PERFORMANCE CHARACTERISTICS OF SHORT HAUL TRANSPORT AIRCRAFT INTENDED TO OPERATE FROM REDUCED LENGTH RUNWAYS

by

D. HOWE
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SUMMARY

This report discusses the design characteristics of future short haul transport aircraft intended to operate from runways of reduced length relative to those used at the present time. Particular attention is paid to passenger comfort considerations and the influence these have on the take off and landing performance.

The results presented show that it should be possible to design reduced take off and landing (RTOL) aircraft to operate safely from runways of 4000 ft length without the need for power augmented lift. Such an aircraft would operate at speeds very similar to those used by current short haul transports, the main difference being in the need to provide a static thrust/weight ratio of the order of 0.4. On the other hand short take off and landing (STOL) aircraft intended to operate from runways of about 2000 ft length require a substantial degree of powered lift both for take off and landing. Installed thrust/weight ratio can be as high as 0.7 and the low approach speed of about 80 knots implies the possibility of serious low speed control difficulties.
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NOTATION

A: Aspect ratio

C_D: Drag coefficient

C_LA: Approach lift coefficient

C_LM: Part of lift coefficient produced by aerodynamic devices.

C_LP: Part of lift coefficient produced by powerplant

C_LUS: Unstick lift coefficient

D: Drag

L: Runway length

R: Bypass ratio of powerplant at cruise condition

T: Thrust

T_O: Static thrust

V: Velocity

V_A: Approach velocity

V_C: Cruise velocity

V_S: Stall velocity

V_US: Unstick velocity

V_1: Take off safety speed, all powerplants functioning

(V_1)_F: Take off safety speed with one powerplant failed

Z: Lift

a_1: Lift curve slope of wing

h: Vertical acceleration factor during initial climb out.

n: Number of powerplants

s_1: Ground roll distance corresponding to speed V_1 or (V_1)_F

s_2: Ground distance during climb to 35 ft, all powerplants functioning

s_2: Ground distance during climb to 35 ft, one powerplant failed.

w: Take off wing loading

w_L: Minimum cruise/landing wing loading

\Lambda_{1/2}: Wing half chord sweep
1. **INTRODUCTION**

During the past two decades the improvements in the design of transport aircraft have been mainly in the direction of higher speed and greater payload. The convenience of air transport and the competitive economics resulting from design improvements have generated a rapidly expanding market. Passengers have come to expect a high standard of comfort, partly as a legacy of the first class image of early air transport and partly because of the smooth flight of high altitude turbine aircraft.

It would appear that air transport is entering a new phase of development. Until now the performance improvement and market expansion have been achieved without serious regard to the environment. Aircraft have been developed at the expense of ever increasing runway length and engine power. This has resulted in expanding noise footprints around aerodromes, a feature made worse by the increased frequency of flights as airport facilities develop towards maximum capacity. The situation is being reached where existing airports can no longer cope with traffic demands. The area sterilised or made unpleasant by an international airport is so large that new sites can only be located at inconveniently remote distances from the centres of population they are intended to serve. General congestion of surface transport aggravates this.

At the same time there is insistent public demand for a reduction of the nuisance of aircraft operating from existing aerodromes, particularly with respect to noise levels. In a recent lecture (Ref.1) Steiner suggested that the prime design considerations for future generations of transport would be noise, comfort and economics, in that order. This is a reversal of past practice where economic considerations have been dominant and have resulted in part in implied comfort improvements. Whilst noise levels have been of concern for some while improvement was not allowed to introduce a significant performance penalty. Safety considerations should perhaps be added to the list given by Steiner, since the increased frequency of operations and larger capacity aircraft must be accompanied by reduction in the accident rate if public confidence in air transport is to be maintained.

New generations of transport aircraft will have to be designed to take full account of environmental considerations. At the same time it will become increasingly more important to find ways of safely and efficiently handling the greater numbers of aircraft serving large centres of population. Proliferation of large airports is not feasible even where it is possible. Increase of capacity of existing facilities is limited by air traffic control and, possibly more significantly, by vortex wake decay from preceding aircraft. One of the ways of alleviating the congestion problem is the development of aircraft able to operate from airfields of very limited size located away from existing airports.
Short haul operations make up a large proportion of all flights and are frequently undertaken by smaller aircraft than those used for long range work. The ground delay associated with remotely located airports is also more significant in the case of shorter total journey time. Thus relatively small short range aircraft are the most likely candidates for operations from restricted airfields, particularly if these airfields can be located reasonably close to departure/destination areas. The transfer of the short haul operations away from the major airports would leave them relatively free for expansion of longer range operations by larger aircraft, and possibly in some cases short haul operations by very large aircraft where passenger density justifies this. A further bonus which would accrue from the development of this new class of short haul aircraft is that they could be used to serve the more remote points where airfield facilities are very limited. At the present time this sort of route employs small, slow aircraft which offer less than the generally acceptable comfort standards.

Current short haul transports with capacity for about 100 passengers require runway lengths of from 4500 ft to 6500 ft. The minimum flying speeds are such that cross wind effects are rarely of importance. Although some airfields with runways of this order of length do exist near to centres of population in both Europe and the United States most have already been developed into major airports. In many cases it is virtually impossible to find suitable new locations, especially bearing in mind the implied take off and landing flight paths and air traffic control restrictions. Therefore the proposed new class of short haul aircraft should be able to operate from smaller airfields.

The purpose of this report is to consider the primary requirements for this class of short haul aircraft and the interrelation of the main design parameters and characteristics.

1.1 Noise

The effect of noise level restrictions on the design of the aircraft is not easily evaluated. In the first place there is no really specific definition of the noise levels which will be regarded as acceptable. The United States FAR Part 36 requirements apply only to conventional aircraft, operated conventionally, and will probably prove to be no more than an interim solution. There have already been legal decisions in the United States in which restrictions have been imposed upon aircraft which meet Part 36. The minimum noise level limitations laid down by Part 36 apply to aircraft of 75,000 lb gross weight or less. The effective noise level below the flight path at 3.5 n.miles from take off must not exceed 93 PNdB for this weight although up to 108 PNdB is allowed for weights in excess of 600,000 lbs. During the approach to landing the comparable figures one n.mile from the threshold are 102 PNdB and 108 PNdB, with similar levels for a worst sideline condition. Some aircraft, such as the McDonnel Douglas DC10, Lockheed Tristar and Cessna Citation already achieve noise levels which are well below these limits.
Part 36 is perhaps best regarded as a device to ensure that the trend towards increasing noise levels was reversed in new designs. There is little doubt that each new type of aircraft will be expected to have a lower level of noise intrusion than its predecessors until such a time as aircraft noise is sensibly within the level of the surrounding ground environment. For urban locations this level will probably become about 80 to 85 PNdB and hence it will represent a severe design condition for aircraft. In practice in the first instance it is likely that the aim will be to keep the 90 PNdB ground footprint virtually within the confines of the airport, at least for smaller aircraft. In the United States the powerplant research aim is to reduce the noise level of aircraft relative to the latest ones in current service by about 10 PNdB. This would result in conventional aircraft of less than 200,000 lb gross weight more or less meeting the 90 PNdB target.

However even when it becomes possible to specify overall noise performance requirements it is still necessary to interpret these for design purposes. Whilst the powerplants are obviously the basic source of the aircraft noise there are many secondary but significant considerations. These include the method of operation of the aircraft, powerplant installation features and the nature of lift augmentation when this is employed. Some of these factors can only be treated subjectively until such a time as the design is actually tested. Others, such as the take off and approach flight conditions, can be analysed specifically. In general it can be said that the steeper the descent and take off paths and the shorter the runway requirement the smaller will be the noise footprint for a given aircraft noise characteristic. Thus these features are desirable from the noise standpoint, as is the reduction in installed thrust to the minimum consistent with performance requirements including climbout angle.

1.2 Passenger Comfort

One aspect of passenger comfort is associated with the furnishings, sound proofing and environmental control of the cabin. Much of this is in the hands of the operator and may be regarded as secondary in the context of the overall layout of the aircraft provided adequate weight and volume provision is made.

The other aspect of comfort is dependent upon the performance characteristics of the aircraft. Included in this category are the take off acceleration and apparent climb out angle, turbulence sensitivity in cruise, apparent descent angle, flare normal acceleration and braking deceleration. Passengers have come to expect certain standards in these respects and it is reasonable to presume that they would be unwilling to tolerate anything more severe than experienced with the best of present designs. Indeed the aim should be to improve upon these.
a) **Take off and climb out**

Forward facing seats are preferable for take off and climb out. The initial acceleration reassuringly forces the passenger back into his seat. Providing the rate of increase of acceleration is acceptable up to 0.5g or even possibly 0.6g initial acceleration may be tolerable. This is of considerable importance as the installed thrust/weight ratios necessary for operations from runways of reduced length are likely to be high. During climb out the effect of a steep apparent angle is merely to bring the passenger into a more reclined position, and quite large angles are acceptable. The limitation appears to be in respect of floor angle and is psychological.

b) **Cruise**

A simple way of interpreting the sensitivity of the aircraft to turbulence in cruise is in terms of the usual sharp edge gust relationship. This suggests that the comfort level is dependent upon the parameter:

\[
\left( \frac{\alpha_1 V_c}{w_L} \right)
\]

where \( V_c \) is the equivalent airspeed in cruise

\( w_L \) is the cruise wing loading

\( \alpha_1 \) is the wing lift curve slope, and is primarily dependent upon wing planform shape for a given aerofoil section. Assuming a typical two dimensional aerofoil section property the value of \( \alpha_1 \) is approximately given by

\[
A / \left[ 0.32 + 0.16A \cos \theta_2 \right]
\]

where \( A \) is the aspect ratio

\( \theta_2 \) is the sweep of the mid chord line.

An analysis of a number of existing civil transport aircraft of all kinds suggests that for acceptable cruise comfort performance

\[
\frac{\alpha_1 V_c}{w_L} \leq 21
\]

\((V_c \text{ in knots EAS, } w_L \text{ in lb/ft}^2)\)

Hence

\[
w_L \geq \frac{AV_c}{21(0.32 + 0.16A \cos \theta_2)} \]

... (1)
This relationship can be used to prescribe minimum values of cruise wing loading for a given planform and cruise condition. As a landing may occur more or less immediately after the end of the cruise it is reasonable to assume that the minimum cruise wing loading is equivalent to the maximum landing value. Actual values of $w_L$ are shown in Figure 1, together with take off values based on the premise that for a short range transport the take off weight is approximately 1.15 times the maximum landing weight.

c) Approach and landing

The approach angle will not be greatly influenced by considerations of passenger comfort providing the actual attitude of the aircraft is not significantly removed from the horizontal. Aerodynamically this should be possible to arrange although a very steep descent could cause difficulties.

Of considerable importance are the normal acceleration during flare out, and the impact and horizontal decelerations as the aircraft is brought to rest. Normal accelerations of 0.25g are only rarely exceeded in transport operations, with 0.15g being a much more typical value. It is reasonable to assume that a maximum value of up to 0.25g may be tolerated during flare out at the end of the approach path or during the actual landing impact.

The longitudinal deceleration during the ground run is of particular importance as the landing distance required by the aircraft is critically dependent upon it. In practice it varies substantially during stopping due to the interaction of various effects such as aerodynamic drag, reverse thrust and ground friction coefficient. It is convenient to discuss the problem in terms of a mean value providing it is understood that the peak value does not exceed this by too great a margin. The assumption of conventional forward facing seats for the passengers has already been assumed in order to tolerate the expected take off performance. Neither passengers nor the operators are likely to be prepared to accept the inconvenience and weight penalties which arise if full restraint harness is fitted, in spite of the fact that a lap-diagonal arrangement is now readily accepted in automobiles. Some evidence of the deceleration which passengers are prepared to expect in normal circumstances can be obtained from investigations undertaken for the Japanese National Railways (Ref.2) and by General Motors (Ref.3). In the former case the sample population consisted of university students and in the latter technicians who might reasonably be expected to be more tolerant to acceleration levels than, say, the elderly. The results are summarised in Figure 2, and in interpreting them for airline operations certain points must be borne in mind.
Airline passengers will expect to notice some deceleration during landing and may well become alarmed if they do not. They will be sitting in well designed, comfortable seats with some degree of restraint. Taking the mean of the population and the 'slightly uncomfortable' rating of 4 as an indication of what might be tolerated suggests that it would be unwise to assume a mean stopping deceleration greater than about 0.22g.

An examination of the stated landing performance of current airliners (Ref.4) indicates that the majority of them use mean design deceleration values of between 0.3g and 0.37g. In deriving these values it would appear that the only consideration is the deceleration which is physically obtainable under the design conditions. However it must be remembered that the quoted runway lengths for landing are in fact obtained by factoring the ideal distance by 1.67 to allow for operational variations and contingencies. In a normal landing this margin is unnecessary and the pilot has more stopping distance available than that used to deduce the mean decelerations. It can be shown that in practice the maximum stopping distance available to the pilot can be up to almost twice the design value and hence theoretically the mean deceleration could be reduced to as low as 0.16g to 0.17g in many landings. Of course even in a perfect landing the pilot will not use the whole of the available stopping distance and if an average distance usage of 0.75 of the maximum available is assumed the mean stopping deceleration is found to be in the range of 0.21g to 0.23g. This suggests that current aircraft actually use longitudinal decelerations which are of the same order as the tolerable comfort level, and therefore that it would be unwise to exceed the implied design value of about 0.33g in new designs. On the other hand it is possible that improved methods of bringing the aircraft to rest could be used to give higher available deceleration levels during adverse conditions, such as wet runways and an argument might then possibly be made for some reduction of the 1.67 runway safety factor.

1.3 Economics

Economic considerations must always rate highly in the assessment of the operators. Of the various items which contribute to direct operating cost the first and fuel costs are of particular interest. First costs have risen steeply in recent years as a result of greater design sophistication and general inflationary trends. It is now becoming increasingly difficult to finance the purchase of new aircraft. Whilst noise and passenger comfort may be short term overriding considerations it will be necessary to find ways to stabilise first cost.

Fuel costs have steadily become less important during the development of jet transport aircraft. There are two reasons for this. Firstly the price of fuel has fallen due to the greater volume used and secondly engine specific fuel consumption has been reduced by some 35 per cent. This latter
trend is partly the result of increased engine bypass ratio and hence further developments in this respect to reduce noise will give additional benefit, possibly resulting in a further 15-20 per cent reduction in specific fuel consumption. Unfortunately the trend towards reduction of fuel price has now been reversed and the signs of a potential fuel shortage are beginning to be apparent. There are a number of reasons why sharp increases of fuel price can be expected in the future. Demand is increasing rapidly and with some of the producer countries now importing oil to meet their own requirements a sellers market exists. Further the likely requirements a decade hence are so great as to seriously threaten to exhaust in a short time the known worldwide reserves of easily obtainable fuel, and conservation of resources is most likely to be achieved by cost control. Therefore it may be concluded that fuel costs will become of ever increasing importance to the economics of the aircraft and could become the dominant design criterion once noise targets have been achieved.

2. PERFORMANCE CONSIDERATIONS

2.1 Approach speed and descent angle

It is important that the approach speed of an airliner should be as high as possible within the limitations imposed by available runway length and air traffic control. There are three main reasons for this.

a) The higher the approach speed the less significant are the effects of crosswind which is a particularly important consideration when operation from single runway airfields is considered.

b) The control power of conventional aerodynamic devices falls rapidly with reduction of approach speed.

c) The wing loading should be as high as possible for reasons of cruise comfort, range performance and weight and this implies a high approach speed for a given lift coefficient.

For a given runway length three major parameters determine the maximum tolerable approach speed.

i) Glide path angle. Conventional aircraft approach along a 3° glide slope and increase of this angle enables some decrease of runway length to be obtained. Further a steeper descent path reduces the size of the noise footprint. Evidence suggests that the real limit on glide angle is established by the vertical rate at which pilots are prepared to descend during the final stage of landing. A figure of 1000 ft/min has been suggested when a conventional flare out procedure is used. The resulting relationship between speed and tolerable descent angle is shown in Figure 3.
This clearly shows that unless the approach speed is low, or the restriction can be removed the allowable increase in descent angle is small. The vertical rate of descent limitation could be overcome by a fully automatic landing or perhaps by designing the aircraft to withstand the impact of landing without the need to flare. With high angles of descent there could be a problem of achieving a correct balance of forces on the aircraft and maintaining the cabin floor more or less horizontal. This is illustrated by Figure 4 but is possibly more serious in the early stages of descent. There may well also be air traffic control restrictions if mixed traffic is operated from the same airfield. The different angles of descent used would have to be sufficiently separated from one another to enable the aircraft to be brought in from different circuits or stacks. The required difference in glide slope angle is likely to be at least 4° which is equivalent to a horizontal spacing of about 4 miles at 2000 ft altitude.

ii) Flare and touchdown. The flare conventionally initiated at the end of the approach is intended to reduce the actual vertical impact velocity to zero but during experiments with steep descents some pilots have expressed a preference for eliminating it (Ref.5). This avoids the problem of judging when to start the flare and enables the pilot to aim more accurately at a specific point on the runway. It has a secondary advantage in further slightly reducing the landing distance and may also enable higher rates of descent to be tolerated. The limitations are established by the compromise between the acceptable undercarriage shock absorber stroke and passenger response to impact deceleration.

iii) Stopping deceleration. This has already been discussed above in paragraph 1.2(c). If a value of 0.17g mean deceleration over the total factored stopping distance is assumed together with, for example, a 0.25g flare and impact at 4 ft/sec vertical velocity the maximum approach velocity as a function of runway length and descent angle is as given in Figure 5. The 4 ft/sec impact velocity has been assumed somewhat arbitrarily. The 1000 ft/min rate of descent limitation is indicated and the corresponding mean deceleration over the unfactored stopping distance is shown in Figure 6.

2.2 Landing wing loading and approach lift coefficient

By assuming the approach speeds given in Figure 5 and the wing loadings of Figure 1 which are based on the cruise comfort criterion it is possible to evaluate the approach lift coefficient. Because of the definition of the cruise comfort criterion, Eq.1, for a given approach speed the wing loading and hence lift coefficient is a function of cruise speed and wing planform. The approach lift coefficient
required to enable an aircraft to land on a runway of given length is shown in Figures 7 to 9 for specific cruise speeds of 250, 300 and 350 knots EAS respectively. These clearly show that in order to keep the wing loading and braking deceleration down to the levels suggested by comfort requirements it is necessary to use high values of approach lift coefficient for STOL type operations on runways of the order of 2000 ft length. If it is assumed that conventional mechanical high lift devices can be used to enable approach lift coefficients in the range of 1.8 to 2.0 to be achieved with the usual 1.3 speed margin relative to the stall then the appropriate runway lengths are shown in Figure 10. This suggests that aircraft using mechanical high lift systems could be developed to enable them to land on runways of from 3000 ft to 4000 ft in length. For example when a lift coefficient of 1.8, corresponding to a maximum usable value of about 3, is associated with a cruise speed of 300 knots EAS and an equivalent unswept aspect ratio of 8 a runway length of about 3500 ft is required if the approach path angle is $7\frac{1}{2}^\circ$ or 3800 ft if it is $3^\circ$. Application of the 1000 ft/min rate of descent limitation suggests a maximum tolerable descent angle of $5^\circ$ in this case but this is not especially critical in terms of runway performance. The corresponding approach speed would be approximately 109 knots with assumed landing and corresponding take off wing loadings of about 72 and 83 lb/sq ft respectively.

3. PERFORMANCE CONSIDERATIONS - TAKE OFF

3.1 Take off requirements

The runway length required for the take off may be determined by any of three considerations:

a) The distance required to lift off and climb to 35 ft altitude when all the powerplants are functioning normally, factored by 1.15.

b) The total distance determined by the necessity to bring the aircraft to rest after a powerplant failure at the decision speed. The decision speed is determined in association with c) below.

c) The total distance necessary to climb to 35 ft altitude after a powerplant failure at, or above, the decision speed. This case is thus related to b) and taken together they determine the decision speed.

The main difficulty associated with determining the take off distance arises from the possible interaction of thrust and lift in those cases where power augmented lift is used. A completely general analysis is complex but a reasonable indication of the requirements can be ascertained if certain simplifying assumptions are made. In particular it will be assumed that there is zero longitudinal acceleration immediately after lift off so that the initial climb out speed is equal to the take off safety speed.
In general the available lift coefficient will decrease in the event of an engine failure. Let the lift coefficient at the take off safety speed with all powerplants functioning, \( V_1 \), be \((C_{LM} + C_{LP})\) where the subscripts \( M \) and \( P \) refer to the contributions from the aerodynamic and powered contributions respectively. After a failure of one out of a total of \( n \) powerplants the lift coefficient is approximately reduced to:

\[
\frac{(n-1)}{n} C_{LP} + C_{LM}
\]

To give the same total lift as previously the speed must be increased to:

\[
(V_1)_F = V_1 \left[ \frac{C_{LP} + C_{LM}}{\left(\frac{n-1}{n} C_{LP} + C_{LM}\right)} \right]^{\frac{1}{2}} \quad \ldots \ (2)
\]

where \((V_1)_F\) is the safe take off speed with one powerplant failed and will correspond to a ground roll of \( s_1 \), say. The total take off runway distance is \( s_1 \) plus the ground distance covered during the climb to 35 ft altitude. When all the powerplants are functioning the vertical acceleration can be higher than in the failed case since the lift coefficient is \((C_{LP}/n)\) greater. Let the distance from lift to the 35 ft altitude be \( s_2 \). Then the runway length must be at least:

\[
L = 1.15(s_1 + s_2)
\]

Alternatively if a powerplant fails at \((V_1)_F\), the aircraft must be able to stop or climb out to 35 ft altitude. To achieve the latter within the all powerplants functioning take off distance, \( L \), the climb out distance must not exceed:

\[
\bar{s}_2 = 1.15s_2 + 0.15s_1 \quad \ldots \ (3)
\]

When the stopping distance is the more critical then the situation is complicated by the need to consider a decision speed below \((V_1)_F\) and the effect of failure between this speed and \((V_1)_F\).

3.2 Unstick lift coefficient and ground roll

Since the forward speed at 35 ft altitude condition must be 1.2 times the stalling speed as it is the take off safety speed, then as a result of the assumption of zero longitudinal acceleration during the initial climb out phase

\[
(V_1)_F = 1.2V_s
\]

where \( V_s \) is the appropriate stalling speed, in this case with a powerplant failed.
However in those cases where there is a longitudinal acceleration during the initial climb out the unstick speed, \( V_{US} \), must not be less than 1.05\( V_s \) and hence as a conservative value:

\[
V_{US} = 0.875\left(\frac{V_1}{F}\right) \tag{4}
\]

In assessing the ground roll to lift off, \( s_1 \), it is necessary to make allowances for the rolling resistance, aerodynamic drag and variation of thrust with forward speed. In normal circumstances it is sufficient to assume that the first of these is equivalent to a friction coefficient of 0.03. The last two are rather more difficult to deal with. As far as the drag is concerned the magnitude of the coefficient is primarily a function of the status of the high lift devices. For simplicity it will be assumed here that the induced drag effects are small during the ground roll, that is the high lift devices are not deployed completely until just prior to rotation. In this case a somewhat arbitrary value of drag coefficient is assumed to give a value of 0.001 for the parameter \((C_D/W)\). The thrust variation with forward speed during take off is mainly determined by the powerplant bypass ratio. An examination of typical engine characteristics (Ref.4) has suggested that for speeds up to 120 knots:

\[
T = T_0 \left[ 1 - 8.5(1+0.13R)V \times 10^{-3} \right] \tag{5}
\]

where \( T \) is the thrust corresponding to a velocity, \( V \) knots, \( T_0 \) being the static value and \( R \) the bypass ratio defined at the cruise condition.

Using these assumptions the ground roll distance can be estimated as a function of velocity, static thrust/weight ratio and powerplant bypass ratio. A typical set of results is shown in Figure 11, where \( s_1 \) is shown for the case of \( R = 10 \) with some values for \( R = 5 \) superimposed. These latter values show the secondary effect of bypass ratio at lower velocities.

3.3 Climb out

The value of unstick velocity, \( V_{US} \), given by Eq.(4) implies an available normal acceleration of up to 0.3g at \((V_1)_F\), the lift off speed, as opposed to a margin of only 0.1g when \( V_{US} = 1.05V_s \), even when a powerplant has failed since \((V_1)_F\) is based on this condition. The latter value of normal acceleration may be taken as an absolute minimum available. In practice allowance for time to deploy high lift devices is necessary and the normal acceleration assumed can make provision for this.
The time taken to reach 35 ft altitude is \((70/h)^{1/2}\)
where \(h\) is the mean vertical acceleration, that is it is not likely to exceed about 4.7 seconds. The ground distance covered in this phase is therefore

\[
(\frac{70}{h})^{1/2} (V_1)_F = s_2 \text{ ft}
\]

when all powerplants are functioning

\[
= s_2 \text{ ft}
\]

when a powerplant has failed.

3.4 Take off runway length

The lift off speed is directly related to the parameter \((C_{LUS}/w)\) by Eq.(4). Figure 12 is a presentation of the factored take off distances required for a bypass ratio 10 powerplant in terms of this parameter. To evaluate the results the sum of \((s_1 + s_2)\) from Figure 10 and Eq.(6) has been factored by 1.15. Figure 13 shows the mean braking decelerations which have to be achieved to enable the aircraft to be brought to rest in the corresponding distance \(S_2\) as given by Eq.(3) after a powerplant failure at speed \((V_1)_F\). Thus cross reference between Figures 12 and 13 for any given acceptable value of mean braking deceleration enables the validity of the derived take off lengths to be checked. For example if it is assumed that in emergency conditions the tolerable mean braking deceleration is 0.5g, then only those results above the validity boundaries shown in Figure 12 are realistic. Below the validity lines the take off length is underestimated within the assumptions made. The additional distance required is readily deduced from Figure 13 by comparison of the achievable and required decelerations.

Since the take off wing loading has been derived in Figure 1 as a function of cruise speed and wing planform it is possible to deduce the required unstick lift coefficient. For example Figures 14 and 15 show the take off distances as a function of wing planform characteristics for a thrust/weight ratio of 0.5, and mean climb out vertical acceleration of 0.1g and 0.2g respectively. The effect of unstick lift coefficient and design cruise speed is shown. Figure 16 shows the effect of thrust/weight ratio for given values of \(C_{LUS}\) and the case of a design cruise speed of 300 knots EAS. In this instance the range of unstick lift coefficient of from 1.4 to 1.8 has been chosen to indicate the performance likely to be possible for an aircraft using only mechanical high lift devices, bearing in mind the desirability of keeping climb out lift/drag ratio as high as possible. Finally Figure 17 presents the required thrust/weight ratio for given values of \(C_{LUS}\), a design cruise speed of 300 knots EAS, climb out vertical acceleration of 0.2g and specific runway lengths of 2000 ft and 4000 ft. These lengths have been selected to represent conditions appropriate to STOL and RTOL operations respectively. Figure 14 to 17 are all based on the use of a powerplant with a bypass ratio of 10 and no
emergency braking restriction has been applied.

A general summary of these results is that STOL operations from runways of 2000 ft length require unstick lift coefficients of the order of three associated with thrust/weight ratios in excess of 0.5. Mechanical high lift devices used alone should enable an RTOL aircraft to operate safely from a 4000 ft runway with an unstick lift coefficient of less than 2.0 and a thrust/weight ratio of the order of 0.4.

4. LOW SPEED CONTROL

Investigation of the low speed control characteristics of a particular STOL aircraft (Ref.6) suggests that the major low speed control problems are associated with powerplant failure and cross wind landing.

4.1 Powerplant failure

The importance of powerplant failure in influencing the low speed control requirements is dependent upon the layout and number of the engines and the degree of powered lift. Thus it is not possible to generalise other than to comment that as the flight speed is reduced the powerplant failure case becomes more significant and is likely to become critical, especially for double failure on approach.

4.2 Crosswind landing

The use of an R/STOL transport from single runway aerodromes introduces the possibility of a severe cross wind landing control problem. The aircraft must be able to approach in a specified mean cross wind and retain sufficient control power to be able to cope with gusting about that mean. Whilst various cross wind approach techniques may be used, a good idea of the severity of the problem can be gauged by the magnitude of the equivalent sideslip angle. The variation of the equivalent sideslip angle with cross wind and approach speed, is shown in Figure 18. The magnitudes of cross wind quoted have been chosen to coincide with the standard wind velocity groups in meteorological tables.

In order to obtain an indication of the significance of the single runway cross wind landing case the record of wind velocities at two locations have been analysed (Ref.7). Purely for comparative purposes the sites chosen were Croydon and Speke. The former is considered to be representative of a relatively sheltered inland site and the latter an exposed coastal site. If it is assumed that the single runway is orientated to minimise the effects of the most severe cross wind conditions the annual occurrences of cross winds, given as a function of equivalent sideslip angle are as shown for the two sites in Figure 19 and 20.
Two boundaries are shown in these diagrams. The 12.5° angle may be regarded as reasonably typical of current practice. On the other hand the 20° boundary is representative of what may be achieved with a specially designed aircraft. The special provisions could well include main undercarriage steering. As can be seen there is little restriction on operations carried out under conditions similar to those experienced at Croydon. Even with the 12.5° limitation and an approach speed as low as 90 knots there are only about 100 hours a year on average when approaches would be precluded. When the conditions experienced at Speke are more typical it is necessary to increase the approach speed to about 120 knots before obtaining the same conditions. It is apparent that a 20° equivalent sideslip condition is only likely to be necessary when the approach speed is about 80 knots or less. A 20° angle is likely to give rise to an adverse passenger reaction.

The investigation undertaken by Ward (Ref. 6) suggests that the lateral gust velocity is just less than half of the mean wind speed. In the case of Speke with the most favourable runway orientation the maximum lateral gust velocity was found to be about 13 knots. This roughly corresponds to the equivalent mean wind condition sideslip angle of 15° at 100 knots approach speed.

5. DISCUSSION

The results presented show clearly the importance of passenger comfort in determining certain vital design parameters. For example it is not possible to use take off wing loadings of much less than 70 lb/sq ft even for moderate cruise speeds and a value of over 80 lb/sq ft is likely to be more typical in practice. Similarly the design braking deceleration on landing is unlikely to exceed 0.35g.

As far as steep descent during approach is concerned the main problem is associated with the rate at which the ground is approached. There is little to be gained here except for low approach speed conditions unless the use of automatic flight control or some other device can be used to remove the 1000 ft/min rate of descent restriction at present imposed by pilot opinion. Any steep descent requires a high effective drag to be developed with the aircraft in a more or less horizontal attitude for passenger comfort. This could cause difficulties or at least require the use of special devices.

The analysis of take off performance in a general way is complex but some indication of likely criteria is presented in Figures 11 to 16. Summarising these it can be stated that take off from relatively short runways necessitates high static thrust/weight ratio. For example this parameter can be expected to be in excess of 0.4 for safe operation from a 4000 ft runway and as much as 0.7 for 2000 ft runway operations. The former of these two is associated with an unstick lift coefficient which could be achieved by using mechanical high lift devices, but the latter certainly requires the use of some powered lift.
Landing behaviour is more readily dealt with and in general is less critical than take off in terms of runway length. As can be seen by reference to Figures 5 to 10 the employment of only mechanical high lift devices enables use to be made of runways of about 3500 ft length with a corresponding approach speed in excess of 100 knots. An approach speed of 80 knots or less is necessary for 2000 ft runway operation and this is associated with approach lift coefficients of 3.0 or more.

Comparison of the take off and landing figures shows that mechanical high lift devices should enable transport aircraft to be operated from runways of 4000 ft or more, with take off being critical. The thrust/weight ratio would be about 0.4 and the approach speed almost 120 knots. If an RTOL aircraft is defined as one which does not primarily use powered lift to improve low speed performance then 4000 ft can be regarded as the approximate lower bound of RTOL performance. For operation from shorter runways some degree of powered lift is necessary during take off although landings without powered lift are possible on runways of 3500 ft length or even somewhat less. This brings the aircraft into the STOL regime although true STOL performance is probably nearer to 2000 ft runway operation. For this case a considerable degree of powered lift is required with both unstick and approach lift coefficients of the order of three or more. Static thrust/weight is likely to be well in excess of 0.5 and the approach speed about 80 knots. Flight speeds as low as this introduce significant low speed control problems, especially those associated with cross wind landing onto single runway airports. In these circumstances it is relevant to question the case for an STOL design and to consider whether a VTOL or near VTOL concept where virtually all the lift is derived from the powerplants is not more logical. Cross wind landing and high rate of descent difficulties together with passenger comfort restrictions on wing loading and acceleration are all virtually removed. Against this it must be stated that the built in thrust needs to be about twice as great with the consequent effect on noise level, fuel consumption and first cost.

6. CONCLUSIONS

Several important conclusions can be drawn from the results derived in this study.

1. Passenger comfort considerations impose overriding limitations which have a significant effect upon the performance of transport aircraft designed to operate from runways of reduced length.

2. In general take off rather than landing performance determines the length of runway required for safe operation.

3. It should be possible to design RTOL aircraft which do not require powered lift augmentation, for operation from runways of 4000 ft length.
4. For operation from runways of less than 4000 ft some degree of lift augmentation is necessary, although if landing is the only criterion this is not required for runways in excess of about 3500 ft.

5. True STOL operation from runways of around 2000 ft length necessitates a substantial amount of powered lift. The thrust/weight ratio required is well in excess of 0.5 and approach speeds are of the order of 80 knots. This in turn introduces significant low speed control difficulties.

6. Noise limitations will introduce severe requirements in the design of future transport aircraft and it will be essential to arrange the layout and operation to alleviate these as much as possible.
## REFERENCES

1. **STEINER, J.**  
   Cost, Noise Level now Dominate Design.  
   Lecture to Swedish Society of Aeronautics and Astronautics,  
   reported Aviation Week 20 Nov. 1972.

2. **URABE, S and NOMURA, Y.**  
   Evaluation of train riding comfort index as a function of deceleration  
   (Japanese National Railways)  

3. **WILSON, E.E.**  
   Deceleration distances for high speed vehicles.  

4. **HOWE, D. and WARD, R.E.**  
   Some design considerations of STOL transport aircraft.  

5. **-**  
   STOL-Inter metropolitan evaluation, Phase X. Final Report.  

6. **WARD, R.E.**  
   Aeroplane Design Study, STOL Airliner (A71), Part 3, Low speed lift and control.  

7. **SHELLARD, H.S.**  
   Tables of surface wind speed and direction over the United Kingdom.  
   Met.0792(HMSO) 1968.
FIG. 1. MINIMUM WING LOADING FOR CRUISE COMFORT
FIG. 2. COMFORT RATING FOR MEAN LONGITUDINAL DECELERATION

FIG. 3. VARIATION OF VERTICAL DESCENT VELOCITY WITH APPROACH ANGLE AND SPEED
FIG. 4. AERODYNAMIC CHARACTERISTICS IN A STEADY DESCENT

FIG. 5. APPROACH SPEED AS FUNCTION OF RUNWAY LENGTH AND APPROACH ANGLE
FIG. 6. EFFECTIVE MEAN DESIGN DECELERATION DURING BRAKING

7½° DESCENT ANGLE - INCOMPLETE
(FOR 3° DESCENT ADD 300FT APPROX)

FIG. 7. REQUIRED APPROACH LIFT COEFFICIENT - 250 KNOTS EAS CRUISE
7½° DESCENT ANGLE - INCOMPLETE FLARE
(FOR 3° DESCENT ADD 300FT APPROX)

FIG. 8. REQUIRED APPROACH LIFT COEFFICIENT – 300 KNOTS EAS CRUISE

FIG. 9. REQUIRED APPROACH LIFT COEFFICIENT – 350 KNOTS EAS CRUISE
7½° DESCENT ANGLE
(FOR 3° DESCENT ADD 300FT APPROX)

FIG. 10. LANDING RUNWAY CRITERIA – MECHANICAL HIGH LIFT DEVICES

FIG. 11. GROUND ROLL DISTANCE AT TAKE OFF
FIG. 12. TAKE OFF RUNWAY LENGTH CRITERIA

FIG. 13. MEAN BRAKING DECELERATION DURING STOPPING AFTER POWERPLANT FAILURE
Fig. 14. Take off distance as a function of cruise speed and unstick lift coefficient.

Fig. 15. Take off distance as a function of cruise speed and unstick lift coefficient.
300 KTS EAS CRUISE

0.2g VERT. CLIMBOUT ACCELERATION

UNSTICK LIFT COEFFICIENT

\[ \begin{align*} 
&\text{CL}_{\text{US}} = 1.8 \\
&\text{CL}_{\text{US}} = 1.6 \\
&\text{CL}_{\text{US}} = 1.4 
\end{align*} \]

STATIC THRUST/WEIGHT

TO/W

ASPECT RATIO

\[ \begin{align*} 
&0.2 \\
&0.4 \\
&0.6 \\
&0.8 \\
&1.0 \\
&1.2 \\
&1.4 \\
&1.6 \\
&1.8 \\
&2.0 \\
&2.2 \\
&2.4 \\
&2.6 \\
&2.8 \\
&3.0 \\
&3.2 \\
&3.4 \\
&3.6 \\
&3.8 \\
&4.0 \\
&4.2 \\
&4.4 \\
&4.6 \\
&4.8 \\
&5.0 \\
&5.2 \\
&5.4 \\
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&6.4 \\
&6.6 \\
&6.8 \\
&7.0 \\
&7.2 \\
&7.4 \\
&7.6 \\
&7.8 \\
&8.0 \\
&8.2 \\
&8.4 \\
&8.6 \\
&8.8 \\
&9.0 \\
&9.2 \\
&9.4 \\
&9.6 \\
&9.8 \\
&10.0 \\
\end{align*} \]

FIG. 16. TAKE OFF DISTANCE AS FUNCTION OF THRUST/WEIGHT AND UNSTICK LIFT COEFFICIENT

300 KTS EAS CRUISE

2000 FT \( h = 0.1g \)

\[ \begin{align*} 
&\text{CL}_{\text{US}} = 3.0 \text{A} \\
&\text{CL}_{\text{US}} = 3.4 \text{B} \\
&\text{CL}_{\text{US}} = 3.8 \text{C} \\
&\text{CL}_{\text{US}} = 4.2 \text{D} \\
&\text{CL}_{\text{US}} = 4.6 \text{E} \\
&\text{CL}_{\text{US}} = 5.0 \text{F} \\
&\text{CL}_{\text{US}} = 5.4 \text{G} \\
&\text{CL}_{\text{US}} = 5.8 \text{H} \\
&\text{CL}_{\text{US}} = 6.2 \text{I} \\
&\text{CL}_{\text{US}} = 6.6 \text{J} \\
&\text{CL}_{\text{US}} = 7.0 \text{K} \\
&\text{CL}_{\text{US}} = 7.4 \text{L} \\
&\text{CL}_{\text{US}} = 7.8 \text{M} \\
&\text{CL}_{\text{US}} = 8.2 \text{N} \\
&\text{CL}_{\text{US}} = 8.6 \text{O} \\
&\text{CL}_{\text{US}} = 9.0 \text{P} \\
&\text{CL}_{\text{US}} = 9.4 \text{Q} \\
&\text{CL}_{\text{US}} = 9.8 \text{R} \\
&\text{CL}_{\text{US}} = 10.0 \text{S} \\
\end{align*} \]

FIG. 17. THRUST/WEIGHT RATIO REQUIRED TO TAKE OFF FROM 2000 FT AND 4000 FT.
FIG. 18. EQUIVALENT SIDESLIP ANGLE IN CROSSWIND LANDINGS

FIG. 19. ANNUAL FREQUENCY OF EQUIVALENT CROSS WIND SIDESLIP ANGLE AT CROYDON
FIG. 20. ANNUAL FREQUENCY OF EQUIVALENT CROSS WIND SIDESLIP ANGLE AT SPEKE