HOW TO SATISFY THE TAKEOFF NOISE REQUIREMENTS FOR A SUPERSONIC TRANSPORT

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Abstract

The noise during takeoff of a supersonic transport is calculated for the flyover and the lateral reference noise measurement points defined by ICAO Annex 16. Only the contribution of jet mixing noise is considered. The influences of the following parameters are studied: jet speed, aircraft weight, aircraft wing loading, aircraft lift-to-drag ratio, and the amount of power cutback after takeoff. The influence of the takeoff procedure is also studied. It is shown that jet speed has the largest influence of all parameters and that values of about 400 m/s or less are required to satisfy the noise limits that are currently valid for subsonic jet aircraft. Such low jet speeds can be achieved by chosing large engine bypass ratios or by employing ejector mixers with large nozzle exit diameters. The first solution may be very difficult to realize technically for a supersonic transport, the second solution requires that the mixer can be fully retracted which may be impossible because of its size.

Nomenclature

C	cutback parameter
c_d	drag coefficient
c_l	lift coefficient
EPNL	equivalent perceived noise level
f	frequency observed on the ground
f_s	frequency of equivalent static jet
M_f	flight Mach number
SPL	one-third-octave level observed on ground
SPL_s	one-third-octave level equivalent static jet
U_f	flight speed
U_j	jet speed
U_p	propagation speed of disturbancies in free shear layer of jet
U_s	jet speed of equivalent static jet
V_2	airspeed of aircraft after liftoff
V_e	maximum airspeed during climb
V_r	airspeed for aircraft rotation
α	angle of attack of the wing
ϑ	emission angle rel. flight direction
ϑ_s	emission angle of equivalent static jet
ρ	air density
ρ_r	density of ISO atmosphere at sea level
σ	jet stretching factor due to U_f
σ_1	turbulence intensity factor due to U_f

1. Introduction

All designs of supersonic transport aircraft exhibit rather small engine cross sections. Apparently, it is difficult to build an engine with a large bypass ratio that can be used efficiently for supersonic flight. Consequently, the jet speeds are rather high and one has to expect that jet-mixing noise will dominate the takeoff noise of such aircraft.

The prediction of aircraft noise heard on the ground is generally based on existing data and empirical scaling laws for the consideration of the likely influence of small changes of the engines or the aircraft. However, in the case of a new supersonic transport, large changes have to be expected in comparison with subsonic aircraft and with the existing supersonic aircraft Concorde. The use of empirical scaling methods for noise predictions may be dangerous in such a case. Therefore, a scaling law will be used in this paper that was derived analytically and has shown excellent agreement with experimental results.

This scaling law for the influence of flight speed on jet-mixing noise was first derived in ref. 1 for the overall sound pressure level and was later extended to one-third-octave band spectra [2,3]. The law agrees almost perfectly with the Aérotrain measurements [4] and explains the "forward arc amplification" for large flight speeds. The law works equally well for single stream jets and for dual stream jets with regular or inverted velocity profiles [5]. It also agrees with noise data of a modern engine with a large bypass ratio [6].

Several reasons may be responsible for the good agreement with experimental data. One of them is the stretching model for the influence of flight speed on jet turbulence which was verified experimentally [2,3]. A second reason is the inclusion of the source terms that are important for heated jets. It is known for the static case that jet noise depends considerably on the density of the jet. The sound power, e.g., of a very hot jet, is proportional to the sixth power of the jet speed U_j rather than the well known eighth power which is only valid for the isothermal jet with constant density. It was shown in ref. 7 that a similar difference exists between isothermal and heated jets concerning the influence of flight speed on jet noise. This may be one reason for the poor performance of empirical scaling laws that are based on a relative velocity index, like the flight effect law recommended by the latest issue of SAE ARP 876 [8]. A relative velocity index is not only a function of emission angle as it is assumed in ref. 8 but also a function of jet and flight speeds and jet density.

One problem exists for any scaling law if it is to be used to predict the flyover noise for an engine that is still on the drawing board: static jet noise data are not available. One possibility is to resort to prediction methods for static jet noise like the semi-empirical SAE method for single stream jets [8]. Another method based more on physics was proposed by Morfey et al. [9, 10]. A comparison of results obtained with the two methods reveals considerable differences in the predicted sound levels for identical jets for certain emission angles and frequencies. Unfortunately, the method of Morfey et al. cannot be used for emission angles close to the jet axis which is very important for aircraft departures. Therefore, the SAE method was used in this paper. Validation studies of the SAE method (referenced in ref. 8) show that between one and two decibels have to be added to the SAE results when wideband noise levels of full-scale engines are to be predicted. This is also done in the predictions of this paper.

A prediction of flyover noise for the Boeing 727 was already carried out following this procedure in ref. 11. Overall and A-weighted free-field levels were computed. The procedure is extended to the equivalent perceived noise level EPNL in this paper. In addition, sound reflection on the ground is now considered, approximately.

It is assumed in this paper that the takeoff noise of a supersonic aircraft is dominated by jet mixing noise. Broadband shock noise is assumed to be negligible. This latter jet noise component exists when turbulence passes through the shock cell structure of a supersonic jet. Broadband shock noise can be minimized by reducing shock cell strength through a proper adjustment of the nozzle exit area of a variable area nozzle.

Two steps are necessary for any prediction of aircraft takeoff noise, (i) the prediction of the aircraft departure, and (ii) the prediction of the noise heard in a given observer position on the ground while the aircraft passes by. The following data are needed as a function of time for the jet noise calculations: number of engines, exit area of the fully expanded jet, position of the aircraft, its flight and jet velocities (including the respective angles), jet temperature. All these quantities are influenced by the design of the aircraft and its engines.

The following influences on the jet noise heard on the ground are studied. (i) jet exit speed, (ii) climb performance, (iii) amount of cutback during climb, (iv) lift-to-drag ratio, (v) wing loading, (vi) departure procedure.

2. Departure flight paths

The departure flight paths are calculated by flying the considered aircraft according to their paper data. All aircraft studied have the following lift coefficient, c_l, as a function of angle of attack, α. Ground effect is not considered.

α	c_l
5 deg	0.26
10 deg	0.61
15 deg	0.96

Three different basic aircraft are studied which differ in wing area and drag coefficient. The drag coefficients, c_d, of these aircraft are given as a function of the lift coefficient, c_l.

wing area	aircraft A 800 m^2	aircraft B 800 m^2	aircraft C 1200 m^2
c_l	c_d	c_d	c_d
0.20	0.020	0.024	0.017
0.40	0.035	0.042	0.032
0.70	0.095	0.113	0.090

The drag increase for the landing gear is assumed to be Δc_d = 0.02. Landing gear was retracted at an altitude of 30 m. Aircraft A and B are identical except that aircraft B has a 20 % higher drag. Aircraft C has a larger wing area for flight at higher altitudes and a smaller drag coefficient because of a relatively smaller fuselage.

Three basic engine designs with different jet speeds are studied. The jet exhaust speeds are set at 400 m/s, 500 m/s, or 600 m/s for an ambient temperature of 15 °C. The corresponding nozzle pressure ratio is used as a climb power setting. The pressure ratio during ground roll and initial climb is increased over this value by the cutback parameter C = 5 %, 10 %, 15 %, or 20 %. Through this definition of cutback it is assured that the climb performances of the aircraft are not influenced by the amount of cutback used. The increased takeoff power of the cases C = 10 %, 15 %, and 20 % in comparison with the baseline case C = 5 % is used to reduce ground roll and increase the initial climb rate before the cutback is applied. The case C = 5 % corresponds to an average cutback from takeoff power to maximum climb power of the Boeing 727.

The corresponding jet temperatures are calculated by assuming a change of bypass ratio. A nozzle efficiency of 98 % and an efficiency of 80 % for the conversion of mechanical power from the primary stream to the bypass stream is assumed. The following data are given as examples.

jet speed	400 m/s	500 m/s	600 m/s
flight Mach number	0.31	0.31	0.31
jet temperature	483 K	583 K	694 K
isentr. exponent	1.33	1.33	1.33
pressure ratio	1.908	2.359	2.898

A takeoff gross mass of 290,000 kg is assumed. A few comparisons for a plane with a shorter range or a lighter structural weight are also made assuming a mass of 250,000 kg.

The nozzle exit area of each aircraft is determined by the required climb performance after cutback. Four different climb rates are studied, 500 ft/min, 1000 ft/min, 1500 ft/min, and 2000 ft/min. 1000 feet/min is used as the baseline performance. In addition, it is assumed that the aircraft accelerates with 1 knot/s while maintaining the climb rate, if the acceleration starts in an altitude of 3000 ft and with an airspeed of V_2 + 10 knots and ends with the airspeed V_e. (The airspeeds mentioned here are called calibrated airspeeds. True airspeeds are higher by a factor $(\varrho_r/\varrho)^{0.5}$, where ϱ is the ambient density and ϱ_r is the reference density of the ISO atmosphere at sea level.)

The takeoff length is determined by the distance between the start of roll and the position where the aircraft clears an obstacle of 35 feet. The airspeed V_2 is reached in this position. The airspeed V_r for rotation and the rate of rotation are chosen appropriately. The value of V_2 is determined by the condition that the fuselage would not scrape the ground during rotation. (The scrape angle is assumed to be 10 degrees.) The airspeed for best lift-to-drag ratio is used for the final airspeed V_e unless this speed exceeded the limit of 250 knots for the controlled air space around large airports.

Three different departure procedures are studied. The IATA noise abatement procedure is used as a baseline procedure. The aircraft climbs with a calibrated airspeed of V_2 + 10 knots and takeoff power to an altitude of 1500 feet. (This is the altitude indicated by the altimeter of the aircraft which is called pressure altitude.) The power is reduced to climb power in this altitude. The airspeed is kept constant until an altitude of 3000 feet is reached where the climb gradient of the aircraft is reduced for acceleration to an airspeed V_e. The above mentioned climb rates between 500 feet/min and 2000 feet/min are maintained during this segment. After the calibrated airspeed V_e is attained, the climb gradient is increased in order to keep the calibrated airspeed constant.

The other two departure procedures are called modified ATA procedure and ATA procedure. The second climb segment of the IATA procedure with the minimum speed V_2 + 10 knots is eliminated in both procedures. In the modified ATA procedure, the acceleration starts already at 1500 feet concurrently with the power reduction. This yields lower altitudes and higher flight speeds in the vicinity of the airport. The altitude for power reduction and start of acceleration is further reduced to 1000 feet in the ATA procedure.

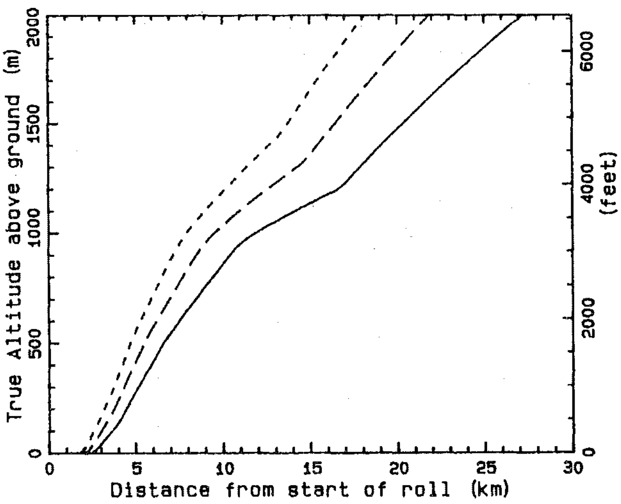

Fig.1: True altitudes as a function of distance from the start of roll for a departure with aircraft A with three different climb rates. 1000 ft/min ———, 1500 ft/min — — —, 2000 ft/min - - - -. Jet speed U_j = 400 m/s, cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg, wind speed zero, IATA departure procedure.

A comparison of the true altitudes as a function of distance for the IATA departure procedure is shown in figure 1 for aircraft A equipped with the 400 m/s engine for the three different climb rates 1000 ft/min, 1500 ft/min, and 2000 ft/min in the acceleration segment. The pressure ratio for takeoff power is increased by C = 5 % over the pressure ratio for climb power. The different climb rates are caused by differing engine sizes and the correspondingly differing thrust values. It can be seen, how much the hight above an observer at the fly-over reference position x = 6.5 km is influenced by the climb performance. Part of this influence is due to the influence of the engine size on the takeoff lengths which are 2630 m, 2240 m, and 1950 m for the climb rates 1000 feet/min, 1500 feet/min, and 2000 feet/min, respectively. The wind velocity was assumed to be zero in all cases in this paper.

Figure 2 demonstrates the situation for the three different jet speeds 400 m/s, 500 m/s, and 600 m/s for a climb rate of 1000 feet/min. The corresponding takeoff lengths are 2630 m, 2850 m, and 3010 m. The reason for the influence of jet speed on the takeoff length is that the net thrust of an engine with a lower jet speed depends stronger on the flight Mach number than the net thrust of an engine with higher jet speed. Since the size of the engines is chosen for equal thrust during the acceleration segment above an altitude of 3000 feet, the thrust on the runway has to be higher for an engine with smaller jet speed.

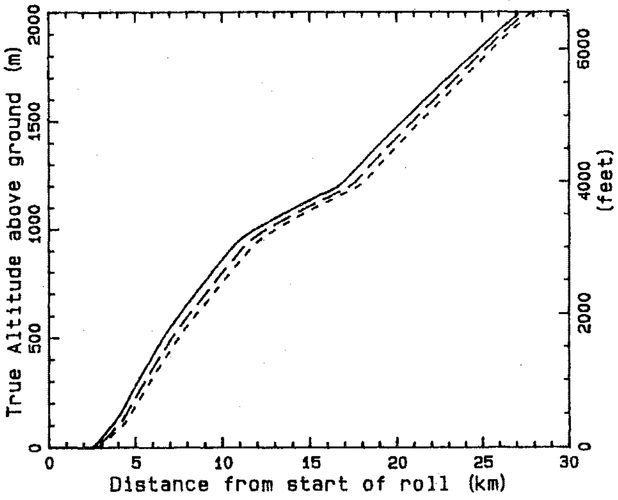

Fig.2: True altitudes as a function of distance from the start of roll for a departure with aircraft A with three different jet speeds. U_j = 400 m/s ———, 500 m/s — — —, 600 m/s - - - -. Climb rate 1000 ft/min, cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg, wind speed zero, IATA departure procedure.

3. Takeoff noise prediction

3.1 Method of computing the takeoff noise

The one-third-octave band level SPL of a jet in flight heard on the ground is related to the one-third-octave band level SPL_s of an equivalent static jet via the relation [2,3]:

$$\begin{aligned} SPL(\vartheta,f,U_j,U_f) \quad &= \quad SPL_s(\vartheta_s,f_s,U_s) \\ &+ 20 \text{ dB } \lg[\sigma\ (1 - M_f \cos\vartheta)] \\ &+ 10 \text{ dB } \lg \sigma_1 . \end{aligned} \qquad (1)$$

The wave-normal distances (distance between source and observer at emission time) and the jet temperatures of the jet in flight and the static jet are identical.

ϑ is the angle between the observer and the flight direction relative to the nozzle at emission time, f is the frequency of the one-third-octave band. U_j and U_f are the jet and flight speeds, respectively. $M_f = U_f/a_0$ is the flight Mach number, where a_0 is the speed of sound in the ambient air. σ is the jet stretching factor and is given by

$$\sigma = 1 + 1.4\ U_f\ /(U_j - U_f). \qquad (2)$$

The factor 1.4 is defined by the ratio $(U_j-U_f)/(U_p-U_f)$, where U_p is the propagation speed of the disturbances in the shear layer. This ratio can be determined numerically from an instability analysis of the jet [12]. It is primarily a function of frequency and jet density, a value of 1.4 seems to be a good average for all cases, however. The factor σ_1 is the only empirical constant of the scheme and considers an increase of the normalized turbulence intensity in flight. A good estimate is given by

$$\sigma_1 = \sigma^{0.5}. \qquad (3)$$

The one-third-octave band level SPL_s of the equivalent static jet has to be evaluated for the angle ϑ_s, the frequency f_s, and the jet speed V_s. These three variables are given by the equations

$$\vartheta_s = \vartheta, \qquad (4)$$

$$f_s = f/\sigma, \qquad (5)$$

$$U_s = (U_j-U_f)/(1-M_f \cos \vartheta). \qquad (6)$$

The one-third-octave band levels SPL_s of the static jet noise are calculated with the SAE method [8]. The accuracy of the predictions for the one-third octave band levels SPL in the flyover case with eq. (1) depends on the accuracy of the static prediction method. The jet speed U_s of the equivalent static jet according to eq. (6) may be particularly high for small angles ϑ (close to the flight direction in the forward arc). This is necessary to simulate the sound interference effects correctly with the static jet. Unfortunately, the SAE method predicts too high noise levels in this direction for high jet speeds which result in too high flyover noise levels according to eq. (1). Fortunately, the sound emitted in this direction has to propagate a relatively long distance and is attenuated accordingly until it reaches an observer on the ground. The influence on the equivalent perceived noise level should be small, therefore.

The sound is attenuated while it propagates from the source to the observer. The atmospheric attenuation is considered according to references 13 or 14. A larger attenuation is observed when the sound waves propagate with a shallow angle relative to the ground surface. This lateral attenuation is considered according to ref. 15. Finally the sound waves travel through a medium with a gradient of the density and sound speed. This influences the wave-normal angle as well as the pressure amplitude. Only the influence on the pressure amplitude is considered here.

3.2 PNL and EPNL

The perceived noise level PNL considers the sensitivity of the human ear and the nuisance of the sound. The noise heard in an observer position on the ground is calculated according to section 3.1 for all required one-third-octave bands as a function of time. The perceived noise level is then processed according to ref. 14.

The equivalent perceived noise levels EPNL are computed according to ref. 14 from time histories of the perceived noise level PNL. In addition, the approximate influence of ground reflections is considered by adding 5.5 dB and the generally too low sound levels predicted by the static SAE method [8] are considered by adding 1.5 dB.

3.3 Reference noise measurement points

The noise is calculated in the flyover and the lateral reference noise measurement points defined by ICAO Annex 16 [16]. The flyover reference noise measurement point is located 6500 m behind the start of roll on the extended center line of the runway. It will be called flyover point in the following. The lateral reference noise measurement point is defined by that position on a line parallel to the runway in a distance of 450 m from the runway center line in which the EPNL is highest. This point will be called sideline point in the following.

4. Results

4.1 Time history for the perceived noise level

The time history of the perceived noise level for the flyover point is shown in figure 3 for the three aircraft of figure 1 which differ only in their engine sizes. The different flyover altitudes of figure 1 result in considerable differences of the

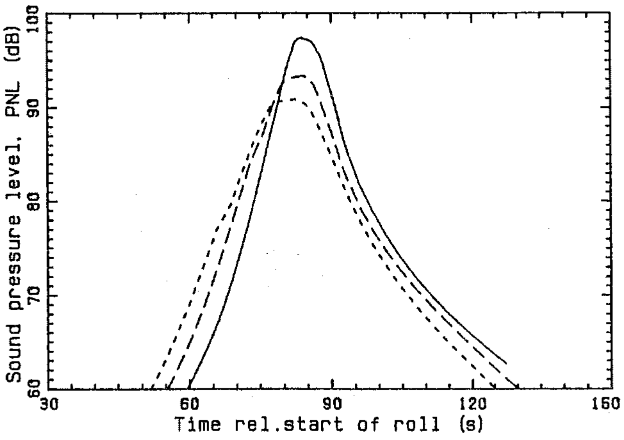

Fig.3: Perceived noise level in the flyover point as a function of time for the three IATA departures of figure 1 with aircraft A. Climb rates: 1000 ft/min ———, 1500 ft/min — — —, 2000 ft/min - - - -. Jet speed U_j = 400 m/s, cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg, wind speed zero.

noise levels in the flyover point. The levels reported here are free-field levels which do not contain the corrections of 5.5 dB and 1.5 dB of sec. 3.2.

The corresponding time histories for the departures of figure 2 are shown in figure 4. The jet speed is seen to have a very strong influence on the noise level. This result cannot surprise, because it is long known for subsonic jet aircraft and was one reason that modern aircraft are equipped with engines with low jet speeds.

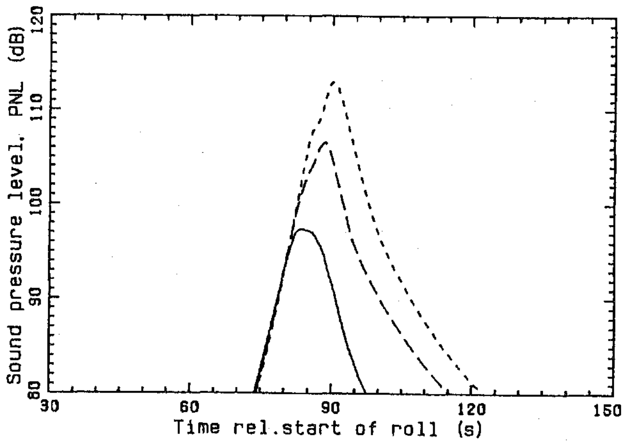

Fig.4: Perceived noise level in the flyover point as a function of time for the three IATA departures of figure 2 with aircraft A with three different jet speeds.
U_j = 400 m/s ———, 500 m/s — — —, 600 m/s - - - -. Climb rate 1000 ft/min, cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg, wind speed zero.

4.2 Influence of climb rate and jet speed on EPNL

The influence of climb rate and jet speed on the equivalent perceived noise level EPNL in the flyover point is shown in figure 5 for the IATA departure procedure. The nozzle pressure ratio for takeoff power is increased by 5 % over its climb ratio (cutback parameter C = 5 %). The strong influence of jet speed is no surprise. However, it can be seen that the climb rate of the aircraft, which is a measure of the available thrust at the specified jet speed, does also have a considerable influence.

Also included in the figure is the noise limit of EPNL = 104.4 dB currently applicable to subsonic jet aircraft with a takeoff gross mass of 290,000 kg according to ICAO Annex 16 [16]. Before a comparison with this limit can be made we have to account for the contributions from all other noise sources of an aircraft. It shall be assumed for simplicity that these contributions can be reduced by suppression methods to one half of the jet noise contribution. The jet noise limit is then given by the ICAO noise limit minus 1.8 dB. We conclude from figure 5 that the flyover jet noise limit of 102.6 dB can be satisfied by the supersonic aircraft A with a cutback parameter C = 5 % if the jet speeds are not higher than about 390 m/s, 420 m/s, or 440 m/s for the 1000 ft/min, 1500 ft/min, or 2000 ft/min aircraft, respectively. The aircraft capable of only 500 ft/min is not considered a realistic candidate for a supersonic transport.

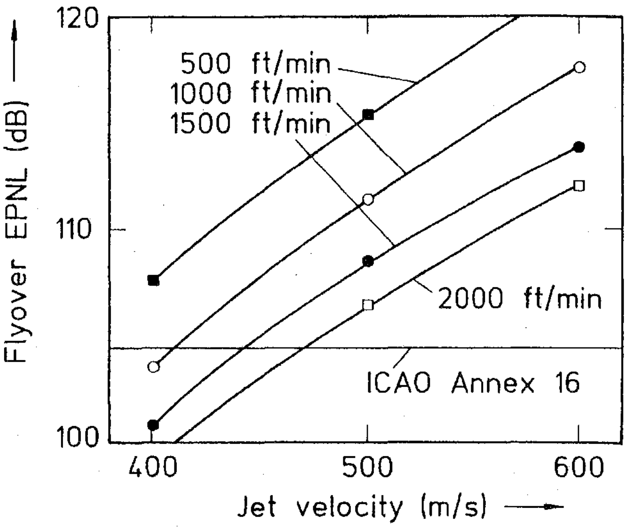

Fig.5: Influence of jet speed and climb rate on the equivalent perceived noise level EPNL in the flyover point. Aircraft A, IATA departure procedure, cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg. Note the possible reduction of flyover jet noise through an increased climb rate.

Figure 6 describes the EPNL produced by the same departures on the sideline point. The influence of the climb rate is small in the sideline point. Unfortunately, the noise levels increase with an improvement of aircraft performance through a higher climb rate. The ICAO noise limit for a subsonic jet aircraft with a takeoff gross mass of 290,000 kg is EPNL = 101.8 dB in the sideline point. The limit for

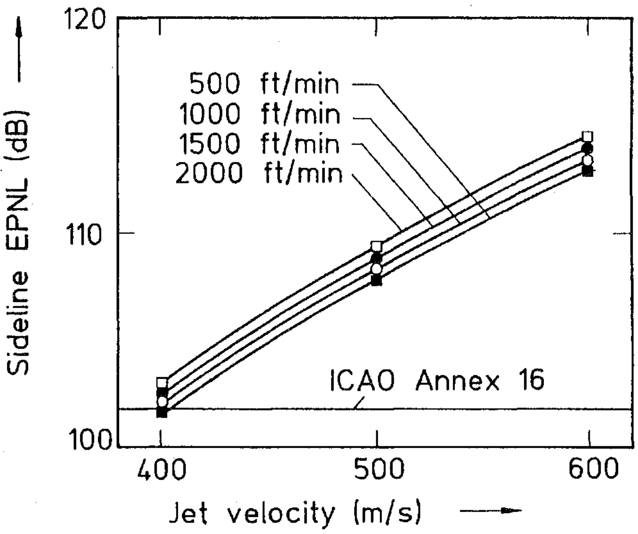

Fig.6: Influence of jet speed and climb rate on the equivalent perceived noise level EPNL in the sideline point. Aircraft A, IATA departure procedure, cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg. Note that an increased climb rate increases sideline noise which is an opposite influence as compared with the flyover noise of figure 5.

the jet noise component would be 100.0 dB if we use the same assumptions about the other noise sources as in the previous paragraph. The sideline noise limit can be satisfied if the jet speed is not higher than about 370 m/s for the climb rate of 1000 ft/min. This is an even smaller speed than for the flyover point.

ICAO Annex 16 [16] permits to exceed the maximum noise level in a reference point if the excess is offset at another point. The maximum excess permitted in a single point is 2 dB. Under this condition, a jet speed of about 380 m/s would satisfy the noise limits for aircraft A with a cutback parameter C = 5 % and a 1000 ft/min climb rate with an excess of about 0.4 dB. The highest permissable jet speed is about 390 m/s for a climb rate of 1500 ft/min, and about 385 m/s for a climb rate of 2000 ft/min. In both cases, the 2 dB maximum excess is reached in the sideline point. The corresponding EPNLs for the jet noise component in the flyover point are only 100 dB and 98 dB, approximately.

4.3 Influence of cutback on EPNL

The influence of cutback is studied next. The aircraft with a given engine is flown four times with different values of the cutback parameter C which describes the increase of the nozzle pressure ratio over its climb value during the takeoff roll and the initial climb. The four values are C = 5 %, 10 %, 15 %, and 20 %. The takeoff power influences the required runway length and the climb gradient in the first climb segment.

The noise level EPNL in the flyover point is shown in figure 7 for the aircraft with a 1000 ft/min climb rate. It can be seen that the flyover noise level is decreased considerably by increasing the takeoff engine power above the climb power. Unfortunately, just the opposite influence of the cutback parameter can be observed in the sideline point. This is shown in figure 8.

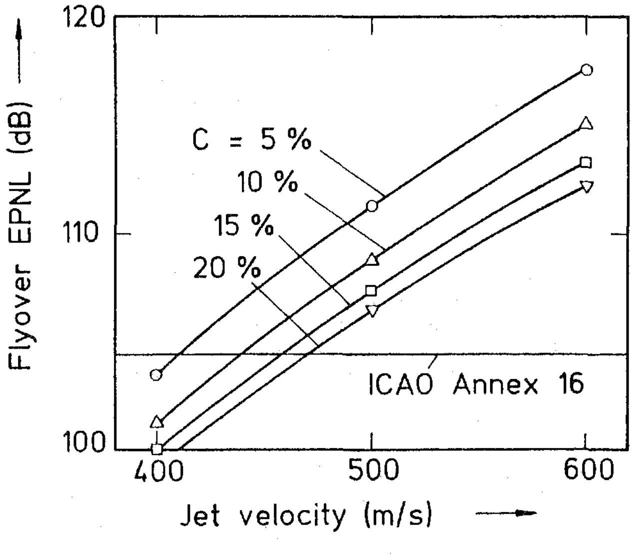

Fig.7: Influence of jet speed and cutback parameter on the equivalent perceived noise level EPNL in the flyover point. Aircraft A, IATA departure procedure, climb rate 1000 ft/min, takeoff gross mass m = 290,000 kg.

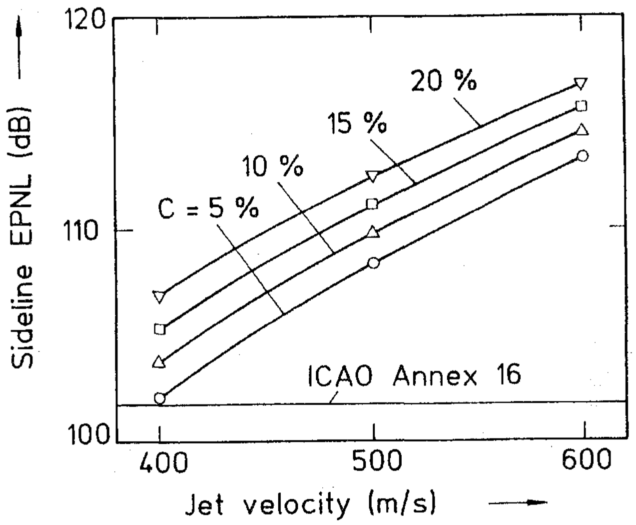

Fig.8: Influence of jet speed and cutback parameter on the equivalent perceived noise level EPNL in the sideline point. Aircraft A, climb rate 1000 ft/min, takeoff gross mass m = 290,000 kg.

This result makes it practically impossible to increase the takeoff power beyond the value that corresponds to C = 5 %. This is unfortunate, because a large value of C would reduce runway length and increase flyover altitudes. This would yield lower EPNL almost everywhere, except in the vicinity of the first climb segment. Large values of C should be possible for a supersonic aircraft because of the high thrust required for the acceleration to supersonic speeds.

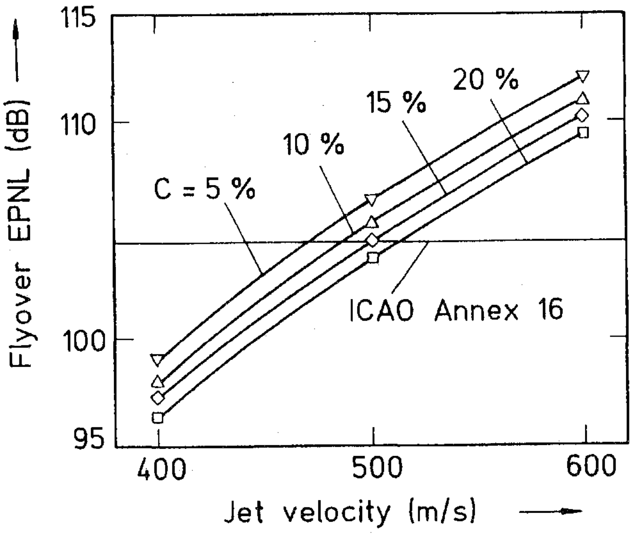

Fig.9: Influence of jet speed and cutback parameter on the equivalent perceived noise level EPNL in the flyover point. Aircraft A, climb rate 2000 ft/min, takeoff gross mass m = 290,000 kg.

Figure 9 illustrates in comparison with figure 7 how much the noise level EPNL in the flyover point is reduced when the aircraft is capable of climbing at 2000 ft/min. Jet speeds of about 500 m/s appear to be possible. However, figure 10 reveals that such a takeoff would exceed the allowable noise levels in the sideline point.

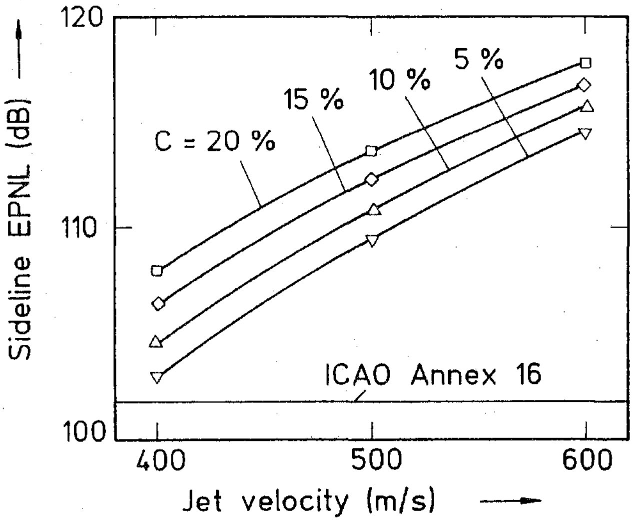

Fig.10: Influence of jet speed and cutback parameter on the equivalent perceived noise level EPNL in the sideline point. Aircraft A, climb rate 2000 ft/min, takeoff gross mass m = 290,000 kg.

4.4 Influence of aircraft drag on EPNL

Lift and drag coefficients of the aircraft A discussed so far are rather uncertain. The noise will probably depend only little on the lift coefficient $c_l(\alpha)$ as a function of α since the influence on the flight path should be small. However, the drag coefficient $c_d(c_l)$ might have a considerable influence, since it influences the thrust required by the aircraft. An aircraft B is defined with a drag that is 20 % higher than that of aircraft A. (The lift-to-drag ratios are still better than those of Concorde.) The higher drag of aircraft B is compensated by increases of the sizes of the 400 m/s, 500 m/s, and 600 m/s engines to keep climb performance identical.

The takeoff noise values of both aircraft are compared in figure 11 for the flyover point. The results are quite surprising since the aircraft B with the higher drag is less noisy by about one half dB. The reason is that the requirement of equal climb performance results in a better runway performance of the high-drag aircraft B. Its takeoff field length is shorter by about 7 % which yields higher flyover altitudes in the flyover point.

The corresponding noise levels in the sideline point are plotted in figure 12. Here we find the expected, though small, increases of the noise levels of the high-drag aircraft B. The shorter takeoff length is accompanied by a corresponding displacement of the sideline reference measurement point. The noise increase of about one half decibel corresponds to the increase of the nozzle exit area of aircraft B over aircraft A. A similar increase would have been registered in the flyover point if the nozzle pressure ratio of aircraft A for takeoff power were increased to yield the same takeoff field length as aircraft B.

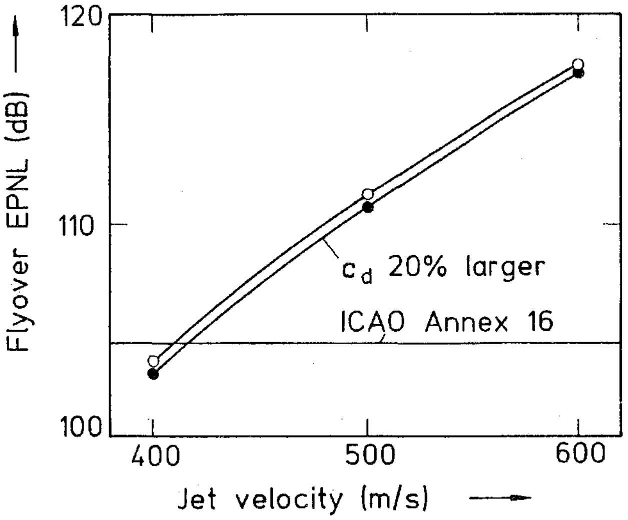

Fig.11: Influence of jet speed and lift-to-drag ratio on the equivalent perceived noise level EPNL in the flyover point. Baseline aircraft A and aircraft B (20 % more drag), cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg.

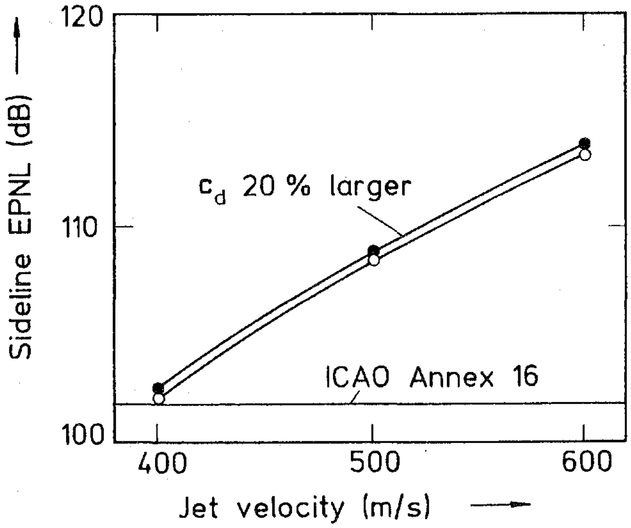

Fig.12: Influence of jet speed and lift-to-drag ratio on the equivalent perceived noise level EPNL in the sideline point. Baseline aircraft A and aircraft B (20 % more drag), cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg.

4.5 Influence of aircraft wing loading on EPNL

The influence of the wing loading on the takeoff noise shall now be studied. Two methods are used to change wing loading, (i) Aircraft C is defined with a wing area of 1200 m^2 rather than the 800 m^2 of aircraft A and B, (ii) both aircraft are also investigated for a reduced takeoff gross mass. The engine size is adjusted to the required thrust in all four cases.

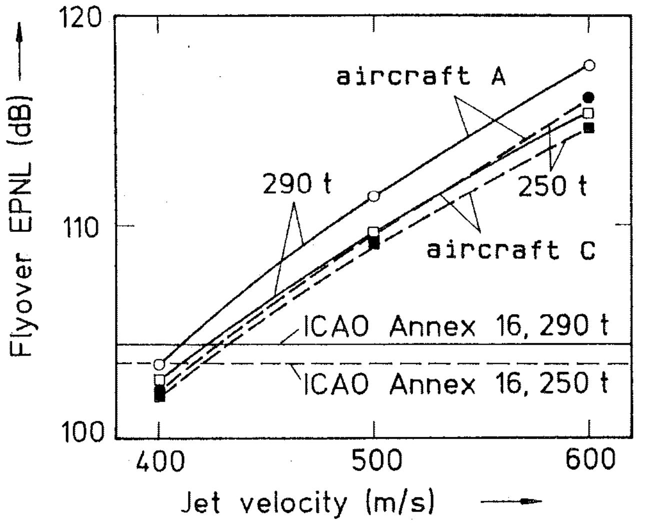

Fig.13: Influence of jet speed and wing loading on the equivalent perceived noise level EPNL in the flyover point. Aircraft A and aircraft C (50 % more wing area), cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg and 250,000 kg.

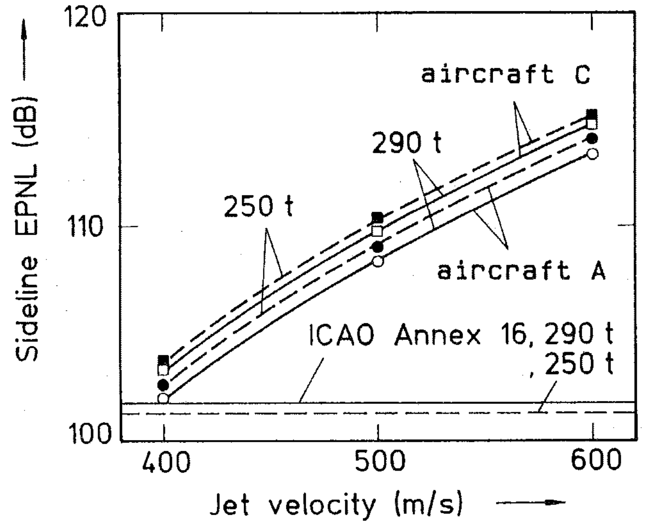

Fig.14: Influence of jet speed and wing loading on the equivalent perceived noise level EPNL in the sideline point. Aircraft A and aircraft C (50 % more wing area), cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg and 250,000 kg.

The noise levels in the flyover point are plotted in figure 13 and show the expected behaviour. An aircraft with a larger wing planform or a smaller takeoff gross mass has a lower noise level. Figure 14 for the noise in the sideline point shows a surprising opposite result. Two reasons are responsible for this result: (i) the airspeed gets smaller, and (ii) the initial climb angle gets larger for a smaller wing loading. Smaller airspeeds yield increased noise duration and larger climb angles yield reduced lateral attenuation.

4.6 Influence of departure procedure on EPNL

The departure procedure may also have an influence on the takeoff noise data. The three procedures compared are described in section 2. Only aircraft A with climb rates of 1000 ft/min and 1500 ft/min equipped with the 400 m/s engine is studied. The three procedures are flown by the same aircraft. The true altitude as a function of distance from the start of roll is plotted in figure 15 for the climb rate of 1000 ft/min.

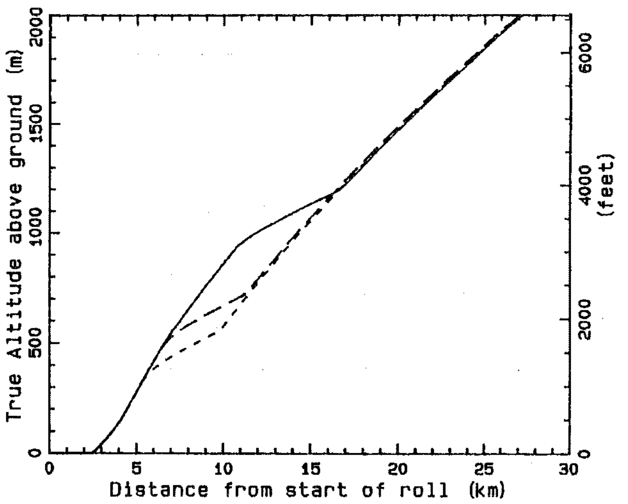

Fig.15: Influence of departure procedure on the true altitude as a function of distance from the start of roll. Aircraft A, jet speed U_j = 400m/s, climb rate 1000 ft/min, cutback parameter C = 5 %, takeoff gross mass m = 290,000 kg. IATA ———, mod. ATA — — —, ATA - - - -.

Since the acceleration is initiated at lower altitudes in the mod. ATA and the ATA procedures, the thrust of the engines is larger. The corresponding slightly higher accelerations could be offset by slightly smaller engines. The results are given in the following table. The noise levels of the mod. ATA procedure and the ATA procedure would have been slightly smaller if the engine sizes were adjusted for an acceleration of 1 knot/s.

procedure	climb rate ft/min	flyover dB	sideline dB	accel. knot/s
IATA	1000	103.5	102.1	1.00
mod.ATA	1000	103.4	102.1	1.24
ATA	1000	103.3	102.1	1.33
IATA	1500	100.8	102.6	1.00
mod.ATA	1500	100.7	102.6	1.27
ATA	1500	101.3	102.6	1.37

We conclude that the departure procedure has almost no influence on the noise levels in the flyover and the sideline points. The situation may be different in measurement points further away from the airport.

4.7 Engine size and fuel consumption

The following table serves to give an impression on how jet speed and climb rate influence the engine size and the fuel consumption for an engine with appropriate bypass ratio. Jet speed and climb rate are defined earlier.

jet speed m/s	climb rate ft/min	nozzle area choked m^2	 end m^2	fuel kg
400	2000		2.18	3750
400	1000		1.73	3820
500	2000	1.09	1.44	4240
500	1000	0.87	1.14	4320
600	2000	0.74	1.04	4670
600	1000	0.59	0.82	4780

Two nozzle areas are quoted. The first column describes the sizes of the smallest cross section of a convergent-divergent nozzle. The second column describes the nozzle exit area for the fully expanded jet. Note that the exit areas of the 400 m/s engines have more than two times the sizes of the corresponding 600 m/s engines.

The fuel consumption is computed for an aircraft with four engines which climbs to an altitude of 12,000 feet and continues its flight in this altitude to a distance of 60 km from the start of roll without wind. It can be seen that the 400 m/s engine with a higher bypass ratio saves about 20 % of fuel during the climb compared with the 600 m/s engine with a lower bypass ratio.

The corresponding thrust-to-weight ratios at the beginning of the takeoff roll vary between 0.28 and 0.51. The small value is sufficient for an aircraft with a climb rate of 1000 ft/min in the acceleration segment, a cutback parameter of C = 5 %, and the 600 m/s engine. The large value is required for a climb rate of 2000 ft/min, a cutback parameter of C = 20 % and the 400 m/s engine.

jet speed m/s	climb rate ft/min	cutback C %	$\frac{\text{thrust}}{\text{weight}}$
400	2000	20	0.51
400	1000	5	0.33
600	2000	20	0.42
600	1000	5	0.28

5. Conclusions

5.1 Low jet speeds required

The noise limits that are currently prescribed for the takeoff of subsonic jet aircraft can only be satisfied by supersonic aircraft if the jet speed of the engines is restricted to values of about 400 m/s. This result is valid for fully mixed jets and is based on certain assumptions for the static jet noise and for the noise attenuation from the source to the observer. These low speeds are no surprise since the jet speeds of current subsonic aircraft are similar. There is no reason why the physical laws found to be valid for the noise generation of subsonic aircraft should not be valid for supersonic aircraft.

The jet speeds are limited by the current noise rules for the sideline point. The noise in this point is determined by the noise emission of the aircraft in its initial climb segment. Therefore, the smallest jet speed for a safe takeoff roll and initial climb has to be used. This prohibits use of a large power cutback of the engines after takeoff or the use of full engine power for a short field length and a rapid climb. A small lift-to-drag ratio and a high wing loading are benefitial for the sideline noise. The departure procedure has no influence.

The low jet speeds require engines with large cross sections. This should not adversely influence wave drag of the engine in the supersonic cruise because the mass flow rate through the engine and the necessary inlet area increase, too.

5.2 Choice between high bypass ratio or ejector

Low jet speeds can be achieved through two alternative solutions. The first one is the development of an engine with a sufficiently high bypass ratio during takeoff. This would probably be a variable cycle engine. The other solution would be the development of an ejector mixer similar to those studied experimentally in ref. 17.

The selection of high bypass ratios has already led to low noise levels of subsonic jet aircraft and also has reduced their fuel consumption through an improved propulsive efficiency. A lower fuel consumption may not be realizable in the supersonic cruise but may be important for the cruise segments with subsonic speeds which have to be used for flights over land and will be very important for European airlines as well as for airlines operating from non-coastal airports in the Unites States. The lower fuel consumption during climb, subsonic flight, and approach may offset the higher weight of such an engine. Unfortunately, it seems to be technically unconceivable at present, that an efficient engine can be designed for a supersonic transport aircraft that has a sufficiently small jet speed during takeoff.

The ejector solution may be possible with current day technology but has several disadvantages.

(i) The noise of the mixer itself can only be accounted for by even lower jet speeds and correspondingly increased exit areas of the mixer nozzle.

(ii) The nozzle exit area of an ejector mixer is probably larger than the nozzle area of the corresponding bypass engine, because the losses of mechanical energy in the mixer yield higher jet temperatures and lower jet densities.

(iii) It will be very difficult to retract the ejector in an engine nacelle that might have only one half of the diameter of the ejector mixer.

(iv) The weight of the ejector will be considerable because of the acoustic fatigue that has to be accounted for. This weight has to be carried over the whole flight distance.

(v) The fuel consumption of the ejector engine is higher than the consumption of the bypass engine in the subsonic flight regime.

5.3 Sideline limit more difficult to satisfy

The sideline noise limit currently valid for subsonic aircraft is more difficult to satisfy by a supersonic transport aircraft than the flyover noise limit. A supersonic aircraft needs powerful engines to be able to accelerate to supersonic speeds. This offers an operation with short takeoff field lengths and large climb rates. A supersonic transport may also be designed with a low wing loading for flight at high altitudes. All this would favorably influence the flyover noise level. Unfortunately, it turns out that all these measures increase the sideline noise.

5.4 Recommendation for noise rules

Rules for supersonic aircraft should ensure that these aircraft yield noise levels in the vicinity of airports that are comparable with those of subsonic jet aircraft. The design task for a supersonic transport aircraft would be simplified if the rules would take account of the high climb rates that are possible with supersonic aircraft. High climb rates result in a large decrease of the noise level with increasing distance from the airport.

To take advantage of the specific properties of a supersonic aircraft it is proposed to increase the sideline noise limit. The flyover noise limit could remain unchanged or could be reduced slightly. The following table considers the case of an aircraft with a certificated maximum takeoff mass of 290 t.

	flyover dB	sideline dB	U_j m/s
current limit	104.4	101.8	370
current limit with 2 dB tradeoff	102.4	103.8	390
choice of new limits (no tradeoff considered)	104.4	105.8	420
	102.4	107.8	420
	100.4	109.8	420
	104.4	109.8	450

The first three proposals allow jet speed to be increased to about 420 m/s. The last proposal allows an increase to 450 m/s. These new limits may yield smaller noise levels in residential areas around airports from supersonic aircraft than from corresponding subsonic long-range aircraft with four engines. Higher noise levels will probably be observed only in the immediate vicinity of airports. This estimate could be verified by a calculation of noise contour maps which could be done with the procedure described in this paper.

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