VTOL Short Range Jet Airliners

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The preclusion of significant increases in the cruising speeds of short range airliners by adverse Mach number effects makes it necessary to examine the factors affecting their revenue earning capacity and direct operating costs. These depend critically upon the turn-round, block times, and total number of hours for which the aircraft is available for operations. A significant fraction of the block time of short range airliners is spent in taxing, takeoff and landing, and in circuits of the airfield. It is shown that this time can be halved by adopting a vertical takeoff and landing procedure. The disadvantage of having to provide extra engines for vertical thrust is offset by the fact that the wing and tailplane can be designed without regard to airfield requirements. A VTOL airliner has been projected. It is estimated that its shorter journey times result in direct operating costs as much as 15% less than those for a comparable conventional design for stage lengths up to 750 naut miles, inspite of a higher first cost.

Nomenclature

C = total direct cost/annum, \$/yr
C_a = annual costs, \$/yr
C_c = crew costs, \$/yr
C_f = fuel costs, \$/yr
C_m = maintenance costs, \$/yr
c = propulsive engine specific fuel consumption in the cruise, lb/lb hr
d = number of years aircraft is in service
F = load factor, i.e., seats occupied/seats available
f_1 and f_2 = constants associated with maintenance time
H = number of hours per annum aircraft is available for operations
H_{max} = maximum number of hours per annum aircraft is available for operations
I = total revenue earned by an aircraft, \$
i = revenue/passenger naut mile, \$/naut mile
k_1 = annual costs/lb of basic weight, \$/lb
k_2 = annual costs/lb of engine, electronics, and other complex items: \$/lb
k_3 = maintenance cost/lb of basic weight/hr of utilization, \$/lb hr
k_4 = maintenance cost/lb of engine electronics, etc.,/hr of utilization, \$/lb hr
k_5 = constant maintenance cost/flying hr, \$/hr
k_6 = fuel used/mile cruised, lb/naut mile
k_7 = fuel used/journey which is independent of range, lb
k_8 = fuel cost/lb, \$/lb
$(L/D)_{cruise}$ = lift to drag ratio under cruising conditions
M = constant associated with maintenance time
n = number of journeys flown/day
R = stage length, naut miles
R_a = distance aircraft flies/annum, naut miles
T = journey time, hr
t_b = block time, hr
t_d = delay time $= t_g + t_w$, hr
t_g = turn-round time, hr
t_u = unusable time, hr
t_w = wasted block time, hr
U = annual utilization, hr
V_c = cruising speed, knots
V_r = revenue speed, knots
W_b = basic weight, lb
W_e = weight of dry engines, electronics, and other complex items, lb
W_f = fuel weight, lb
W_p = payload weight, lb
W_m = mean aircraft weight during the cruise, lb

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Part 1. Basic Analysis

1.1 Introduction

THE advent of the turbojet engine has enabled aircraft designers to increase the productivity of airliners by significantly increasing their cruising speeds. The products of one firm illustrate this trend: the Viscount, capable of cruising economically at 280 knots, superseded the 180-knot Viking and has been succeeded by the 435-knot British Aircraft Corporation (B.A.C.) 1-11. In spite of this change in speed, most of the other basic economic characteristics, such as the ratio of lift to drag in the cruise and the ratio of empty to gross weight, have hardly changed.

A similar percentage increase in the cruising speed, beyond that of the B.A.C. 1-11, would correspond to a Mach number in excess of unity. As a result, the cruise lift to drag ratio would fall; and the structure and equipment weights to gross weight ratios would increase to such an extent that the advantage of the increase in productivity, caused by the increase in speed, would probably be nullified by the increase in operating costs. Although it seems probable that an airliner cruising at a Mach number of 2.2 or more, over long stage lengths, can be justified economically because of its large block speed advantage over its subsonic rivals, this is unlikely to be the case for short range airliners, even if the intensity and frequency of the sonic booms were acceptable. An analysis of the earning capacity and operating costs of short range airliners is necessary to indicate the trends that should lead to greater economic efficiency.

1.2 Time Analysis

1.2.1 Components of an average day

Whitby and Kiddle,[1] in assessing the variation of aircraft utilization with block time, divide the average day of an airliner into flying time, turn-round time, and maintenance and unusable time which they write, respectively,

$$nt_b + nt_g + (M + f_1nt_b + f_2n) + t_u = 24 \text{ hr} \qquad (1)$$

where n is the number of journeys flown per day; t_b and t_g are the block time and turn-round time in hours, respectively; and t_u is the unusable time in hours. M, f_1, and f_2 are constants associated with the maintenance time. When

Table 1 Constituent parts of the average day of an airliner

Block time, t_b	0.5 hr	2.0 hr	3.5 hr
Flying time	14.3%	26.0%	29.4%
Turn-round time	28.6%	13.0%	8.4%
Maintenance time	37.1%	41.0%	42.2%
Unusable time	20.0%	20.0%	20.0%

typical values for European operations are substituted in (1), it becomes

$$nt_b + n + (5.5 + 0.6nt_b + 9.2n) + 4.8 = 24 \text{ hr} \quad (1a)$$

Table 1 shows how the constituent parts of an average day of an airliner vary with block time.

It can be seen that, irrespective of block time, an aircraft spends about 40% of its time on operations, and 60% of its time being maintained or idle. Only 30% of the day is spent actually earning revenue, even when operating over relatively long stage lengths; whereas a fleet average of about 20% of the day is usual. A prime objective in the design of any new airliner system must be to increase the number of revenue earning hours.

1.2.2 Maintenance and unusable time

Most passengers prefer not to travel between the hours of 11 PM and 7 AM. Assuming that the daily average operating period of the fleet is 1 hr less than the maximum, there are 9 hr a day during which flying operations cannot take place. Cheap night flights are not included in this analysis; they can be regarded as a bonus.

Major overhauls involve periods in excess of 9 hr and necessitate the aircraft being maintained during potential operating periods. A typical period is 12.5 days for 2000 hr flying a year, rising proportionately with the annual utilization. Thus the maximum number of hours available for operations $H_{\max}$ can be written as

$$H_{\max} = 15[365 - (12.5U/2000)] = 5475 - 0.094U \text{ hr/annum} \quad (2)$$

where U is the annual utilization in hours.

$H_{\max}$ is about 5300 hr for an annual utilization of 2000 hr, decreasing by only 100 hr if the utilization or the period required for major overhauls increases by 50%. Reference 1 suggests that the average number of hours available for operations per aircraft year of British European Airways (B.E.A.) in the period 1960–1962 was 3125 hr. During this time two new aircraft came into service, the Comet 4B and the Vanguard, which decreased the average. A peak value of 3760 was achieved in 1960–1961 with Viscount 802 operations. The difference between these achieved values and $H_{\max}$ represents the time lost in flight inspections, unscheduled maintenance, and unusable time.

Table 1 suggests that an average day divides into 10 hr that are available for operations, 10 hr that are required for maintenance, and 4 hr that cannot be used. At first sight it seems strange that any unusable time exists, since the time required for maintenance exceeds the unusable hours overnight. Preflight inspections and unscheduled maintenance are necessary during the day, the latter averaging 0.2 hr/flying hr in recent years. These reduced the number of hours available for operations by 500–600 hr/annum. It is significant that this is more than twice that lost because of major overhauls.

Considerable design effort must be devoted to increasing the reliability of components and to decreasing the time required to repair small faults. A detailed analysis of unscheduled faults on current airliners would assist in this aspect of the design of new aircraft. Experience of missile reliability problems has led to the grouping of like components such that access to, and replacement of, any group is simple, and the whole vehicle is not delayed while the detailed location and form of a fault is found before it can be rectified.

Active cooperation between airline maintenance engineers and the design and service staffs of aircraft and engine firms is an essential feature in the design of future airliners. It seems probable that a result of active cooperation in this sense could be to raise the total time available for operations by 500 hr. Timetables cannot be planned so precisely as to eliminate all idle aircraft time, although flexibility of aircraft role and high block speeds, leading to short journey times, should yield a reduction in the idle time.

A target of 4000 for the number of hours H available for operations per aircraft year should be set for the next generation of short range airliners. The best domestic operators in the United States achieve some 3750 hr/annum.

1.2.3 Operating time

The total time for an operation consists of the block time plus the ground time. Thus,

$$T = t_b + t_g \quad (3)$$

The ideal block time corresponds to the time the aircraft would take to fly the stage distance R at the cruising speed V_c. Time lost in taxiing, takeoff, climb, descent, holding, circuits, and landing is, in a sense, wasted time.

Writing

$$t_b = (R/V_c) + t_w \quad (4)$$

Eq. (3) becomes

$$T = (R/V_c) + t_w + t_g = (R/V_c) + t_d \quad (5)$$

where t_d is the total delay time.

If H is the total number of hours per aircraft year available for operations, the distance flown by an aircraft a year becomes

$$R_a = \frac{HR}{T} = \frac{HR}{(R/V_c) + t_d} = \frac{HV_c}{1 + (V_c t_d/R)} \quad (6)$$

The total revenue earned by an aircraft can be written as

$$I = (i.\,N.F.R_a.d) = (i.d.)(F.N.H.)\left[\frac{V_c}{1 + (V_c t_d/R)}\right] \quad (7)$$

where i is the revenue/passenger nautical mile; d is the number of years the aircraft is in service; F is the load factor, i.e., the average number of seats occupied/seats available; and N is the number of seats in the aircraft.

The terms in the first bracket of Eq. (7) correspond to factors over which the aircraft designer has no control, those in the second bracket represent factors over which he has limited control, whereas those in the last brackets are connected intimately with the design of the aircraft. The designer has control over the number of seats in the aircraft, but it is not the object of this investigation to consider the effect of seating capacity on operating economy.

The numerator of the last bracket of Eq. (7) shows the primary factor in the postwar development of civil aircraft, viz., that revenue is proportional to the cruising speed. However, this statement is strictly true only when the wasted flight time and the time on the ground between flights are zero.

If

$$V_r = \frac{V_c}{1 + (V_c t_d/R)} \quad (8)$$

then V_r represents a revenue earning speed and is related

Table 2 Influence of basic parameter changes on direct operating costs

Parameter	Percentage change in aircraft seat mile costs
1% increase in basic weight W_b	+0.57
1% increase in engine weight W_e	+0.20
1% increase in lift-drag ratio L/D	−0.10
1% increase in annual operating hours H	−0.39
1% increase in cruising speed V_c	−0.53
1% increase in wasted time t_w	+0.24
1% increase in ground time t_g	+0.12

to the annual utilization since

$$V_r H = R_a = UR/t_b \qquad (9)$$

A comparison of airliners on the basis of revenue speeds rather than annual utilization is desirable, since the former is directly proportional to the revenue.

Figure 1 illustrates the variation of revenue speed and annual utilization with stage length for two aircraft: one similar to the Viscount, the other having a greater cruising speed and a smaller delay time; it also illustrates the large increases in revenue and utilization with increase in stage length. It is obvious that an assumption of a fixed annual utilization, such as the 3000 hr often used irrespective of stage length, will yield misleading results, especially for short haul aircraft. It seems more sensible to assume a constant number of hours per annum available for operations. Figure 1 shows clearly that although the annual utilizations of the two aircraft are very nearly the same for a specified range, their revenue speeds are very different.

The beneficial effects of attaining a high cruising speed together with a low delay time exist throughout the whole range spectrum. Figure 2 illustrates the effects of these factors on revenue speed for two particular stage lengths by comparing the revenue speeds associated with various combinations of these parameters with that estimated for a typical Viscount operation.

For the shorter stage length, the dominating factor is the delay time, an increase in cruising speed being relatively ineffective if it is associated with a long delay time. Over longer ranges, the effect of an increase in cruising speed becomes more marked. It is apparent that the full benefit of an increase in cruising speed is only realized if $V_c t_d/R$ remains constant. Thus for aircraft designed for short range operations, it is essential to achieve low delay times if high revenue speeds are to be attained.

An analysis of U.S. Domestic Routes showed that in 1963 the mean ground time between flights was 47 min, whereas the lowest regularly achieved was 32 min. The lowest scheduled times between departure and arrival for Trident, Comet, and Caravelle on European routes exceed the times to overfly the routes at the cruising speeds by 31, 30, and 29 min, respectively, when averaged over a variety of routes. The higher values of this "wasted time" for the faster aircraft is to be expected since they will take longer to achieve their cruising and approach speeds.

1.3 Direct Operating Costs

The method devised by B.E.A.[2] has been used to determine the relative importance of the various parameters affecting direct operating costs. Appendix A shows that on this basis the costs can be expressed as

$$\frac{280}{NR}\left[\frac{t_b}{U}(11.3W_b + 20.5W_e) + t_b(88.4 + 0.00205W_b + 0.01W_e) + (W_b + W_e)\left(0.0205\frac{Rc}{V_c L/D} + 0.00098\right) + \frac{361Rc}{V_c L/D} + 55\right] \text{cents/aircraft seat naut mile} \qquad (10)$$

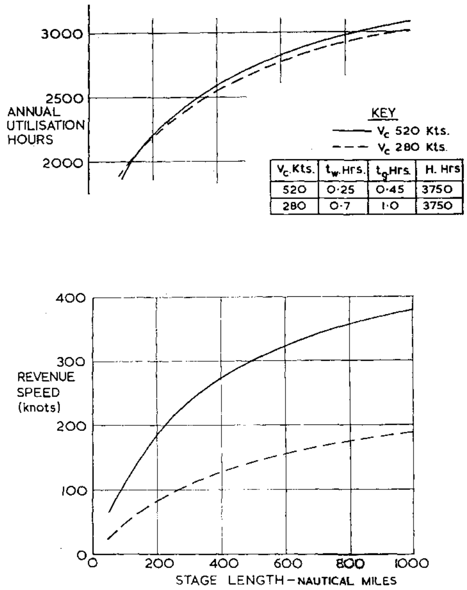

Fig. 1 Variation of revenue speed and annual utilization with stage length.

For a typical short haul airliner it is assumed that 1) stage length R is 400 naut miles, 2) cruising speed V_c is 435 knots (500 mph), 3) annual time available for operations H is 3750 hr, 4) wasted time t_w is 0.5 hr, 5) ground time t_g is 0.65 hr, 6) engine specific fuel consumption is 0.85 lb/lb hr, and 7) lift-drag ratio at cruise is 13.7 at 25,000 ft altitude. Thus the block time t_b is 1.42 hr, the journey time 2.07 hr, the number of flights a year U/t_b is 1810, and the annual utilization U is 2570 hr. The basic weight for an airliner of 63 seats is about 38,500 lb, whereas the engines and electronics weigh about 5500 lb.

On the basis of these figures, the percentage change in aircraft seat mile cost for a 1% change in each of the basic parameters has been calculated. The results are shown in Table 2.

It can be seen that weight and cruising speed are significant parameters. The results given in Table 2 must be viewed in the light of the possible improvements that are likely to be achieved. An attempt has been made to gage these, leading to the results given in Table 3.

It is clear that the most promising improvement in direct operating costs comes from an increase in cruising speed, with savings in wasted and ground time next in importance. However-

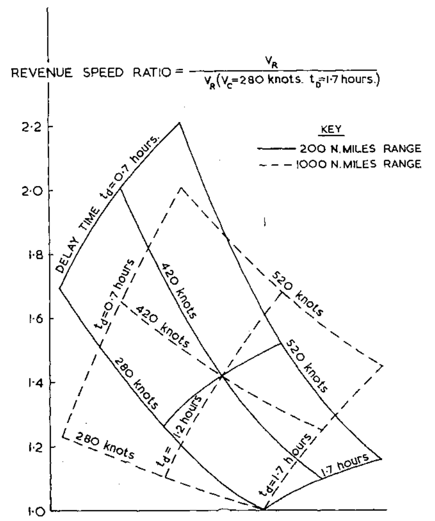

Fig. 2 Variation of revenue speed with cruising speed, delay time, and range.

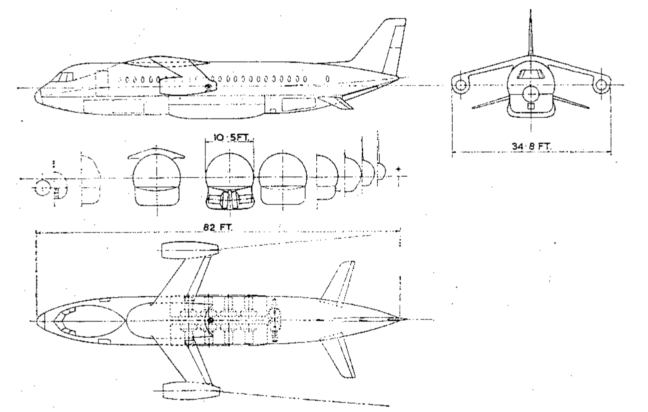

Fig. 3 Proposed VTOL airliner cruise configuration.

ever, these results assume that a change in any one parameter will not change the values of the other parameters. This is obviously not true with regard to cruising speed.

1.4 Interrelationship between Cruising Speed, Wing Loading, and Lift-Drag Ratio

For a specified number of passengers, the fuselage size is determined within fairly close limits. Again, the maximum wing loading is limited to about 80 lb/ft^2 by airfield requirements. These two factors mean that the total wetted area of an airliner of orthodox layout cannot be a function of cruising speed; the zero lift drag must increase significantly with increase in design cruising speed if moderate altitudes are to be maintained. An integrated layout for 100 passengers or less offers no advantage since trim, stability, and airfield requirements dictate the wetted area. It follows that with an increase in design cruising speed, the ratio of cruising speed to minimum drag speed increases and the lift-drag ratio falls. This is exaggerated by the increase in sweep and decrease in aspect ratio which must follow an increase in design cruising speed. In Table 4 the characteristics of a typical short range airliner of orthodox layout have been extrapolated to illustrate this effect. A constant cruise altitude of 25,000 ft has been assumed. An increase in cruising height with increase in speed would mitigate these effects, but the additional time and fuel to climb and descend, and the increase in weight associated with the higher cabin differential pressure prevent this technique from offering any significant relief.

An increase in speed in accompanied by an increase in wasted time associated with the longer acceleration and deceleration phases, an increase in fuel weight caused by the reduction in lift-drag ratio, and an increase in wing weight associated with the increase in sweepback and the decrease in aspect ratio and thickness. An assessment of these over-all effects on direct operating costs in Appendix B suggests that there is little to be gained by increasing the cruising speed of an orthodox short range airliner from 435 to 550 knots.

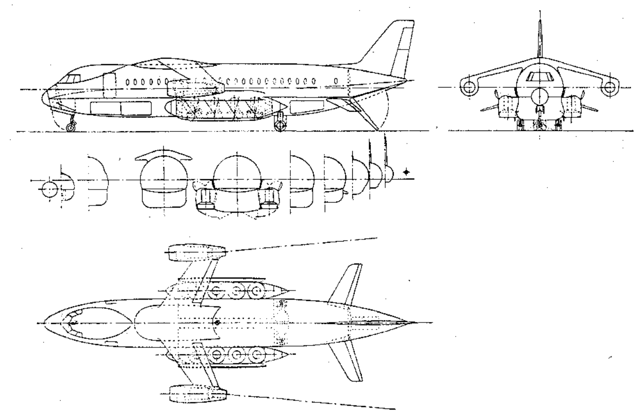

Fig. 4 Proposed VTOL airliner ground configuration.

Table 3 Effect of possible improvements on direct operating costs

Change in basic aircraft	Percentage change in direct operating costs
1000-lb decrease in basic weight	−1.5
150-lb decrease in bare engine weight	−0.5
2.5 increase in lift-drag ratio	−1.4
115-knot increase in cruising speed to 0.9 Mach No.	−11.0
250-hr increase in time available for operations	−2.5
10-min reduction in wasted time	−6.4
15-min reduction in ground time	−4.7

If the restriction on wing loading associated with orthodox takeoff and landing requirements is removed, the wing area for maximum lift-drag ratio occurs when the zero lift drag of the wing group equals the drag caused by lift. Table 4 shows that the wing loading for this condition increases significantly with increase in the design cruising speed.

The optimum wing loadings will be considerably higher than these since they will correspond to the conditions where the rate of increase in costs with increase in drag balances the rate of decrease in costs with decrease in wing group weight. It is significant that at a Mach number of 0.9, increasing the wing loading from 163 to 300 lb/ft^2 only decreases the lift-drag ratio by 7.7%.

1.5 Vertical Takeoff and Landing

Table 2 shows that a reduction in wasted time significantly reduces direct operating costs. One way of reducing block time is to minimize the time spent in taxiing, takeoff, climbing, circuiting, approaching, and landing. An aircraft using a vertical takeoff and landing technique need taxi only a few hundred yards before lift-off, can accelerate rapidly to moderate speeds by using vectored lift thrust, and does not need a long approach into wind. Because of the relatively short period the aircraft spends in the vicinity of the airfield and the small takeoff and landing area required, a considerable easing of air traffic congestion should result, and delays caused by air traffic control should be less.

It is estimated that a VTOL aircraft should save some 4 min of taxiing time, $1\frac{1}{2}$ min on takeoff and initial climb times,

Table 4 Effect of speed and wing loading on aircraft of orthodox layout

Lift = 67,500 lb	Height = 25,000 ft						
Mach number	0.4	0.5	0.6	0.7	0.8	0.85	0.9
Cruising speed, knots	241	301	361	422	482	512	542
Zero lift drag of fuselage group of components, lb	715	1118	1610	2190	2860	3240	3620
Zero lift drag of wing group of components for 80-lb/ft^2 wing loading	585	918	1320	1790	2350	2660	2970
Aspect ratio	10	10	9	8	7.5	7	6.5
Drag due to lift for wing loading = 80 lb/ft^2	2340	1500	1155	956	780	740	715
Lift-drag ratio for wing loading = 80 lb/ft^2	18.5	19.1	16.6	13.7	11.3	10.2	9.25
Wing loading giving lift-dependent drag equal to zero lift wing drag, lb/ft^2	40	63	86	110	139	152	163
Maximum lift-drag ratio	22	19.5	16.6	14.1	12.15	11.2	10.35
Lift-drag ratio for wing loading = 300 lb/ft^2	7.0	9.64	10.70	10.80	10.53	10.05	9.55

$5\frac{1}{2}$ min on descent, approach, and landing time and reduce air traffic delays by an average of 4 min. Thus a total of 15-min saving of wasted time is likely to result if the full capability of a VTOL airliner is used. Other advantages of adopting a VTOL technique are that very small wing areas are required and landing fees are less because of the smaller area of prepared surface required.[2]

The disadvantages of adopting VTOL are the weight, bulk, and cost of the lifting engines required and the extra fuel needed. It is worth noting that the extra fuel required is not as high as one might think, because of the saving in block time.

1.6 Comparison of VTOL and Orthodox Airliners

Part II outlines the design considerations that led to the VTOL airliner project shown in Figs. 3 and 4. This aircraft has a much higher wing loading than orthodox airliners; hence the saving in the weight of the lifting surfaces helps to offset the additional weight associated with the lift engines. The layout allows the maximum possible grouping of the systems, with easy access. Ground servicing during turn-round should be rapid because access points are well separated. An example of this is the wing tip refueling stations that site the refueling bowsers well clear of the other servicing vehicles.

A maximum stage length of 750 naut miles with full payload has been chosen. Figure 5 compares, on the basis given in Ref. 2, the direct operating costs of the project with those estimated for an orthodox airliner similar to the B.A.C. 1-11. The project direct operating costs are 10 to 15% lower than those of the orthodox aircraft; a result that stems mainly from the lower block times shown in Fig. 6.

It might be argued that an airliner with a maximum full payload range of only 750 naut miles was not entirely suitable for an airline such as B.E.A. because longer stage lengths are operated. Figure 6 shows that although the projected aircraft is not as attractive economically as the orthodox airliner over the longer stage lengths, it has a time advantage even though it has to land, refuel, and take off again after flying 750 naut miles. Since the average stage length for B.E.A. operations is somewhat less than 400 naut miles,[3] the attraction of operating a fleet of aircraft of all the same type might outweigh the disadvantage associated with the few routes of over 750 naut miles.

The shorter block times associated with VTOL airliners promise a greater economic advantage than that shown directly by Fig. 5. Ground crew time is saved by achieving quicker turn-rounds, thus allowing more aircraft to be serviced by one crew. The short block time associated with the simpler takeoff and landing aerodrome control problem should permit more frequent operations. Elle,[4] in his study of the interplay between supply and demand in air transport, shows that an increase in frequency of operations often generates a greater demand and, hence, a greater annual revenue.

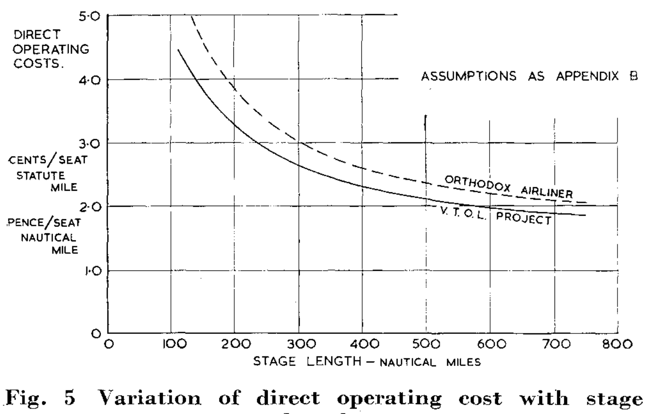

Fig. 5 Variation of direct operating cost with stage length.

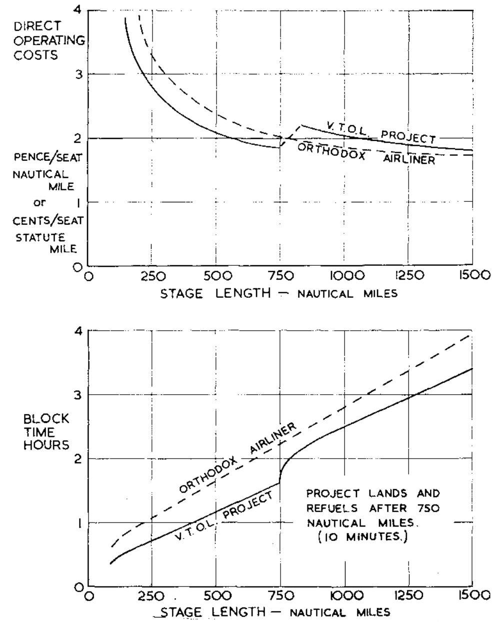

Fig. 6 Variation of costs and block time with stage length.

There should be little difficulty in designing ground aids such that services can operate in all weather conditions. A reliable service of high frequency is ideally suited to a "walk-on" system similar to that operated by other modes of transport. A wait of $\frac{1}{2}$ hr because one has just missed a flight is probably tolerable, whereas delays in excess of this are probably not. The reduction of the booking service should save a considerable part of the indirect costs of the operations and time on the part of the traveller.

Part II. Project Design

2.1 Introduction

The requirements derived in Part I asked for an airliner with vertical takeoff and landing capability, a high subsonic cruising speed, a short turn-round time, and easy access to grouped components to minimize the servicing time. A payload identical to that of the B.A.C. 1-11 was chosen to facilitate an economic comparison and, as a result, the cockpit and cabin layouts are the same as those for the 1-11.

The design considerations for the major components of the project are discussed in the following section. It must be emphasized that this project has been designed as a feasibility study of the ideas suggested in Part I and that very little in the way of optimization has been attempted.

2.2 Major Component Design

2.2.1 Engines

An analysis of a typical operation suggested that the lift thrust would be required for only a $\frac{1}{15}$th of the block time and would need to be equal to about four times the static thrust associated with propulsion. As a result, separate propulsive and lift engines were chosen because each could be designed for its particular function.

An assessment of the total thrust required to cover normal operations under hot and high airfield conditions was 140% of the maximum takeoff weight. An emergency overspeed condition for the engines was adopted to cover the contingency of an engine failure under these conditions. It was attractive to use the deflected thrust of the propulsive engines to provide some of the extra thrust because this reduced the weight and bulk of the special lift engines, thus requiring them to provide a thrust 15% in excess of the takeoff weight at normal maximum rpm.

Under standard aerodrome conditions, transition is achieved with the lift engines running at about 95% maximum rpm because of the supplementary thrust from the propulsive engines running at a speed that allows them to respond rapidly to a demand for full thrust. Wilde[5] has shown that the lift engine life under these conditions is considerably greater than that associated with regular use at maximum rpm. On this basis, it was estimated that the lift engines would have a life of 16,000 airframe hr, an attractive feature in view of their relatively high cost. An aspect that must receive serious consideration in any VTOL aircraft design study is the optimization of the lift engine weight, cost, and life between overhauls. This is not only a function of the size of engine but also of the end of transition speed. Ashill,[6] in a preliminary study of a possible VTOL airliner, has shown that a minimum of eight lift engines are required if a failure of more than one engine on any particular journey is not to lead to unacceptable risks. Assuming a single engine failure rate of once in every hundred thousand times it is run, he showed that the probability of two engines failing on any one journey is less than one in ten million; a probability generally accepted for fatigue life and gust loading calculations. It was assumed that if an engine failed, the engine symmetrically opposed to it would be shut down automatically to maintain trim.

Simple jet engines of the Rolls-Royce 162 type have very low specific volumes and weights, but their high jet exit velocities lead to excessive aerodrome noise, complicate emergency landings on unprepared sites, and preclude the use of a simple concrete surface for normal takeoff and landing areas. Wilde and Coplin[7] have shown that bypass ratio has only a slight effect on the noise levels generated, and that increase in bypass ratio increases the installed weight but reduces the fuel consumption. An optimization of the bypass ratio has not been attempted, but an analysis of published work suggests a bypass ratio of 4:1. The data given in Refs. 5 and 7 have been used to estimate the characteristics of the lift engines. A thrust to dry weight ratio of 13 and an installation weight to dry weight ratio of 1.9 have been used. The latter takes into account that part of the lift pod structure is common to the fuselage structure. An efflux velocity of about 1000 fps was adopted.

Very preliminary investigations suggest that the maximum fan noise will be in the order of 100–110 PNdB in the immediate surroundings of the aerodrome. Current research on fan noise promises a reduction in their peak levels. It is assumed that the boarding area will be separated from the engine run-up and takeoff area by effective soundproof barriers.

The bulk of the lift engines, together with interference effects, made it impossible to design an attractive wing installation. The high-speed cruise requirement demanded that the lift engines should be faired, at least in that condition, and as a result the retraction of the engines into the lower fuselage was an obvious solution. The disadvantage of the large doors in the fuselage became less significant when it was realized that something similar is required for easy access for servicing. As a consequence, the aircraft's systems have been designed to group the main services between the fore and aft keel members that divide the port and starboard lift engine bays, or immediately forward or aft of these. The engine bays are closed when the lift engines are operating to avoid buffeting troubles at the high-speed end of transition and therefore will protect this equipment from debris and mud during operations on or near the ground.

The lift engines can be tilted 10° forward to 30° aft of the normal to the fuselage datum during transition. It is probably desirable to make this movement part of an automatic control system, simply giving the pilot an emergency override control. In addition to this movement, the engines as pairs can be tilted ±5° about any mean setting by movement of the control column or rudder bars. This allows the pilot to supplement the aerodynamic control system during transition. The engine throttles are paired in the same way.

Two Spey engines were chosen for propulsion. They were positioned on the wing tips to minimize the interaction of their efflux on the rest of the aircraft, particularly the lift engines; and to facilitate easy access for maintenance. The anhedral of the high wing brings these engines within comfortable reach of the ground, and well away from the passenger, baggage, and catering access positions.

2.2.2 *Undercarriage*

A tricycle undercarriage with a steerable nose wheel has been selected for the project. A three-point touchdown on landing is expected and the loads on each undercarriage leg should be similar under this condition. Although the main undercarriage wheels are close to the exits of the lift engines at takeoff, it is not anticipated that they will be damaged because the efflux will be cool and of relatively low velocity.

2.2.3 *Wing and tailplane*

The adoption of a vertical takeoff and landing procedure obviates the necessity to design the wing and tail to give adequate lift in a trimmed condition at the low speeds associated with orthodox takeoff and landing. Factors that must be considered are the following: 1) at the end of transition, the wing and tail must provide lift at reasonable incidences and body attitudes; 2) gusts at the cruising speed must not induce excessive accelerations; 3) the induced drag during and subsequent to the transition phase must not be excessive; 4) compressibility effects such as the drag rise and shock stalling phenomena must not occur; and 5) the optimum design occurs when the change in basic aircraft cost associated with a small change in wing or tail area is just balanced by the fuel and basic weight costs associated with the change in fuel requirements.

Items 1, 3, and 4 suggest a high aspect ratio and a low wing loading, whereas items 2 and 5 require the opposite characteristics. The wing loading for the project was fixed by limiting the maximum wing lift coefficient in the cruise to 0.425 since it was felt that there was a danger of shock stalling at higher lift coefficients. The aspect ratio selected was as high as was possibly consistent with minimizing distortion effects with the tip mounted propulsive engines. The combination of wing loading and aspect ratio selected resulted in a wing body angle near the maximum acceptable if the fuselage floor was to be horizontal during the cruise, and a wing span that enabled a fin and rudder of normal size to cover the case of a single propulsive engine failure.

Except at center of gravity positions near the aft limit, an orthodox aircraft usually has a down load on the tail to trim. Consequently, the wing lift must exceed the weight of the aircraft by this amount, and the wing size must reflect this extra load if the coefficient at cruise is fixed. The down load on the tail results from the relative inefficiency of the tailplane contribution to stability, because of the downwash from the wing and the need to trim an orthodox aircraft near the ground when the flaps are fully down.

Since the landing design case does not apply, the tailplane of a VTOL aircraft can be mounted well below the plane of the wing and the wing interference will be minimal.[8] The smallest combined wing and tailplane area, in the absence of interference effects, occurs when both the wing and tailplane operate at the maximum allowable lift coefficient. Some interaction between the wing and the tailplane must exist in practice and this, together with the need to meet stability requirements, necessitates adopting a tailplane lift coefficient lower than that for the wing.

With a central center of gravity position, the tailplane of the project carries a positive lift equal to 22% of the aircraft's weight under cruise conditions. Apart from the lower weight and induced drag relative to an orthodox layout of the same aspect ratio, this layout has several advantages. The wing is mounted high on the fuselage and well ahead of the center of gravity, thus allowing the deflected thrust line of the tip mounted engines to pass through the center of gravity. The forward position of the wing increases the distance between the wing and tailplane and therefore reduces their interference still further, whereas the fuselage is supported in two places and experiences smaller peak bending moments as a result. The "wing-loading" of the project, based on the exposed wing area plus the tailplane and elevator area, is 250 lb/ft^2 compared to that of about 60 lb/ft^2 for the B.A.C. 1-11.

When cruising at a Mach number of 0.9 at 25,000 ft altitude and a weight of 70,000 lb, the project achieves a lift to drag ratio of 10.4. Under these circumstances the zero lift drag is almost twice that associated with lift, which indicates that a still higher wing loading would increase the lift to drag ratio. In spite of the high equivalent air speed in the cruise, the very high wing loading and moderate aspect ratio lead to normal accelerations in gusty conditions of only a third of those experienced by orthodox airliners.

Full span ailerons and elevators are fitted to give powerful aerodynamic controls to assist the engine control system during transition. The ailerons can be drooped to increase the lift at a given incidence during the transition.

In the very remote case of a fire in the fuselage lift engine bay causing a complete failure of the lift engines, a belly landing could be made touching down at about 170 knots. In general, the aircraft is considerably safer than orthodox ones because its kinetic energy when close to the ground is much less and it can make emergency landings on unprepared sites.

2.3 Transition Technique

It is important that the transition time should be as short as possible to give a long period between lift engine overhauls and to minimize the fuel used in transition. A short transition time can be achieved by adopting a low transition end speed, but large penalties would result from the large wing area required for airborne flight at this speed, and the slow subsequent acceleration to cruising conditions. Too high a transition end speed leads to excessive values of the intake momentum drag of the lift engines, especially when they have a relatively low efflux velocity.

Aerodynamic lift should be as large as possible at all stages of the transition since the induced drag is small compared with engine momentum drag. However, incidence is an embarrassment since it reduces the propulsive thrust component of the lift engines if their movement, relative to the fuselage datum, is limited.

The transition path of the aircraft should start with a vertical, or near vertical, lift-off followed by a rapid climb that should reduce as the aircraft gains height. Estimates suggest that a height of 200 ft should be achieved in 200 ft horizontal distance after about 10 sec. For this phase the efflux of the main engines is deflected downwards and their throttles set to give the minimum thrust which allows a rapid increase in the event of an emergency. At about 200 ft altitude the aircraft should accelerate horizontally, by switching the main engines to the normal thrust condition, until the best climbing speed of about 270 fps is reached. The aircraft should climb at this speed to about 5000 ft and then accelerate in a near horizontal path to the transition speed of 420 fps. Calculations show that a height of 5000 ft is reached in 9000 ft horizontal distance from the lift-off point. Throughout this phase, the ailerons are drooped to give an incremental lift coefficient of 0.2. The limitation on rate of climb during the initial lift-off phase and during the constant speed climb phase is likely to be on the cabin floor angle to the horizontal, since angles of 30° or more can be achieved. Throughout transition, the lift engines operate at 95% maximum rpm.

Table 5 General particulars of projected aircraft

Over-all length	82.0 ft	Fuselage max height	12.5 ft
Over-all height	24.2 ft	Sea level static thrust of each propulsive engine	10,400 lb
Over-all span	34.8 ft		
Gross wing area	270 ft^2	Sea level static thrust of each lift engine	10,500 lb
Aspect ratio	4.5		
Wing sweep at ¼ chord	35°	Max takeoff weight	74,000 lb
Gross horizontal tail area	138 ft^2	Max landing weight	74,000 lb
		Max payload	14,000 lb
Fuselage maximum width	10.5 ft		

At the transition end speed the lift engines are shut down and the lift engine pods retracted. A normal energy-height climb to the cruise condition follows.

Ground aids are used to determine the point of initiation of the descent transitions, which is basically the reverse of the ascent procedure. The lift engines are tilted forward to assist in deceleration and the incidence is limited to avoid gust induced stalling. The descent transition takes longer than the ascent transition phase because of the need to position the aircraft accurately before the final descent.

2.4 General Particulars of the Projected Aircraft

Table 5 lists the main features of the projected aircraft. It should be emphasized that only a preliminary study has been made to suggest a feasible layout and to provide a basis for comparison with airliners using an orthodox takeoff and landing procedure. The maximum stage length with full payload and the cruising speed were chosen arbitrarily.

A typical mixed class layout of the cabin would be 6 rows of 4-abreast seats at 37-in. pitch for first class passengers, and 7 rows of 5-abreast, plus 1 of 4-abreast at 34-in. pitch, giving a total accommodation for 63 passengers. Forward and ventral passenger doors allow rapid embarkation and disembarkation well clear of other access points.

Two forward cargo holds and one aft give a total freight and baggage capacity of over 500 ft^3. The doors are the full size of the sides of holds allowing the freight to be prepacked in panniers that slide into the holds.

The aircraft is designed to cruise at a Mach number of 0.9 at 25,000 ft altitude, but it can operate at much lower altitudes, without passenger discomfort from gust effects, in order to minimize the block time for very short stage lengths.

A maximum stage length of 750 naut miles with full payload can be flown without a refueling stop. Reserve fuel allows for a second transition after a baulked landing, 15 min hold at 320 knots at 5000 ft, and a subsequent deceleration, transition, and landing. A preliminary assessment of the component weights for the project is given in Table 6.

Table 6 Weight summary

Wings	2,450 lb				
Fuselage	9,350 lb				
Tail	1,200 lb				
Undercarriage	2,300 lb				
Structure		15,300 lb			
Propulsion engines and nacelles		6,800 lb			
Fuel system		400 lb			
Flying controls		700 lb			
Hydraulics		700 lb			
Auxiliary power unit		450 lb			
Bare lift engines		6,400 lb			
Lift engines, nacelles, equipment, retracting mechanism		5,700 lb			
Bare weight			36,450 lb		
Equipment			9,900 lb		
Empty weight				46,350 lb	
Crew, catering, and unused fuel				1,650 lb	
Operating weight empty					48,000 lb
Passengers and baggage 63 @ 209 lb					13,200 lb
Fuel for taxiing, transition, climb, and descent taking 24 min and covering a distance of 150 naut miles					3,500 lb
Maximum cruise fuel					6,600 lb
Reserve fuel					2,700 lb
Maximum takeoff weight					74,000 lb

3. Conclusions

An assessment of the revenue earning capacity and the direct operating costs of short range airliners reveals the importance of attaining a high annual operating time, a low journey time, and a low aircraft equipped weight. The concept of a revenue speed that directly relates the revenue to the annual time an aircraft is available for operations shows that revenue is significantly reduced by wasted time both during the flight and on the ground, particularly for aircraft capable of high cruising speeds.

To achieve a high annual operating time, the maintenance time for the aircraft, particularly that for unscheduled maintenance, must be a minimum. It is suggested that an improvement would result if extra emphasis were put on the reliability of components and if the aircraft systems were grouped to allow simple access and replacement.

Easy and uncongested access for passengers, freight, refuelling bowsers, and catering and servicing vehicles is an essential design feature if short turn-round times are to be achieved. The wasted time associated with the taxiing, takeoff, circuits, climb, descent and landing of current short haul airliners is a very large part of their block time. It is shown that an airliner using vertical takeoff and landing can halve this wasted time.

A VTOL airliner is projected to allow a comparison with an orthodox airliner. Provided the VTOL aircraft is designed as such and has the high wing loading and more efficient tailplane that are possible when orthodox takeoff and landing procedures are not required, its direct operating costs can be as much as 15% lower over stage lengths up to 750 naut miles. It is probable that the shorter journey times of a VTOL airliner would attract more revenue and decrease indirect costs.

Appendix A: Direct Cost Analysis

It is usual to divide direct operating costs into annual costs, hourly costs, and journey costs as in the method[2] used in this study.

1. Annual Costs

These comprise amortization, interest, and insurance costs; each of which is directly proportional to the initial cost of the aircraft and spares. This initial cost can be estimated with fair accuracy by assuming a scale of costs/unit weight for various groups of components. For the purpose of preliminary studies on similar types of aircraft, only two cost rates need to be used; one associated with the main structure, equipment, and furnishings and the other with the more complex items such as engines and electronic equipment. Thus the annual costs can be expressed as

$$C_a = k_1 W_b + k_2 W_e \text{ \$/annum} \qquad \text{(A1)}$$

where k_1 and k_2 are the lower and upper cost rates, respectively; W_b is the aircraft empty weight less W_e; and W_e is the weight of dry engines, basic electronics, and other complex items.

The assumptions made to calculate the values of k_1 and k_2 are as follows: 1) the cost of the basic aircraft less engines and electronics is \$56/lb; 2) the cost of the engines and electronics is \$84/lb; 3) airframe spares cost 15% of the cost of the basic aircraft less engines and electronics; 4) engine and electronic spares cost 45% of their cost in the new aircraft; 5) the residual value of the aircraft after 7 yr service is 25%; 6) the interest/annum is 6% of the mean value of the aircraft and spares; and 7) the insurance rate is 3.5% of the prime cost of the aircraft. It follows directly that the annual costs are

$$C_a = 11.3 W_b + 20.5 W_e \text{ \$/annum} \qquad \text{(A1a)}$$

2. Hourly Costs

The hourly costs can be divided into two parts, maintenance costs and crew costs; both of which are directly proportional to the number of flying hours or utilization U. Since the cost of maintenance must cover the cost of the spare parts used, the cost is written in the form

$$C_m = U(k_3 W_b + k_4 W_e + k_5) \text{ \$/annum} \qquad \text{(A2)}$$

where k_3 and k_4 are the maintenance costs per flying hour per unit weight of W_b and W_e, respectively, and k_5 is a constant maintenance cost per flying hour. Reference 2 divides maintenance costs in the following way: 1) for the aircraft less engine, the cost per flying hour, assuming an initial cost of \$56/lb, is $(19.6 + 0.00205\, W_b)$ dollars; and 2) for the engines and electronics, the costs per flying hour is $(4.2 + 0.01\, W_e)$ dollars; assuming that the initial cost/lb weight is \$84 and that the servicing of electronic components costs the same per unit weight as the bare engines. On the basis of the rates supplied in Ref. 2, the hourly costs for a crew of two pilots and two stewards are \$64.6.

3. Journey Costs

These consist of the fuel costs and the landing fees. For short range operations, the fuel used per journey can be predicted with reasonable accuracy by the expression

$$W_f = k_6 R + k_7 \qquad \text{(A3)}$$

where k_6 is the weight of fuel used per nautical mile cruised and k_7 is the weight of fuel associated with taxiing, takeoff, climb, hold, descent, and landing in pounds. Now

$$k_6 R \doteq \frac{R}{V_c} \frac{c}{(L/D)} W_m \qquad \text{(A4)}$$

where L/D is the ratio of lift to drag in cruising flight, c is the engine specific fuel consumption lb/lb thrust hour, and W_m is the mean weight during the cruise in pounds.

$$W_m = W_b + W_e + W_p + (W_f/2) \text{ approximately} \qquad \text{(A5)}$$

where W_p is the payload, crew, catering, and reserve fuel weight. Thus the fuel costs can be written as

$$C_f = k_8 \frac{U}{t_b} \left[\frac{\frac{Rc}{V_c L/D}(W_b + W_e + W_p) + k_7}{\frac{Rc}{2V_c(L/D)}} \right] \qquad \text{(A6)}$$

where k_8 is the fuel cost/lb.

If airliners similar to the B.A.C. 1-11 are considered, the fuel used in taxiing, climb, descent, and landing is about 1800 lb, whereas the payload, etc. W_p is 17,600 lb. Since the value of $Rc/(V_c L/D)$ will not differ significantly from 0.06 for a 400-naut-mile stage length, the denominator of Eq. (A6) can be assumed to be 0.97 without serious error.

If a fuel cost of 2.05¢/lb is assumed, the annual fuel costs approximate to

$$C_f = 0.0205 \frac{U}{t_b}\left[\frac{Rc}{V_c(L/D)}(W_b + W_e + 17{,}600) + 1800\right] \text{ dollars} \qquad \text{(A6a)}$$

Reference 2 suggests a cost per pound landing weight per occasion for an aircraft of about 70,000 lb gross weight as 0.098 cents. Thus annual landing fees per aircraft are

$$C_1 = 0.00098(U/t_b)(W_b + W_e + 17{,}600) \text{ dollars} \qquad \text{(A7)}$$

The total direct operating cost per aircraft per annum is equal to

$$C = C_a + C_m + C_c + C_f + C_1 \text{ \$/annum} \qquad \text{(A8)}$$

and number of passenger miles flown/annum is (RU/t_b). Thus for N seats/aircraft, the total direct operating costs

Table 7 Comparison of VTOL project with orthodox airliners designed to cruise at Mach numbers of 0.72 and 0.9

Aircraft	Orthodox airliner	Developed orthodox airliner	VTOL project
Stage length, naut miles	400	400	400
Cruising speed, knots	435	550	550
Cruising altitude, ft	25,000	25,000	25,000
Wasted time t_w, hr	0.5	0.55	0.25
Block time t_b, hr	1.42	1.28	0.98
Ground time t_g, hr	0.55	0.50	0.45
Journeys/annum $[H/(t_b + t_g)]$	1,905	2,100	2,630
Basic weight W_b, lb	37,000	39,500	34,400
Basic engine and electronics weight W_e, lb	5,500	5,600	11,900
Extra fuel for takeoff, climb, descent, landing, and taxiing, lb	1,800	2,000	3,104
Lift-drag ratio at cruise L/D	12.5	9.25	10.0
Annual costs, ¢/seat mile	1.105	1.052	0.934[a]
Hourly costs, ¢/seat mile	1.296	1.145	1.056[a]
Fuel costs, ¢/seat mile	0.463	0.517	0.573
Landing charges, ¢/seat mile	0.233	0.244	0.124[b]
Total direct operating cost, ¢/seat naut mile	3.03	2.96	2.68

[a] Lift engine costs taken as 90% of propulsive engine costs because of larger production quantity.
[b] Quoted at half rates, as suggested in Ref. 2.

become

$$\frac{280}{NR}\left[\frac{t_b}{U}(11.3W_b + 20.5W_e) + t_b(88.4 + 0.00205W_b + 0.01W_e) + (W_b + W_e)\left(0.0205\frac{Rc}{V_c(L/D)} + 0.00098\right) + \frac{361Rc}{V_c(L/D)} + 55\right] \text{cents/passenger mile} \quad \text{(A9)}$$

Appendix B

The direct cost equation developed in Appendix A has been used to compare the costs of an aircraft similar to the B.A.C. 1-11 with a development designed to cruise at $M = 0.9$ and with the VTOL project. The equation has been modified to allow for the extra takeoff fuel required. An outline of the assumptions and results is given in Table 7. The number of hours available for operations H has been taken as 3750 in all cases.

It is worthy of note that if current trends of a more rapid rise in first costs than in fuel costs with time continues, the VTOL aircraft becomes increasingly attractive.

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