procedures and flight tracks.

Landing Operational Procedures

As with takeoff, landing operational procedures can be varied somewhat to affect the certificability of the airplane, its ability to meet local airport requirements, or its environmental impact on certain communities.

Similar to the takeoff situation, for a given airplane design, the noise under the approach flight path (and to the sideline) is determined by the thrust, flap, and landing gear schedules. For the typical landing situation, the gross weight and approach speed determine the required lift coefficient. The flap setting and required lift coefficient determine the angle of attack. The flap setting, landing gear position, and angle of attack determine the drag coefficient, which, together with the glide slope, determines the thrust required. The altitude is determined by the glide slope and the distance from threshold. Thus, the noise-determining parameters (thrust, altitude, and flight Mach number) are fixed by approach speed, flap setting, and glide slope.

The normal landing approach follows a 3° glide slope and the flap setting corresponds to the minimum safe landing speed. This results in a reasonably high landing thrust requirement and typically corresponds to higher than minimum noise on approach.

Decelerating Approach

In a decelerating approach, as the airplane proceeds down the glide slope, the flight speed is progressively reduced to the final landing speed, with a corresponding increasing angle of attack and increasing thrust until the final approach thrust is reached. The decreased thrust reduces the noise levels during the initial phases of final approach.

Reduced Flap Settings

Approach noise may also be decreased by reducing the flap setting, retaining the lift by increasing the landing speed, and hence reducing the drag and the required thrust. The result is reduced noise at the expense of longer landing field length and additional tire and brake wear.

Multisegment Approach

In a multisegment approach procedure, the initial segments are carried out at a steeper glide slope. These segments require lower approach thrust, which, together with the higher altitude, reduces approach noise. The overall effect is usually small, since approach noise in the community remote from the airport is not typically as important on landing as on takeoff.

Consistency Versus Special Procedures

The same comments made previously regarding takeoff procedures also apply to landing procedures. Safety is again the paramount consideration.

The Design and Development Process

The noise engineering aspects of an airplane are a part of a very complex design process that has many engineering and economic factors and can require as much as 5 years to complete. This section outlines typical phases and milestones for a new airplane model.

The Preliminary Design Phase

The preliminary design phase of an airplane includes the determination of customer airline needs, together with enough depth in the airplane and major subsystem design to assure that the airplane can meet these needs.

Initial Preliminary Design and Airline Discussions

The initial preliminary design of an airplane involves developing an understanding of the airline customers' needs in terms of payload, range, economics, community and interior noise, airplane price, and other parameters. These needs are translated into an airplane design, including layout drawings that incorporate the major aspects of the configuration.

Initial discussions with engine suppliers result in selection of candidate engines, together with installation concepts and acoustic treatment designs. For these airplanes and installed propulsion systems, the spectra and directivity of each (treated) propulsion and airframe noise source are estimated, summed, and projected to points in the community at which flight noise time histories are constructed. These time histories are then used to estimate flight noise levels, which are compared with design requirements and objectives at specific locations and also to estimate certification confidence. If the engine model is already in operation on another airplane type, available flight data are used in the analysis. If the engine is in the initial development phase, ground test data may be available for these analyses.

During this same phase of the development process, the corresponding work for interior noise, including preliminary treatment designs, is carried out. The airplane design effort and the airline discussions are iterative and interactive. During this period, the design requirements and objectives are adopted, including those for noise.

Initial Application for Type Certificate

As the airplane begins to take shape, preliminary application is made to one or more certifying authorities, for example, the FAA, for a type certificate. Associated with this application are discussions regarding the plan for noise certification of the airplane. For example, if the airplane is the first of a model, a certification flight test is required. If it is a derivative airplane with a new engine, family plan certification may be proposed. The result of this phase is a specific plan for noise certification.

Preliminary Design Review

At the culmination of the preliminary design effort, a preliminary design review is conducted to scrutinize the design that has evolved. A team of experts reviews the design to develop an independent opinion of its quality and appropriateness. This review is often accompanied by audits of different aspects of the design, including noise. Noise levels and risk assessments are reviewed in detail. Major design changes beyond this time period can seriously affect program cost and schedule.

Configuration Freeze

Following the preliminary design review, the configuration is usually "frozen." In effect the freeze applies to the major aspects of the design. Detailed design has not yet been accomplished, but there is high confidence that the major aspects will be amenable to successful detailed design.

Airplane and Engine Specifications

The process of preliminary design of the airplane and engine includes the formulation of airplane and engine specifications, both of which include noise level estimates and guarantees. These specifications are the basis for contractual commitments by the airplane manufacturer and engine supplier, respectively.

The Firm Commitment Phase

After the preliminary design phase, the airplane development moves into the firm commitment phase firm commitments on the part of the airline customers, the engine suppliers, and the airplane manufacturer.

Firm Proposals to Airline Customers

When the preliminary design and airplane and engine specifications have been completed, the next step in airplane development process is that of making firm proposals to the airline customers. These proposals include guarantees for community, interior, and ramp noise. The guarantees may vary for different customers, depending on specific needs in terms of local airport regulations, route structures, and interior noise configurations and desires.

Engineering Go-Ahead

At engineering go-ahead, detailed design of the airplane begins, with the goal of supporting a given production schedule with an airplane that meets the specification. In order to protect the delivery date of the first airplane, engineering go-ahead may be authorized before the steps necessary for a production go-ahead have been completed.

Initial Orders and Production Go-Ahead

An airplane manufacturer requires a certain number of airplane purchase commitments by the airline customers prior to a production go-ahead. Once the required number of orders is obtained, a full production go-ahead is made, and the engine contracts are signed. This go-ahead includes a commitment to incur the immense costs of hard tooling for manufacturing.

The Final Design and Fabrication Phase

After firm commitments have been made, the next phase of the airplane development process is the detailed design and initiation of manufacturing, which culminates in rollout of the prototype airplane.

Detailed Design

The detailed design of the airplane includes the design of the hardware that influences community, interior, and ramp noise. The noise engineer works very closely with hardware designers, manufacturing people, and engine company engineers to develop the optimum design. Details of acoustic treatment, structural damping, and interior trim panels are among the decisions that are made during this phase. Often, developmental testing of selected hardware elements is conducted to assure the desired acoustic performance.

Manufacturing and Rollout

The design phase dovetails into the manufacturing phase. The fabrication of the first parts and major subassemblies, delivery of the first engines, and final assembly of the first airplane are, of course, major steps in the development process.

A key event for the first airplane is the rollout, in which the first airplane of the model leaves the final assembly building, usually accompanied by considerable publicity.

The Flight-Test and Certification Phase

After rollout, the airplane enters the flight-test and certification phase, which culminates in the first delivery to a customer.

After several weeks or months of taxi tests, the first flight of the airplane is performed by the flight-test organization. Initial flight noise measurements are often made at this time to identify any unforeseen noise level characteristics as early as possible.

The certification flight-test program for a new type of airplane typically includes a noise certification flight test, witnessed by the certificating authority, to demonstrate compliance with FAR Part 36 (ref. 1) and the ICAO Annex 16 (ref. 3) requirements. Detailed documentation of the test is submitted as evidence of compliance.

In addition to the certification flight test, additional testing is typically performed to demonstrate compliance with guarantees to airline customers. Additional community noise testing may be required; as a minimum, interior and ramp noise compliance must be demonstrated.

The culmination of the engineering process is the initial delivery of the airplane to the customer.

Product Improvement and Derivative Phase

The noise engineering does not end with delivery of the first airplane. Product improvements (to the engine and/or airframe) and/or major derivatives require effort until the delivery of the last airplane of a model.

Product Improvements

After the design and delivery of the prototype airplane, an airplane model is continually improved throughout its production life. The design is modified to improve performance, enhance passenger and airline appeal, and reduce cost. Each design modification is checked for noise implications. For any change that has noise implications, the manufacturer must submit evidence to the FAA (and/or other certification agencies) that the resulting certification levels still comply with the applicable regulatory requirements. This step is often done by analysis; sometimes engine ground testing or flight testing may be necessary.

Derivative Airplanes

The previous discussion focused on the typical steps in developing the first design of a particular model. The same basic steps are performed for a derivative airplane as for the first of a model; however the central idea is to use as much of the design of the original airplane as possible, in order to significantly reduce cost and flow time from that required for the parent design. Correspondingly, the noise engineering relies as much as possible on knowledge of the noise aspects of the parent airplane (and engine). Analyses are performed incrementally relative to the established noise levels of the parent; designs of various noise aspects are identical or similar within the limitation that they still meet the design requirements and objectives of the derivative.

The certification of a derivative airplane is also based on that of the parent airplane to the greatest degree possible. In some cases, the noise changes can be shown by analysis to be negligible, for example, if the same engine is used and the gross weight increase is very small. In other cases, a supplemental flight test is needed to extend the data into a higher gross weight range. For a new engine, the family plan certification scheme described previously is often used, in which ground test increments are superimposed on the flight-test data base of the parent.

Noise Engineering of Other Flight Vehicles

The previous discussion has centered upon the engineering of subsonic commercial airliners powered by conventional turbojet or turbofan engines, which represent the largest share of the noise engineering and certification to this point in time. The basic ideas and philosophies of applying noise engineering principles to other flight vehicles are similar, with differences in emphasis resulting from differences in the function of the vehicle and the applicable regulatory climate.

Propeller Airplanes

The propeller airplanes that preceded the turbojets as the mainstay of the commercial fleet were certificated prior to the age of noise regulations. Smaller (less than 12 500 lb takeoff gross weight) propeller-driven airplanes are subject to FAR Part 36 (ref. 1, appendix F) requirements, which are specified in terms of maximum A-weighted sound level for level flyovers at 1000 ft.

Recent aerodynamic developments have resulted in renewed interest in advanced high-speed propellers as a propulsion system with the potential for significant fuel savings compared with the turbofan. These ultrahigh-bypass-ratio engines will have no inlet or fan duct available for acoustic treatment and will have low-frequency propeller tones that must be recognized and controlled in both the community and the interior noise engineering process. Also, in the absence of inlets to control and direct the flow upstream of the propeller, forward speed simulation, as is available with wind tunnel testing, will be required for valid simulation of flight noise during isolated tests of engines or propellers.

Military Airplanes

In military airplane design, noise is not as important as in the design of commercial airplanes, partly because their utility is not typically in proximity to populated communities and partly because of the paramount performance requirements of a military airplane. FAA and ICAO noise requirements apply specifically only to civil aircraft, and military requirements are typically less stringent. However, some military procurement contracts require compliance with FAR Part 36 unless serious losses in performance would result.

The near-field noise of high-performance closely coupled power plants has sonic fatigue implications that are important in service life design.

Supersonic Transports

Noise is a major consideration in supersonic transport design. Supersonic cruise performance considerations tend to promote low-diameter, high-pressure-ratio, low-bypass-ratio engine designs, which in turn result in much higher jet noise than a high-bypass-ratio engine. Noise considerations may drive the propulsion system design to a variable-cycle engine, having higher bypass ratios and lower noise on takeoff, and lower bypass ratios at cruise for superior supersonic cruise performance.

An additional important consideration is the en route noise associated with sonic booms caused by shock waves fixed with the airframe extending to the ground. FAR Part 91 (ref. 2) prohibits supersonic flight over U.S. land, and thus prevents sonic booms (reaching the ground) from civil aircraft. This requirement plays a significant role in the design of a supersonic transport.

Boundary-layer noise at supersonic cruise Mach numbers is critical to the passenger acceptance of a supersonic transport airplane.

Business Jets

Business jets are subject to the same FAR Part 36 noise regulations as commercial airliners. Because of their small size, most business jet airplanes meet FAR Part 36 standards, particularly those being produced with high-bypass-ratio engines. However, business jets make frequent use of small airports, at which stringent local airport regulations often apply. Consequently there are pressures toward low-noise designs.

Rotorcraft

Helicopters are subject to FAR Part 36 (ref. 1, appendix H) and ICAO Annex 16 (ref. 3, chapter 8) certification requirements for noise. Helicopters face severe constraints because they operate close to populated areas, both at heliports and en route. Rotor noise, particularly from the main rotor(s), is the most prevalent source. Interior noise and vibration due to both the rotor(s) and the gearbox are also very important design considerations.

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Glossary of Terms

Absorption coefficient—The ratio of sound energy absorbed by a surface to the sound energy incident upon the surface.

Acoustic power level (PWL)—Ten times the logarithm to the base 10 of the ratio of the acoustic power of a sound source to a reference power:

$$\text{PWL} = 10 \log_{10} \frac{W}{W_{\text{ref}}}, \text{dB}$$

where, in this text, $W_{\text{ref}} = 10^{-12}$ W and W is the radiated acoustic power corresponding to a particular frequency bandwidth.

Acoustic shadow region—A region in which sound pressure levels decrease rapidly as distance increases. It exists at distances larger than those for which the limiting rays refracted upward just miss the ground.

Active noise control—The use (by electronic means) of auxiliary sound sources to cancel or partially cancel the original sound field.

Airborne noise—Noise generated by aeroacoustic sources such as propellers and jet exhausts. It impinges directly on the external aircraft surfaces and is then transmitted into the cabin.

Atmospheric refraction—Varying conditions of wind and temperature with height in the atmosphere result in a varying speed of sound which causes sound waves to propagate along curved paths. For upwind propagation, the sound speed generally decreases with height and ray paths curve upward. In a temperature inversion or for propagation downwind, the ray paths curve downward.

A-weighted sound pressure level (SLA)—Sound pressure level that has been weighted to approximate the response of the human ear. It is measured with a standard sound level meter equipped with an "A" weighting network.

Bulk absorber acoustic duct liner—Consists of a single-layer construction with a solid backplate and a porous face sheet of negligible resistance. The cavity between the backplate and face sheet is filled with a fibrous mat having very small air passages.

Cabin insertion loss—Loss determined by subtracting cabin sound pressure levels measured after the acoustic treatment is in place from levels measured before treatment installation. Treatment may sometimes increase the sound pressure level; therefore, insertion loss can be negative.

Cutoff, cut-on modes—Acoustic duct modes which are attenuated with distance and carry no acoustic power are referred to as being "cutoff," while modes which propagate in the usual sense are said to be "cut on."

Decelerating approach—A noise abatement procedure that may be used to achieve lower noise exposures under the approach path during the initial phases of final approach. The airplane flight speed is progressively reduced to the final landing speed, with a corresponding increased angle of attack and increased thrust until final approach thrust is reached.

Derivative airplanes—Growth versions of the parent airplane which arise as a result of operational experience, improvements in technology, or customer demands. Growth in payload and/or range is usually accompanied by higher takeoff thrust and gross weight and associated higher noise levels.

Diffraction—The amplitude and phase distortion of a sound field due to the presence of a barrier or other solid body.

Dispersive waves—Those waves whose propagation speed is proportional to the square root of frequency. For instance, bending waves in a plate are dispersive.

Duct insertion loss—Loss determined by subtracting the sound pressure levels measured for a hard-wall, untreated duct from those levels measured after treatment panels have been inserted.

D-weighted sound level (SLD)—Sound pressure level that has been weighted to reduce the effects of low-frequency noise and to increase the effects of high-frequency noise. It is measured with a standard sound level meter equipped with a "D" weighting network.

Eddy convection speed—The speed at which an eddy embedded in the flow is transported by the flow. Convection speeds are typically 0.5 to 0.7 times the free-stream value.

Effective perceived noise level (EPNL)—Derived from perceived noise level (PNL), but includes correction terms for the duration of an aircraft flyover and the presence of audible pure-tone components.

Equivalent continuous sound level (LEQ)—Calculated from A-level noise measurements to provide an equivalent steady-state value.

E-weighted sound level (SLE)—Sound pressure level weighted to approximate the perceived level of a sound. It is measured with a standard sound level meter equipped with an "E" weighting network.

Excess attenuation—That attenuation which is over and above that due to normal geometrical spreading and atmospheric absorption.

Geometrical spreading—The spreading out of acoustical energy as it propagates away from a source. For the special case of a point source, the corresponding decrease in sound pressure level is 6 dB per doubling of distance for all frequencies.

Hydrodynamic coincidence—Occurs when the convection speed of the boundary-layer fluctuating pressure field (about 70 percent of flight speed) equals the flexural wave speed of the skin structure.

Loudness—The perceived intensity of a sound.

Molecular (classical) absorption—The absorption of sound in the atmosphere due to the direct transfer of acoustic energy into heat energy through processes involving viscosity and heat conduction and due to molecular relaxation which is redistributed into rotational and vibrational modes of the molecules through binary collisions.

Multisegment approach—A noise abatement procedure that may be used to achieve lower noise exposures under the approach path during the initial phases of final approach. The initial segments are carried out at a higher altitude, at a steeper glide slope, and at a lower approach thrust.

Noise—Sound that produces adverse effects.

Noise abatement cutback—A noise abatement takeoff procedure that is sometimes used and involves reducing the engine power for a short time to a lower, but safe, level to reduce noise exposures over a certain area. This results in a shallower climbout angle and tends to increase the noise exposures over other parts of the community farther from the airport after normal climbout power is reapplied.

Noise certification of aircraft—Usually a requirement for operation of certain aircraft, particularly for commercial purposes. Certification rules are set by Federal and/or international authorities and specify maximum noise levels allowable during landing approach operations, during takeoff-climbout operations, and in some cases during en route operations.

Noise exposure forecast (NEF)—Used to determine the relative noise impact of aircraft noise near an airport. It is expressed as the total summation (on an energy basis) over a 24-hour period, weighted for the time of day, of the effective perceived noise level (EPNL) minus the constant 88 dB.

Noisiness—That characteristic or attribute of a sound which makes it unwanted, unacceptable, disturbing, objectionable, or annoying and which may be distinguishable from loudness, which is also a subjective quantity.

Nondispersive waves—Those waves whose propagation speed is independent of frequency. For instance, longitudinal and transverse waves are nondispersive.

Normal full-power takeoff—At airports for which noise in proximity to the airport is not a concern, the normal procedure is to maintain full takeoff rating until reaching a given altitude, after which the thrust is reduced to climb thrust.

Normal landing approach—Approach which follows a 3° glide slope and the flap setting corresponding to the minimum safe landing speed. This results in a relatively high landing thrust requirement and in higher noise levels on approach.

Overall sound pressure level (OASPL)—A physical measure which gives equal weight to all frequencies. This is not standardized but is generally considered to extend from 20 to 20 000 Hz, a range which corresponds to human hearing.

Overspeed takeoff—A noise abatement procedure that may be used to achieve lower noise exposures along the sideline and far from the airport. Provided field length is not critical, rotation can be delayed to higher speeds, thus permitting lower flap settings, more favorable lift-drag ratios, and higher climb rates.

Perceived noise level (PNL)—Calculated from broadband noise measurements to provide a rating of noisiness for sounds which have similar time durations and which do not contain strong discrete frequency components.

Reduced flap settings—A noise abatement procedure that may be used to achieve generally lower noise exposures under the approach path. The lift is maintained by increased landing speed; hence, the drag and the required thrust are reduced, but with the requirement of greater field length.

Reduced-power takeoff—A noise abatement procedure that may be used where takeoff field length is not critical. This results in lower sideline noise levels than with full takeoff power; however, the liftoff point is delayed and initial climb rate is reduced, thus eliminating noise benefits under the flight path.

Single-degree-of-freedom acoustic duct liner— Consists of a single-layer sandwich construction with a solid backplate. A porous face sheet and internal partitions are used, as would be provided by honeycomb separator material.

Sound exposure level (SEL)— A duration-corrected noise metric used to predict the annoyance of a single noise event such as an aircraft flyover. It is time-integrated A-level noise and is expressed by the level of an equivalent 1-sec-duration reference signal.

Sound pressure level (SPL)— Equal to 20 times the logarithm to the base 10 of the ratio of the sound pressure to a reference pressure:

$$\text{SPL} = 20 \ \log_{10} \frac{p}{p_{\text{ref}}}, \text{dB}$$

where, in this text, $p_{\text{ref}} = 2 \times 10^{-5}$ Pa and p is the sound pressure corresponding to a particular frequency bandwidth.

Speech interference level (SIL)— Developed to evaluate the effects of aircraft noise on passenger communications. It is calculated from the arithmetic average of the sound pressure levels of four octave bands having center frequencies of 500, 1000, 2000, and 4000 Hz.

Structure-borne noise— Noise generated by mechanical means, such as engine unbalance, transmitted along the airframe structure, and then radiated into the cabin.

Turbulent scattering—Occurs due to local variations in wind velocity and temperature which induce fluctuations in phases and amplitudes of the sound waves as they propagate through an inhomogeneous medium. There is a tendency for high frequencies to be affected more than low frequencies.

Two-degree-of-freedom acoustic duct liner—Consists of a double-layer sandwich construction with a porous septum sheet or midsheet and a porous face sheet. Internal partitions from material such as honeycomb provide spacings for the two layers.

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16. Abstract
This document is oriented toward flight vehicles and emphasizes the underlying concepts of noise generation, propagation, prediction, and control. Authors are from government, industry, and academia in the United States, England, and Canada. This volume includes those chapters that relate to flight vehicle noise control and operations: Human Response to Aircraft Noise; Atmospheric Propagation; Theoretical Models for Duct Acoustic Propagation and Radiation; Design and Performance of Duct Acoustic Treatment; Jet Noise Suppression; Interior Noise; Flyover-Noise Measurement and Prediction; and Quiet Aircraft Design and Operational Characteristics.

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