# Design and Operating Considerations of Commercial STOL Transports

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**The use of STOL aircraft for a commercial short-haul transportation system is studied. Design, operating characteristics, and costs of these aircraft are examined and compared to conventional aircraft. The study shows that there are many reasons for providing short-haul commercial transports with STOL capability. Among these are an increase in the number of airfields from which the aircraft can be operated and an increase in safety and/or a reduction in instrument flight rules (IFR) minimums. The study also shows that a STOL aircraft capable of 60-knot approach speeds and 1500-ft civil air regulations (CAR) field lengths can be operated at about the same cost as an airplane requiring a field length of 3000 ft. Finally, a review of available flight experience with existing STOL aircraft indicates that the conclusions are conservative and well within the state of the art.**

## Introduction

A NEW short-haul transport is needed. The Federal Aviation Agency and the local service airlines suggest that this new transport should have a moderately high cruising speed (over 200 knots) and a low landing speed (about 60 knots), in addition to a low operating cost and a high degree of safety and reliability.[1, 2]

The economy of long-range transport aircraft lies in high cruising speed. This high cruising speed has often resulted in increased landing and takeoff speeds that, in turn, have meant longer field lengths and more time spent taxiing and maneuvering near the airport. This has been acceptable because the cruising time was usually much greater than the taxiing and maneuvering time. For short hauls, however, the time in cruise may not be much greater than the time for taxiing and maneuvering. Consequently, greater emphasis must be placed on low-speed performance without sacrificing cruise performance and economy of operation.

Recent flight tests[3, 4] have shown that STOL aircraft can have better low-speed performance than conventional aircraft with no compromise in cruise performance and with little increase in complexity. This suggests that STOL capability will benefit short-haul aircraft.

The purpose of this paper is to show the relative merits of STOL aircraft in a commercial short-haul system. The paper is presented in three parts. The first section examines operational advantages that can be realized by low takeoff and landing speeds. The second section presents the tradeoff between operating cost and low-speed performance. The final section summarizes recent flight and simulator results to show the low-speed performance possible with STOL aircraft, and the aerodynamic characteristics necessary for acceptable handling qualities.

## Discussion

### Operational Considerations

Historically, landing and takeoff speeds have not been reduced as improved high-lift devices have been developed, because these devices have allowed development of aircraft with higher cruise speed (e.g., Ref. 5). However, since high cruise speed may not be a dominant consideration for short-stage lengths, it is necessary to re-evaluate the tradeoff between low-speed performance and cruise performance for short-haul transports, such as used by the local service airlines.

#### *Airfields*

One of the advantages of low landing and takeoff speeds is that shorter fields can be used; hence, the aircraft can be operated from more airfields. The relation between the airfield length and the number of airports in three highly populated sections of the United States (California, the Atlantic seaboard, and the north central states) is shown in Fig. 1. The approximate speeds required to operate commercially from these fields is also shown. As an example, local service transports approach at about 90 knots and require an airfield at least 3500 ft long. Consequently, they can fly into less than 35% of the existing airports. If the approach speed were reduced to 60 knots, only a 1500-ft field would be required, and this airplane could land in 95% of the existing fields.

#### *Pattern size and IFR minimums*

Reduced approach speed also benefits aircraft operated from airports with long runways. For example, since the size of the landing approach and takeoff pattern is approximately proportional to landing and takeoff speeds, lower approach speeds will reduce the size of the pattern.[6] This is shown in Fig. 2 where it is seen that airplanes with low landing approach speeds are capable of using air space not required by or available to higher-speed aircraft. This has important implications in reducing both traffic control problems and time lost in air maneuvering. As will be discussed later, reductions in air

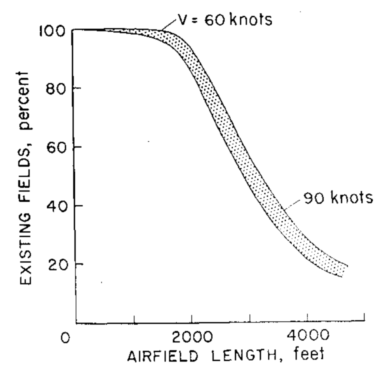

**Fig. 1 Percent of existing fields which can be used by aircraft with different approach speeds and field length requirements.**

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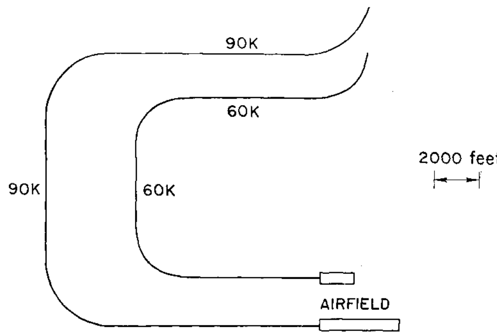


**Fig. 2 Effect of approach speed on pattern size.**

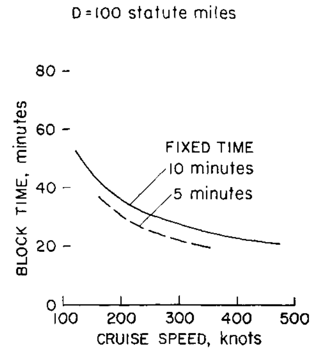


**Fig. 4 Variation of block time with cruise speed for two values of fixed time.**

maneuver time can provide important reductions in block time and direct operating costs.

Airplanes with lower approach speeds should also be able to land with a lower ceiling and less visibility; this should allow lower minimums under instrument flight rules (IFR). This is shown in Fig. 3 where the permissible altitude above the airport and the distance out for an airplane approaching at 90 knots is compared with one at 60 knots. For both cases equal time is available to line up with the runway after coming out of the clouds. Consequently, the minimum ceiling and visibility should be one-third lower for the airplane approaching at one-third lower speed. These reductions in IFR minimums should improve schedule reliability, which is even more important for the short-haul transports than for the conventional long-range transports. If the IFR minimums are not reduced, the lower speeds increase safety since additional time is available for the pilot to make corrections.

### *Block time*

Reference 1 pointed out that the average stage length for the existing short-haul airliner is about 100 statute miles, and that the fixed time is about 10 min. The fixed time is the term commonly used for nonproductive time such as taxiing and maneuvering in the air near the airport. The variation of block time with cruise speed for this stage length is shown in Fig. 4 for a fixed time of 10 min as well as for 5 min. This figure indicates that, even for this short range, cruise speeds of 250 knots or greater are desired; however, cruise speeds above 350 knots give little reduction in block time. Also, it is seen that a 5-min reduction in nonproductive fixed time is equivalent to an 80-knot increase in cruise speed (at a cruise speed of 250 knots). Examination of the fixed times listed in Ref. 1 indicates that decreasing approach speed and operating closer to the terminal (i.e., in a manner similar to a helicopter) could reduce the fixed time from 10 min to 3 min. For a later analysis of direct operating cost, the following fixed times will be assumed: 10 min for conventional aircraft at 90 knots, 5 min for STOL at 60 knots, and 3 min for VTOL.

In summary, a reduction in landing and takeoff speed for short-haul transports will provide the following important benefits: 1) increase the number of existing airfields that can be used, 2) improve flight safety, 3) reduce minimum ceiling and visibility requirements under IFR, and 4) reduce ground and air maneuver time and consequently reduce block time and direct operating cost.

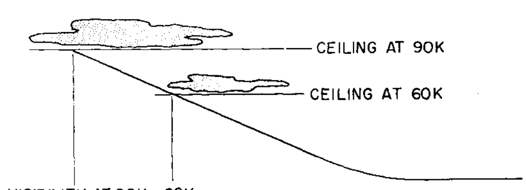


**Fig. 3 Benefits of reduced approach speed under IFR conditions.**

## Vehicle Design and Operating Cost

It was shown previously that low approach speeds were desirable; however, the operating cost of aircraft designed for such performance must be compared to that of conventional aircraft. Previous studies comparing VTOL and conventional aircraft have not provided sufficient information to study the tradeoff between low speeds and operating costs when more modest steps have been taken (e.g., modern STOL techniques). To obtain comparative values for VTOL, STOL, and conventional aircraft when used in a short-haul mission, several designs were studied. All aircraft had a fuselage sized to carry 20 passengers plus 800 lb of cargo. These aircraft were designed to fly either 690 statute miles or four 100-statute-mile stage lengths (without refueling), whichever mission required more fuel. Details of the designs studied are contained in Tables 1 and 2, and the assumptions used are given in the Appendix. It is strongly emphasized that the primary purpose of these calculations was to determine the relative cost of reducing approach and takeoff speeds, not the absolute cost. It is shown in the Appendix that the relative cost is not greatly affected by large changes in airframe and engine cost.

### *Landing and takeoff performance*

The discussion in later sections will pertain mainly to landing performance, because it is generally more difficult to achieve good low-speed landing performance with satisfactory handling characteristics than it is to achieve good takeoff performance. Although the tradeoffs are presented in terms of landing-approach speed, it should be understood that sufficient power thas been installed to provide takeoff distances equal to or less than the landing distances. Reducing the field length from 3500 to 1500 ft requires only a small increase in thrust-weight ratio compared to that necessary for VTOL performance. In these studies, cross shafting and opposite rotation propellers have been included

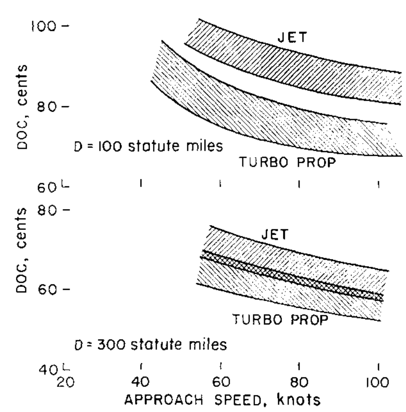


**Fig. 5 Direct operating cost, cents per airplane statute mile, for aircraft with different low-speed characteristics; fixed time 10 min, 20 passengers.**

Table 1 Summary of weight and performance

| Aircraft number and type | Turboprop VTOL, 1 | Turboprop STOL, 2 | Turboprop Low-wing loading, 3 | Turboprop Conventional, 4 | Turboprop Conventional, 5 | Jet STOL lift fan, 6 | Jet Conventional turbofan, 7 |
|---|---|---|---|---|---|---|---|
| Number of engines | 4 | 4 | 4 | 4 | 2 | 2 | 2 |
| Gas generator power or thrust, per engine | 2,850 hp | 550 hp | 550 hp | 550 hp | 1,065 hp | 2700 lb | 4,200 lb |
| Propeller or fan diameter, ft | 12 | 10 | 10 | 8.4 | 10 | 5.4 | 2.5 |
| Static thrust, per prop or fan, lb | 9,200 | 2,550 | 2,550 | 2,300 | 3,900 | 8,200 | 4,200 |
| Interconnect | Yes | Yes | No | No | No | Yes | No |
| Wing area, ft$^2$ | 400 | 400 | 910 | 400 | 400 | 600 | 400 |
| Aspect ratio | 6.5 | 6.5 | 8.0 | 6.5 | 12.0 | 6.0 | 8.0 |
| Propulsion wt,[a] lb | 9,100[b] | 3,150[b] | 3,200 | 2,900 | 2,450 | 2,700 | 2,100 |
| Empty − propulsion wt, lb | 10,700[c] | 9,350[c] | 11,550 | 9,100 | 9,850 | 11,000[c] | 10,800 |
| Empty wt, lb | 19,800 | 12,500 | 14,750 | 12,000 | 12,300 | 13,700 | 12,900 |
| Payload and crew, lb | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 |
| Design fuel wt, lb | 6,200 | 3,000 | 3,550 | 3,000 | 2,800 | 7,100 | 6,200 |
| Design gross wt, lb | 31,000 | 20,500 | 23,300 | 20,000 | 20,100 | 25,800 | 24,100 |
| Cruise speed, knots | 400 | 265 | 225 | 270 | 270 | 390 | 410 |
| Approach speed, knots | 45 | 60 | 70 | 90 | 90 | 60 | 100 |
| CAR landing field length,[d] ft | 0 | 1,500 | 2,000 | 3,000 | 3,000 | 1,500 | 3,500 |
| CAR takeoff safety field length, ft | 0 | 1,200 | 1,500 | 2,300 | 3,400 | 1,100 | 4,500 |

[a] Includes engines, gear boxes, interconnect shafting, propellers, nacelles, and fuel tanks.
[b] Utilizes lightweight propellers.
[c] Includes additional 10% wing-weight penalty for high lift flaps and control system for turboprop, and 15% wing-weight penalty for lift-fan design.
[d] 1.67 times landing distance over 50 ft.
[e] Takeoff to 35 ft with allowance for an engine failure.

in the designs with approach speeds below 65 knots and VTOL type of controls when speeds are below 50 knots.

### *Direct operating cost*

Figure 5 shows grossly how designing aircraft with lower landing speeds affects the operating cost on 100- and 300-mile routes. One band is shown for turboprop craft that include two- and four-engine airplanes with various wing loadings. The other band is for jet-powered craft that include turbofan, cruise-fan, and lift-fan designs. These computations indicated that, for the 100-statute-mile stage length of interest, the jet craft were clearly more expensive to operate than the turboprops with equal low-speed performance. The jet craft were not competitive until the stage length was longer than 300 miles. The two-engine and four-engine turboprops had similar costs when designed for 3000-ft field lengths. Since the jet-powered aircraft were more expensive, and since the four-engine turboprop airplanes are more suitable for development to STOL or VTOL development (considering thrust remaining after an engine failure and amount of wing in slipstream), the remainder of this study was directed toward variations of the four-engine turboprop design of Fig. 6.

Figure 7 shows the direct operating costs (DOC) of turboprop aircraft designed for different approach speeds for a stage length of 100 statute miles and a fixed time of 10 min. Two curves are shown, one for low approach speeds obtained by increased wing size and hence reduced wing loading; for this curve the approach speed was assumed to be 1.3 times the power-off stall speed, based on a $C_{L_{max}}$ of 3.0. The other curve was for a higher wing-loading aircraft that achieved low speed by modern STOL techniques. In this paper, STOL does not describe an explicit field length but rather implies an operating regime in which the propeller slipstream is used to augment wing lift to develop higher lift coefficients. This operation will be discussed in more detail in the section entitled "Flight Experience."

Several points from Fig. 7 will be discussed, namely, 1) that only a small increase in cost need be incurred as the approach speed is reduced from 90 knots to about 60 knots; 2) that cost penalities for the STOL design become progressively greater as the approach speed is reduced below about 60 knots; and 3) that it is less expensive to reduce approach speeds by STOL techniques than by low wing loadings.

The STOL airplane with a 60-knot approach speed did not require an increase in power over the conventional aircraft because the installed power for both aircraft was determined by the 250-knot cruise speed (noted earlier as being desired). The only differences between these aircraft were that the STOL design had flaps and control surfaces with higher lift

Table 2 Summary of costs

| 100-statute-mile state length and 10-min fixed time | | | | | | | |
|---|---|---|---|---|---|---|---|
| Aircraft number | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Block speed, knots | 221 | 158 | 147 | 159 | 162 | 215 | 219 |
| Block fuel, lb | 1,230 | 540 | 600 | 535 | 520 | 1370 | 1,450 |
| Propulsion system cost, $ | 702,000 | 136,000 | 108,000 | 106,000 | 75,000 | 246,000 | 138,000 |
| Cost of electronic, $ | 35,000 | 35,000 | 35,000 | 35,000 | 35,000 | 35,000 | 35,000 |
| Airframe cost, $ | 292,000 | 252,000 | 313,000 | 246,000 | 265,000 | 299,000 | 292,000 |
| Total cost, $ | 1,029,000 | 423,000 | 456,000 | 387,000 | 375,000 | 580,000 | 465,000 |
| DOC, cents per airplane statute mile | 124 | 76 | 83 | 74 | 69 | 91 | 82 |
| **300-statute-mile stage length and 10-min fixed time** | | | | | | | |
| Block speed, knots | | 215 | | 220 | | 310 | 320 |
| Block fuel, lb | | 1,380 | | 1,360 | | 3,315 | 2,720 |
| DOC, cents per airplane statute mile | | 60 | | 59 | | 69 | 57 |

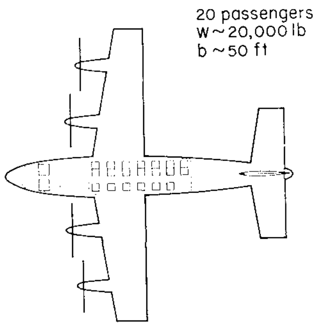


**Fig. 6 Basic airplane design used for study.**

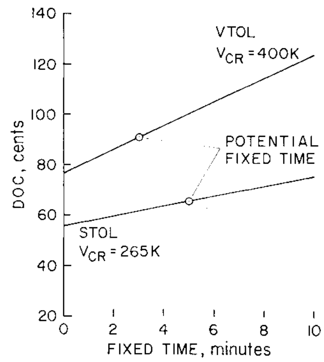


**Fig. 8 Effect of reducing fixed time on direct operating cost of VTOL and STOL aircraft designs.**

effectiveness, and also propellers that were interconnected. Consequently, the DOC of both aircraft was about the same.

The increase in cost penalties for improving low-speed performance of STOL aircraft below 60 knots resulted from increased engine power, and increased wing and tail areas. For equal approach speeds, low wing-loading aircraft are more expensive than STOL aircraft because of the combination of effects caused by larger wing areas. This increased area not only increased the structural weight, but also decreased the cruise efficiency, which increased block fuel and time.

The previous cost figures were based on a stage length of 100 statute miles and a fixed time of 10 min. Figure 8 shows how the DOC is affected by this fixed time. The potential reductions in time for STOL and VTOL aircraft (discussed earlier) are noted. It is seen that, if these reductions can be achieved, the DOC of the STOL and VTOL aircraft can be reduced significantly from the values of Fig. 7.

The foregoing results are summarized in Fig. 9 in which the DOC's are presented for three types of short-haul aircraft with different field length requirements. As indicated on this figure, field length is one measure of the utility of the aircraft. Also, as discussed previously, reductions in required field length are accompanied by reduced approach speed, fixed time, and IFR minimums, and by increased safety in landing and takeoff operations. It is seen that the operating cost of the STOL airplane could be less than that of the simple conventional airplane, but that a VTOL would incur a large increase in cost. Therefore, a short-haul transport should be capable at least of STOL performance from 1500-ft fields since the utility would be increased at no extra cost. VTOL capability involves increases in DOC which must be justified by a market analysis of the revenue potential of this capability. Such an analysis is beyond the scope of this paper.

## Flight Experience

The performance of the STOL designs discussed earlier was based on experience obtained by NASA and others with various VTOL and STOL aircraft,[3, 4, 7, 8] wind-tunnel tests,[9, 10] and simulator studies (Ref. 11 and unpublished data). Extensive use was made of our recent flight tests[4] with the STOL Breguet 941. This 40,000-lb aircraft has four interconnected propellers, highly deflected flaps, a wing fully immersed in the slipstream, and effective control surfaces for low-speed flight. Flight tests with this aircraft, which represents the type of STOL considered in this study, showed that acceptable handling characteristics at low speeds could be obtained relatively simply without the use of stability augmentation, and that operation at low speeds was possible with a high degree of safety.

### *Low-speed envelope*

Figure 10 presents the low-speed envelope obtained with a STOL aircraft in a landing configuration. In this figure, rate of sink is plotted against forward speed, and the Breguet 941 is used as an example. It has a power-off stall speed of 60 knots. The curve to the left of the power-off stall speed is the minimum flight speed obtained when the propeller slipstream augments wing lift, and represents the STOL flight regime. This boundary is related to the effectiveness of the high-lift devices and the available thrust-weight ratio. The Breguet uses multiple slotted flaps deflected almost 100°, and it has a thrust-weight ratio of almost 0.5. The upper line of the curve corresponds to a full power condition such as encountered in a wave-off, when a positive climb rate is desired. The range of approach speeds selected by the pilots for various descent rates is also shown. These approaches were about 10 knots above the power-on stall speed, 10° angle of attack below the stall, and allowed a 0.1 $g$ change in vertical acceleration. These approaches of about 60 knots compare to an 80-knot value if current CAR[12] (1.3 times the power-off stall speed) had been used. The approaches at 60 knots were considered to be at least as safe because good control was available down through the minimum flight speed; engine failure caused no concern because of the interconnect features; and steep, slow approaches allowed good judgment of the touchdown point.

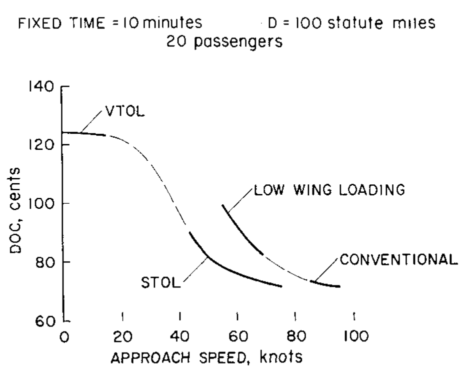


**Fig. 7 Effect of desired approach speed on direct operating cost of turboprop aircraft, cents per airplane statute mile.**

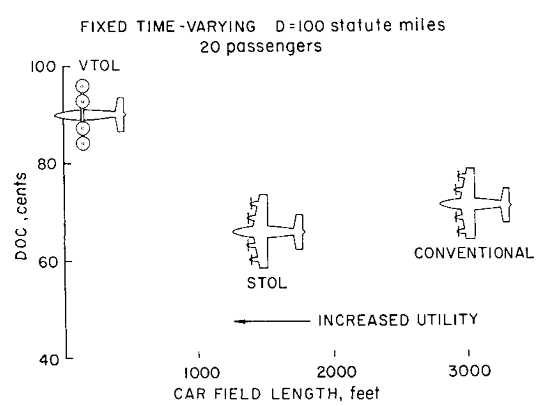


**Fig. 9 Variation of direct operating cost with utility; assuming reduced fixed times for STOL and VTOL aircraft.**

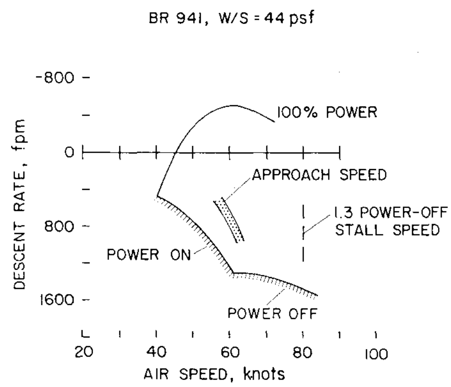


**Fig. 10 Low-speed envelope for STOL aircraft.**

### *Landing*

A high degree of consistency is obtained with good safety when the low-speed characteristics of the STOL aircraft are fully utilized. To do this requires somewhat different piloting technique during landing than is used for conventional propeller-driven transport aircraft. Details of these techniques are given in Ref. 3, 4, and 8. Because of the large effect of power on the stall speed, angle of attack is displayed in the cockpit and is used to obtain the correct approach speed. Engine power is varied to maintain the desired rate of sink; as an example, a value of 800 ft/min and an approach speed of 60 knots were considered to be comfortable for the final approach with Brequet 941. When the aircraft is about 15 ft from the ground, it is rotated and partially flared so that the contact sink rate is 200–300 ft/min and the fuselage attitude is level. Reverse pitch is used to spoil lift and to provide additional braking. The French Air Force has reported[8] measurements of some 60 landings over a simulated obstacle. These landings, summarized in Fig. 11, were made with a simple landing aid that also simulated the 50-ft obstacle height. This aid, similar to a shipboard mirror system, was set for an 8° glide slope so that a straight line intersection of the simulated obstacle and the runway occurred 350 ft from the obstacle. These landings were made under a variety of conditions, including no wind, 20-knot head wind, and a 15-knot wind 60° to the runway. They also included values obtained during the indoctrination of a pilot. It is seen that good accuracy could be attained in hitting a prescribed touchdown point close to an obstacle being cleared. There was a larger dispersion in the stopping area; however, the various wind conditions must be considered. For these tests the average ground roll was less than 400 ft, and the stopping point was 550–850 ft from the obstacle. These latter values compare with the 1500-ft CAR field length listed in Table 1 for the STOL transport of this study with the same approach speed of 60 knots. These flight results show that good low-speed performance can be achieved with high consistency using a STOL transport, and further that the performance described in the preceding section for a STOL transport is conservative and well within the present state of the art.

### *Control characteristics*

In the preceding sections, it was stated without proof that low flight speeds required for STOL operation can be achieved with control from aerodynamic surfaces only, and that VTOL control systems, such as reaction jets, tail rotors, etc., are not required. This statement will now be examined in detail since part of the low cost of the STOL airplane depends on the fact that VTOL control systems are not necessary (at least not for flight speeds above 50 knots). Control about the lateral axis has been found to be most important for the maneuvering required for STOL aircraft. It also has been found to be more difficult to design satisfactory lateral controls for STOL aircraft than longitudinal and directional controls. For these reasons, this discussion is restricted to lateral controls. However, the general conclusions stated are valid for longitudinal and directional controls. Figure 12 compares the required initial angular acceleration in roll with that available from full deflection of lateral control surfaces; the initial angular acceleration corresponds to the ratio of moment produced by the control to the inertia of the aircraft. The required value for satisfactory control power in STOL flight is based on flight tests of the Breguet 941 and other STOL aircraft with damping values that normally exist at the flight speeds considered. Figure 12 shows that conventional ailerons will not provide sufficient control at speeds below about 80 knots, but that improved ailerons and/or spoilers in the slipstream can be adequate to below 50 knots. Our experience has shown, however, that such controls may have undesirable adverse yawing moments. These moments can easily be eliminated if differential pitch is used between the propellers of the left and right wing panels. This differential pitch will also increase the rolling acceleration. It is possible through careful design also to alleviate adverse yaw without using differential propeller pitch, for example, by differential-aileron deflection, rudder-aileron interconnect, etc.

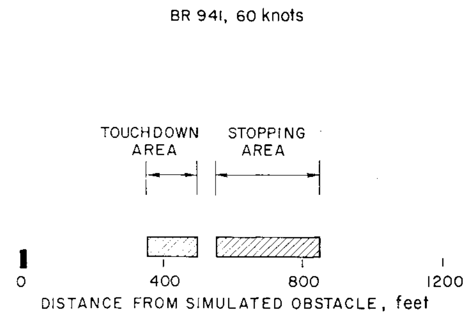


**Fig. 11 Summary of 60 landings over 50-ft obstacle (Ref. 8).**

### *Stability characteristics*

At the low airspeeds desired for STOL operation, the stability and damping may be lower than for conventional aircraft. These reduced levels will naturally influence the pilot's opinion of the handling qualities. Satisfactory stability and damping have been easier to attain in the longitudinal mode than in the lateral-directional mode.[3, 4] When the horizontal-tail volume is sufficient for satisfactory longitudinal control, the damping is adequate. The longitudinal stability depends on angle-of-attack stability and speed stability, both of which depend on power and c.g. location. Judicious location of the c.g. range (vertically as well as horizontally) can

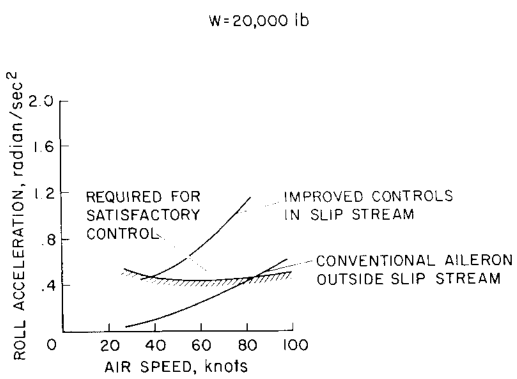


**Fig. 12 Lateral control characteristics for short-haul transport; $I_x$ = 60,000 slug-ft²**

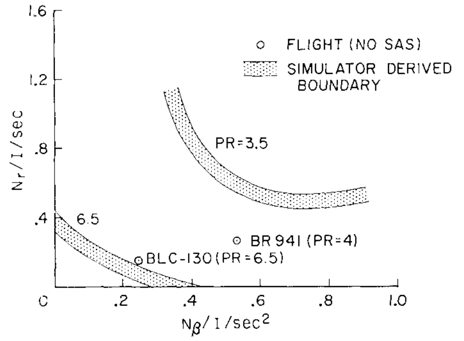


**Fig. 13 Directional stability and damping boundaries for STOL with approach speed of about 60 knots; $N\delta_r\delta_r/I = 0.2$ rad/sec$^2$, $L\beta/I \sim 0$ to $-0.3$.**

give satisfactory longitudinal stability for the STOL designed to have an approach speed of 60 knots. The difficulties encountered with the lateral-directional stability and damping at STOL speeds with the BLC-130 were reported in Ref. 3, and the effect of varying aerodynamic parameters in the simulator study were reported in Ref. 11. Additional studies were made with the Breguet in flight[4] and on the Ames moving-base simulator. The directional stability and damping boundaries from the simulator tests are summarized in Fig. 13. The satisfactory and unsatisfactory boundaries correspond to pilot ratings[4] of 3.5 and 6.5, respectively. Flight-test points from the BLC-130 and Breguet 941 without stability augmentation are also included. It should be noted that compliance with these boundaries is not necessarily sufficient for a satisfactory aircraft because coupling and cross-coupling effects can markedly alter the lateral-directional handling of STOL aircraft. All of these results were in the lift coefficient range of 3–4 (airspeed 55 to 70 knots) and were for a directional control power ($N_{\delta_r}\delta_r/I$) of about 0.2 rad/sec$^2$ and a dihedral effect ($L_\beta/I$) of 0 to $-0.33$. Based on these results and on estimated aerodynamic and inertia characteristics of the 60-knot STOL design, it appears that acceptable lateral-directional handling could be obtained without augmentation and that characteristics could be improved with augmentation about one axis. Recent simulator studies and flight tests with the BLC-130 indicate that augmentation provided by a yawing moment proportional to sideslip rate ($N_{\dot\beta}/I$) or a yawing moment proportional to roll rate ($N_p/I$) is preferable to straight yaw damping ($N_r/I$). Such augmentation requires only a small portion of the available directional control power.

### *Civil air regulations*

Commercial operation of VTOL and STOL transport aircraft requires that existing CAR be modified. A preliminary examination of the regulations for V/STOL aircraft has been presented by the Federal Aviation Agency (FAA) in Ref. 13. Although this is a creditable start, it must be recognized that meaningful regulations for V/STOL aircraft will have to be based (as they have been in the past for conventional aircraft) on the actual operation of aircraft of appropriate size and performance under conditions simulating commercial transport operation.

## Concluding Remarks

This study has shown that there are many reasons for providing short-haul commercial transports with STOL capability. Among these are 1) an increase in the number of airfields from which the aircraft can be operated and 2) an increase in safety and/or a reduction in IFR minimums. This study has also shown that a STOL aircraft capable of 60-knot approach speeds and 1500-ft CAR field lengths can be operated at about the same cost as an airplane requiring a field length of 3000 ft. Finally, a review of available flight experience with existing STOL aircraft indicates that the foregoing conclusions are conservative and well within the state of the art.

## Appendix

This Appendix contains the assumptions used to study the operating cost of several aircraft designs. It is emphasized that the calculations were made to indicate tradeoffs in aircraft size and cost as the low-speed performance was varied, and not to determine the absolute level of performance and cost. References 1 and 2 were used to establish the capacity and range of the short-haul aircraft of interest. A capacity of 20 passengers (including baggage) plus 800 lb of cargo was used. These aircraft were designed to fly either 690 statute miles at a cruise altitude of 8000 ft or four 100-mile trips (without refueling), whichever mission required more fuel.

The fuselage was assumed to be 52 ft long, 7 ft wide, and 7 ft high. Several wing areas were studied, but all wings had a taper ratio of 0.6. The total tail area to wing area was about 0.6. All aircraft had a design load factor of 3.75. A drag coefficient of 0.004, based on wetted area, was used with an airplane efficiency factor of 0.8 to estimate the cruise performance. Propeller and engine performance and weights were estimated from manufacturers' manuals.

The estimated weight and performance for seven designs are given in Table 1. Values are given for conventional turboprop and turbofan aircraft, for STOL and VTOL turboprop, and for a lift-fan aircraft. The CAR landing field length[12] listed is 1.67 times the landing distance over a 50-ft obstacle. It was assumed that the rate of sink at 50 ft could not be greater than 1000 ft/min and that braking would be initiated after a 2-sec free roll at an average deceleration of 0.4 $g$. The CAR takeoff field length[12] is the total distance to 35 ft with allowance for an engine failure. A rolling resistance coefficient of 0.03 was used, and standard atmospheric conditions were assumed.

Table 2 lists the DOC's for the example designs. These DOC's were calculated by the method described in Ref. 14. The major portion of the calculations was based on a stage length of 100 statute miles, a cruise altitude of 8000 ft, a fixed time of 10 min, a utilization of 2000 hr/yr, engine overhaul time of 1100 hr, and a fuel cost of 12.5 cents/gal. as suggested in Ref. 1. The cost of electronic equipment ($35,000) and of the airframe ($27/lb) were obtained from Ref. 15. Engine costs were also obtained from Ref. 15 and from correspondence with engine manufacturers. The block speed was computed from the block time, which was the summation of the fixed time, takeoff and climb time, cruise time, and descent and landing time. On-course credit was included for the climb and descent, but not for the fixed time. The block fuel was computed on the basis of each element of time and corresponding power settings. Additional calculations for several designs were made with reduced fixed times and also for stage lengths of 200 and 300 statute miles.

Short-haul aircraft cruising at moderate speeds and low altitudes cannot take advantage of high aspect ratio wings for efficient cruising; therefore, wings with moderate aspect ratios and lighter weights were chosen for several of the designs. Aircraft numbers 5 and 7 required higher aspect ratio wings to achieve the desired takeoff distances allowing for failure of one engine. The propulsion system for airplanes 2–5 was based on relatively inexpensive, simple engines available in the 500- to 700-hp range and which have moderately high specific fuel consumption and weight. This type of engine cannot be used for the VTOL (airplane 1) because lower specific fuel consumption and weight are required. For this design a more sophisticated and much more expensive engine (per horsepower) is necessary i.e., engines of the type available in the higher powers. If the relatively inexpensive engine is not available in the power range for airplane 5, so that the more expensive engine must be used, the DOC increases about 15% over the value listed.

The sensitivity of the direct operating cost to different values of airframe cost and propulsion cost is indicated by the following calculations for airplane 2. A 50% increase in airframe cost changed the DOC by about 7%, and a 50% in-increase in propulsion cost changed the DOC by about 5%. Therefore, it can be concluded that large changes in the airframe cost per pound of weight and in the engine cost per horsepower will have little effect on the relative DOC of aircraft with different low-speed performance.

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