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OPTIMIZED ENGINE-OUT PROCEDURES TO EXTEND THE RANGE OF JET TRANSPORT AIRPLANES

Melville R. Byington, Jr., and Miltos Miltiadous

ABSTRACT

Transoceanic jet transport service, once the exclusive domain of four-engine airplanes, will continue the trend toward two-engine airplanes. This has become possible due to larger, more fuel-efficient and reliable engines and airplanes. Improved reliability demonstrations may soon permit two-engine airplane tracks as far as 120 and 180 minutes flying time from the nearest suitable diversion airport. Although the probability of diversion for a given flight is extremely remote, safety dictates a worst case fuel reserve scenario based on engine-out diversion from the furthest point. This study focuses on engine-out optimum range flight techniques for typical two- and four-engine transports. Various engine-out scenarios for the Boeing 767 and Boeing 747 were investigated using airplane models in wind tunnel experiments. Engine-out specific range improvements up to 9% appear possible through proper techniques of zero sideslip, minimum drag flight. During a rare actual diversion, following proper minimum drag techniques will optimize engine-out specific range and stretch onboard reserves. Similarly, knowledge of such efficiency gains could routinely be translated into reduced diversion fuel reserves--without reduction in safety margin. Reduced contingency fuel translates to some combination of increased payload or improved all-engine cruise economy, thereby increasing operating efficiency and profitability.

INTRODUCTION

Until recently, extensive over-water flights were limited by regulation to three- and four-engine airplanes. International Civil Aviation Organization (ICAO) regulations for extended over water flights further state that no airplane may fly on a route which is more than 90 minutes flying time from a suitable alternate aerodrome unless, after the failure of two engines, it can maintain a prescribed minimum climb performance (Mortimer, 1984).

This 90-minute rule was established in 1946 and applied only to four-engine airplanes. Unfortunately, ICAO records do not show the origin of this

figure. It can only be surmised that it was an empirical rule based upon the airplane capabilities of that period (Mortimer, 1984). More recently, the primary airplane used in extensive over-water operations is the four-engine Boeing 747, because it has a greater flying range and can carry a large number of passengers.

The Federal Aviation Administration (FAA) has a similar regulation that concerns the operation of twin-engine airplanes. Part 121 of the Federal Aviation Regulations states that no airplane may fly on a route more than 60 minutes flying time from a suitable alternate aerodrome after the failure of one engine.

However, demonstrated reliability of modern engines and systems led to provisions for further relaxation of the diversion constraints. Inflight engine shutdown rates of about one per 50,000 hours have been experienced (FAA Advisory Circular 120-42A, 1988). Two-engine airplane operational reliability is evidenced by the diversion of only six flights in the last five years of extended range operations (Broderick, 1990).

The recently revised FAA AC 120-42A (12/30/88) contains specific criteria for extending diversion times to 120 and 180 minutes from the nearest suitable alternate airport. The governing philosophy is that the relaxed provisions must be accomplished with no adverse changes in risk. Normally, an operator must accumulate 12 months of engine-airframe service experience before applying for the 120-minute diversion. Similarly, a further 12 months of experience is required before requesting 180-minute operating authority.

Long range, two-engine airplanes such as the Boeing 767 and the new Boeing 777 are among the candidates to benefit from improved flexibility implicit in the current doctrines. These new operational domains require critical planning to optimize efficiency and economy of operation without adverse impact on risk. This study is focused on planning for the operations influenced by engine-out considerations.

STATEMENT OF THE PROBLEM

The purpose of this study is to develop optimum engine-out procedures for the Boeing 747 and Boeing 767 on extended flights. These procedures will extend the airplane's range in case of engine failure. For the purposes of this

study, optimum engine-out procedure is the procedure that should be followed to maximize specific range upon experiencing an engine failure.

REVIEW OF RELATED LITERATURE

In a multi-engine airplane, the failure of a powerplant should not result in an accident since flight may be continued with the remaining powerplants. Yet the performance of a multi-engine airplane with one or more powerplants inoperative will be seriously affected for two reasons. First, an asymmetrical thrust condition results when an off centerline powerplant fails. This asymmetrical thrust condition creates a yawing moment on the airplane, causing it to sideslip (Hurt, 1965). This sideslip has two disadvantages. It increases drag and decreases the tail fin's angle of attack. This creates a weathervaning tendency that compounds the yaw from asymmetric thrust (Byington, 1989). Additionally, when an engine fails during optimum cruise of a turbojet airplane, the airplane must descend to a lower altitude. The adverse effect of reduced altitude on the range of a turbojet airplane is of great importance, and a decrease in altitude will reduce specific range. The greater density produces a lower true airspeed (TAS) for the same amount of thrust or fuel flow (Hurt, 1965).

The cited factors seriously affect range capability of a turbofan airplane. In long distance over-water flights, range performance may become critical when an airplane experiences engine failure at maximum distance from a suitable field.

When an airplane experiences an off-center engine failure with wings level, it will necessarily sideslip toward the failed engine(s). Yet, it is possible to bank the airplane into the operative engine and eliminate the disadvantages caused by the sideslip (Byington, 1989). Known studies on this subject relate only to light twin-engine propeller airplanes, and none to large transports.

When a two- or four-engine transport experiences an engine failure, it may still cruise successfully to its original destination. The zero sideslip techniques advocated below will minimize the deterioration in specific range. Regardless of the flight technique, engine(s)-out cruise will inevitably result in substantial range penalties. Under some scenarios, the airplane could not reach its destination if the fuel reserve were based on normal, rather than

engine-out, cruise. However, regulatory authorities such as the FAA or ICAO require that the airplane carry an amount of reserve fuel sufficient to reach a suitable aerodrome.

Reserve fuel requirements are discussed at length in part 121 of the Federal Air Regulations (FARs) and in AC 120-42A. Also, specific rules for calculating the amount of reserve fuel are given by the Air Transport Association of America (ATA). The amount of reserve fuel given by these rules is in excess of minimum FAR requirements, but represents current airline operational practices (Loftin, 1985).

The reserve fuel requirements specified by the ATA for subsonic turbine-powered airplanes employed in international operations are as follows:

1. Fly for 10% of trip air time at normal cruise altitude at a fuel flow for end of cruise weight at the speed corresponding to 99% of maximum range.
2. Execute a missed approach and climbout at destination airport; fly to an alternate airport 200 nautical miles away.
3. Hold for 30 minutes at alternate airport at 1500 feet altitude.
4. Descend and land at alternate airport.

Following a two-engine failure on the 747 or an engine failure on the 767, the Operating Manual of each airplane states that the crew should initiate wings level "driftdown" enroute to a suitable aerodrome. The crew may select any of several methods of driftdown that best meets the existing conditions. Figure 1 (Adapted by: Taylor 1985) presents the available driftdown options for the Boeing 767. If there is no other emergency, the crew can slowly descend from 39,000 to 27,400 feet in about 60 minutes and maintain this altitude until reaching an airport. The time indicated in the figure is the time to fly 690 nautical miles (ICAO 90-minutes guideline) at the selected speed and thrust combination (Taylor, 1985).

			Maximum Continuous Thrust		Maximum Cruise Thrust	
	Driftdown Speed	Cruise Speed After Level-Off	Level-Off Altitude (ft)	Time (min)	Level-Off Altitude (ft)	Time (min)
1	Max. L/D Speed	Resultant	27,400	115	25,700	119
2	0.80M/LRC	Long-Range Cruise	25,700	105	21,100	108
3	0.86M/360 KCAS	360 KCAS	15,000	91	-	-

Figure 1. Driftdown options with one engine inoperative.

STATEMENT OF THE HYPOTHESIS

Theory suggests that, for the asymmetric thrust situation, an optimum amount of bank will both minimize drag and assist in counteracting the yawing moment. Therefore, it is hypothesized that by banking the airplane into the operative engine(s) by that optimum bank angle, the range of the airplane can be improved significantly.

THEORY

Twin-Engine Airplanes

Research by Byington (1988) for optimizing engine-out performance on multi-engine airplanes established that the engine-out zero slip bank angle (ϕ) depends on the individual design geometry and thrust-to-weight ratios. The following relationship applies:

$$\phi = \sin^{-1} \left\{ \frac{T}{W} \frac{a}{b} \right\} \quad (1)$$

T is the engine thrust, W is the airplane weight, a is the distance by which the engine thrust is off-set from the centerline (moment arm), and b is the longitudinal distance between the center of gravity (CG) and the tailfin's aerodynamic center (Byington, 1988).

Assuming thrust equal to drag (D) and lift (L) equal to weight, Byington modified Equation 1 to:

$$\Phi = \sin^{-1} \left\{ \frac{a/b}{L/D} \right\} \quad (2)$$

The ratio of L/D was estimated based on the airplane's best glide ratio, $(L/D)_{\max}$. Yet it is unlikely that an airplane experiencing an engine failure will fly precisely at its $(L/D)_{\max}$; therefore, it is assumed that (L/D) will be approximately 0.9 $(L/D)_{\max}$ (Byington, 1988). For the small bank angles involved, the sine of the bank angle and the angle in radians are assumed equal (Byington, 1988). Thus, since one radian is 57.3 degrees, Equation 2 became:

$$\Phi = 57.3 \left\{ \frac{a/b}{0.9(L/D)_{\max}} \right\} \quad (3)$$

The wings-level sideslip angle (β) resulting from an engine-out condition is difficult to measure but can be estimated based on the following equation (Roskam, 1972):

$$\beta_{\max} = \left\{ \frac{(N_T)}{C_{n_\beta} q S B} \right\} \quad (4)$$

where (N_T) is the yawing moment produced by the asymmetric thrust condition and is equal to the thrust (T) produced by each operative engine times the distance that the engine thrust is off-set (a), q is the dynamic pressure (Pounds per Square Foot), S is the wing area (Square Feet), B is the wing span (Feet), and C_{n_β} is the variation of the yawing moment coefficient with sideslip angle (Roskam, 1972).

The dynamic pressure q is given by the following equation:

$$q = \frac{\sigma V^2}{295} \quad (5)$$

where σ is the density ratio and V is the true airspeed of the airplane in Knots (Hurt, 1965). Thus, Equations 4 and 5 can be combined in the following equation:

$$\beta_{\max} = \left\{ \frac{295 (T a)}{C_{n_{\phi}} \sigma V^2 S B} \right\} \quad (6)$$

The operative engine thrust is assumed equal to the drag, thus:

$$T = D = \frac{W}{(L/D)} \quad (7)$$

As stated above, the L/D ratio is assumed to be approximately $0.9(L/D)_{\max}$ (Byington, 1988). Thus, Equation 7 can be modified to:

$$T = \frac{W}{((0.9)(L/D)_{\max})} \quad (8)$$

Based on Equation 8, Equation 6 can be modified to:

$$\beta_{\max} = \left\{ \frac{295 (W a)}{(0.9 (L/D)_{\max}) C_{n_{\phi}} \sigma V^2 S B} \right\} \quad (9)$$

Boeing 767 Engine Failure

One case was considered for the Boeing 767. The parameters used to obtain the optimum amount of bank angle for the zero slip condition are the $(L/D)_{\max}$ and the a/b ratios. For the Boeing 767-200, $(L/D)_{\max}$ equals 17.60 (Lan & Roskam, 1981). Also, assuming a mid center of gravity, b is equal to 85 feet (Boeing Aircraft Company [BAC], 1989).

Based on Equation 9, the parameters required to obtain the sideslip angle in the engine-out condition are: W, a, $(L/D)_{\max}$, $C_{n_{\phi}}$, σ , V, S, and B. For large transport airplanes, $C_{n_{\phi}}$ is equal to approximately 0.09 (Roskam, 1972). For the Boeing 767-200, S equals 3,050 feet² (Lan & Roskam, 1981), B is equal to 156 feet (BAC, 1989).

For purposes of analysis, a cruise altitude of 39,000 feet is assumed. After engine failure, the airplane is assumed to descend to 27,000 feet, thus σ is equal to 0.41729. Based on the Boeing 767 Operations Manual long range cruise table with an engine inoperative, for 27,000 feet and gross weight 270,000 pounds, V is equal to 492 knots true airspeed (KTAS) (0.79 Mach).

In the Boeing 767, the thrust centerlines are displaced from the airplane centerline by distance a , equal to 26 feet (BAC, 1989).

Substituting the above values into Equation 3, it follows that:

$$\phi = 57.3 \left\{ \frac{(26\text{ft}/85\text{ft})}{(0.9)(17.60)} \right\} = 1.12 \text{ degrees}$$

Four-Engine Airplane

For a four-engine airplane, the basic equations above need to be modified before implementation. The items that require modification are the generalized moment arm (a') and the total thrust T . The moment arm (a') will vary with the type of engine failure; i.e., inboard, outboard or both engines on same side.

Inboard Engine Failure

For an inboard engine failure the moment arm a' was found based on Figure 2. Since both outboard engines are assumed to produce equal thrust (t), the resulting moments from these engines are equal and opposite, thus canceling. The only other thrust moment results from the remaining operative inboard engine, thus the moment arm is equal to distance a shown in Figure 2.

Figure 2. Schematic of an inboard engine failure on a four-engine airplane.

Based on the above, Equation 1 was modified to represent an inboard engine failure of a four-engine airplane:

$$\Phi = \sin^{-1} \left\{ \frac{t}{W} \frac{a}{b} \right\} \quad (10)$$

Since t is one-third of the total thrust and total thrust is equal to drag, it can be deduced that $t = D/3$. Also, lift (L) is assumed equal to weight (W). Substituting the above relationships in Equation 10, the following equation results:

$$\Phi = \sin^{-1} \left\{ \frac{D}{3L} \frac{a}{b} \right\} \quad (11)$$

Equation 11 can be rearranged to:

$$\Phi = \sin^{-1} \left\{ \frac{1}{3} \frac{a/b}{L/D} \right\} \quad (12)$$

Employing the assumptions previously explained, Equation 12 becomes:

$$\Phi = \frac{57.3}{3} \left\{ \frac{a/b}{0.9(L/D)_{\max}} \right\} = 21.22 \left\{ \frac{a/b}{L/D_{\max}} \right\} \quad (13)$$

Equation 6 also requires modification for this case by substituting t for T . Thus Equation 6 becomes:

$$\beta_{\max} = \left\{ \frac{295 (t a)}{C_{n_p} \sigma V^2 S B} \right\} \quad (14)$$

As mentioned earlier, for three engines operating, the thrust produced by each of the airplane's operative engines is equal to one-third of the total thrust, thus:

$$t = \frac{T}{3} = \frac{D}{3} = \frac{W}{3(L/D)} \quad (15)$$

As stated above, the L/D ratio equaled $0.9(L/D)_{\max}$ (Byington, 1988).

Thus, Equation 15 can be modified to:

$$t = \frac{W}{((0.9)(3)(L/D)_{\max})} = \frac{W}{(2.7)(L/D)_{\max}} \quad (16)$$

Outboard Engine Failure

For an outboard engine failure, the moment arm a' must be redefined. Since both inboard engines produce equal thrust (t), their moments are equal and opposite. The only thrust moment left results from the remaining operative outboard engine, thus the moment arm is equal to distance c shown in Figure 3.

Figure 3. Schematic of an outboard engine failure on a four-engine airplane.

The outboard engine failure case is similar to that of the inboard engine, with only the difference of the moment arm distance. Therefore, Equation 13 can be modified for this type of engine failure by substituting the distance c for distance a .

$$\Phi = \frac{57.3}{3} \left\{ \frac{c/b}{0.9(L/D)_{\max}} \right\} = 21.22 \left\{ \frac{c/b}{(L/D)_{\max}} \right\} \quad (17)$$

Both Inboard and Outboard Engine Failure (Same Side)

For a combined inboard and outboard engine failure, the calculation of the moment arm is more complicated. Here, both inboard and outboard operative engines produce equal thrust (t), and the resulting moments add. The resulting moment arm a' equals the sum of the distances of each operative engine (a and c), thus the moment arm is equal to $a+c$ (see Figure 4).

Figure 4. Schematic of both an inboard and outboard engine failure (same side) on a four-engine airplane.

Based on the above, Equation 1 was modified to represent a combined inboard and outboard engine failure of a four-engine airplane:

$$\Phi = \sin^{-1} \left\{ \frac{t}{W} \frac{(a+c)}{b} \right\} \quad (18)$$

Since t is half the total available thrust and the total thrust equals drag, it can be deduced that $t = D/2$. Also, lift (L) is equal to weight (W). Substituting the above relationships in Equation 18, the following results:

$$\Phi = \sin^{-1} \left\{ \frac{D}{2L} \frac{(a+c)}{b} \right\} \quad (19)$$

Equation 19 can be rearranged to:

$$\Phi = \sin^{-1} \frac{1}{2} \left\{ \frac{(a+c)/b}{L/D} \right\} \quad (20)$$

Employing the assumptions previously explained, Equation 20 becomes:

$$\Phi = \frac{57.3}{2} \left\{ \frac{(a+c)/b}{0.9(L/D)_{\max}} \right\} = 31.83 \left\{ \frac{(a+c)/b}{(L/D)_{\max}} \right\} \quad (21)$$

Boeing 747

Three cases were considered for the Boeing 747. Based on Equation 3, the parameters necessary to obtain the bank angle for the zero slip condition are the $(L/D)_{\max}$ and a/b ratios. Both the $(L/D)_{\max}$ ratio and the distance b are assumed the same for all cases. For the Boeing 747-200, $(L/D)_{\max}$ equals 17.74 (Lan & Roskam, 1981). Assuming a mid center of gravity, the distance b is equal to 105 feet (BAC, 1981).

Based on Equation 9, the parameters needed to obtain the angle of sideslip corresponding to the wings-level engine-out condition are: W , a , $(L/D)_{\max}$, C_{n_β} , σ , V , S , and B . From these parameters, S and B are the same for all three cases. For large transport airplanes, C_{n_β} is equal to approximately 0.09 (Roskam, 1972), and assumed constant.

For the Boeing 747-200, S equals to 5,500 feet² (Lan & Roskam, 1981), B is equal to 196 feet (BAC, 1981).

For all three cases, an initial altitude of 35,000 feet is assumed. After a single engine failure, the airplane is assumed to descend to 31,000 feet, where σ is 0.36053. Based on the Boeing 747 operations manual long range cruise

Byington and Miltiadous: Optimized Engine-Out Procedures to Extend the Range of Jet Transportable with one engine inoperative at 31,000 feet and gross weight of 500,000 pounds, V is equal to 488 KTAS (0.766 Mach).

For the third case, after double engine failure, the airplane is assumed to level off at 24,000 feet, where σ equals 0.46416. Based on the Boeing 747 operations manual cruise table with two engines inoperative, at 24,000 feet and gross weight of 500,000 pounds, V is 411 KTAS (0.68 Mach).

Case 1: Inboard Engine Failure.

For an inboard engine failure, the asymmetric line of thrust is displaced from the centerline to the inboard operative engine. Therefore, the distance a is equal to 40 feet (BAC, 1981).

Substituting the above values into Equation 13, it follows that:

$$\Phi = 21.22 \left\{ \frac{(40\text{ft}/105\text{ft})}{(17.74)} \right\} = 0.46 \text{ degrees}$$

Case 2: Outboard Engine Failure.

Similarly, for an outboard engine failure, the line of thrust is displaced from the centerline to the outboard operative engine. Thus, the distance c is equal to 70 feet (BAC, 1981).

Substituting the above values into Equation 17, it follows that:

$$\Phi = 21.22 \left\{ \frac{(70\text{ft}/105\text{ft})}{(17.74)} \right\} = 0.80 \text{ degrees}$$

Case 3: Both Inboard and Outboard Engine Failure (same side).

For both engines out (same side), the line of thrust is displaced from the centerline by a distance equal to the sum of the engine offset distances. Thus, the distance $(a+c)$ is equal to 110 feet (BAC, 1981).

Substituting the above values into Equation 21, it follows that:

$$\Phi = 31.83 \left\{ \frac{(110\text{ft}/105\text{ft})}{(17.74)} \right\} = 1.88 \text{ degrees}$$

WIND TUNNEL PROCEDURES

Two airplane models, one of a Boeing 747 and one of a Boeing 767, were used for wind tunnel testing to investigate the hypothesis. The models were manufactured by Pacific Miniatures (PACMIN), a subcontractor of the Boeing Aircraft Company. PACMIN produces the models used by Boeing for various projects.

Each model was fastened on the tare of the force balance in the wind tunnel, using a straight heading and wings-level attitude simulating the cruise condition of the airplane. The drag and side force at this wings-level straight position was measured through the force balance, and displayed on the graphics terminal. The models were then yawed gradually from the straight heading condition to sideslip angles well beyond the predicted maximum, in both the positive and negative direction. Measurements of the drag and the side forces were made and plotted against the yaw angle.

In the wind tunnel experiments, it was not possible to duplicate the asymmetric thrust wings-level flight that, in real airplanes, produces sideslip toward the dead engine(s). However, by varying the model sideslip angle, it was possible to correlate sideslip and the resultant drag increase. Using Equation 9 and similar techniques, the inflight wings-level sideslip angles were estimated for the four airplane and failure mode combinations. By combining theoretical estimates of sideslip with measured drag rises due to sideslip, it was possible to estimate the drag increments resulting from the corresponding real airplane engine-out flight.

The percentage increase in the coefficient of drag corresponding to a failure of a Boeing 767 engine was found to be 6.04%. Also, the increases in the coefficient of drag for the Boeing 747 were obtained as shown in Table 1.

Table 1**Percentage Increase in Drag for Three Different Engine Failure Cases for the Boeing 747 Model**

Case	% Increase in Drag
Inboard Engine Failure	1.25
Outboard Engine Failure	2.17
Both Inboard and Outboard Engine Failure (Same Side)	5.23

Upon initial contemplation, drag increases in the 5-6% range seemed high. This skepticism was reinforced when compared to the small bank angles (1.12-1.88 degrees) expected to neutralize sideslip and produce minimum drag in the real airplane. These predictions were compared to flight experiments performed by Byington (1988) for optimizing engine-out procedures in multi-engine airplanes. In flight tests of three light twins, he showed that flying in the banked, zero slip condition produced drag reductions in the 4-8% range. Corresponding bank angles were 1.5-2.7 degrees. Therefore, Byington's observations bracket the Boeing 767 and Boeing 747 (two-engine) cases, lending credence to the present methodology.

Relationship of Drag to Specific Range

Specific range (SR) is one of the most important items of transport airplane performance and represents the ability of an airplane to convert fuel energy into flying distance. The specific range can be defined by the following relationship:

$$\text{Specific Range} = \frac{\text{Velocity(Knots)}}{\text{Fuel Flow(Pounds per hour)}} \quad (22)$$

Therefore, to relate drag to SR, it will be necessary to relate drag to both velocity (TAS) and fuel flow (FF). Starting with fuel flow, by assuming a constant Thrust Specific Fuel Consumption (TSFC), FF becomes proportional to drag. Relating TAS to drag is somewhat more complicated. TAS is

proportional to the reciprocal of the square root of the density ratio, $1/\sqrt{\sigma}$, where σ is the density ratio. Also, thrust available (T_a) may be assumed proportional to σ over small changes. Observing that thrust available equals drag under conditions of maximum altitude and maximum continuous thrust, then drag is proportional to σ . Therefore, TAS becomes proportional to $1/\sqrt{\text{drag}}$. Combining the two relationships for TAS and FF in the specific range equation, the final relationship of SR to drag resulted:

$$SR = \frac{TAS}{FF} = C \left(\frac{1}{\text{drag} \sqrt{\text{drag}}} \right) = C (\text{drag})^{-3/2} \quad (23)$$

where C is a constant of proportionality. If the engine-out wings-level SR of the airplane (SR_1) is divided by the SR at the zero slip condition (SR_0), the constants of proportionality cancel and the following relationship results:

$$\frac{SR_1}{SR_0} = \frac{(\text{wings level drag after engine failure})^{-3/2}}{(\text{zero sideslip drag after engine failure})^{-3/2}} \quad (24)$$

The wings-level engine-out drag is proportional to the drag coefficient at the sideslip angle resulting from asymmetric thrust (C_{d1}). The zero slip drag is proportional to the drag coefficient for the straight and level position (C_{d0}) as measured in the wind tunnel.

$$\frac{SR_1}{SR_0} = \frac{(C_{d1})^{-3/2}}{(C_{d0})^{-3/2}} = \frac{(C_{d0})^{3/2}}{(C_{d1})^{3/2}} \quad (25)$$

To obtain the percent increase in SR available by banking the airplane to the zero slip position, Equation 25 was inverted.

$$\frac{SR_0}{SR_1} = \frac{(C_{d1})^{3/2}}{(C_{d0})^{3/2}} = \{1 + \text{increase in drag}\}^{3/2} \quad (26)$$

By substituting into Equation 26 the drag increase obtained by testing the Boeing 767 model, the increase in SR for the Boeing 767 was found to equal 9.20%. Similarly, for the Boeing 747 model, Table 2 presents the optimum percentage increase in SR for the three different engine failure cases.

Table 2**Zero Sideslip Percentage Increase in Specific Range for Three Different Engine Failure Cases for the Boeing 747 Model**

Case	% Increase in SR
Inboard Engine Failure	1.88
Outboard Engine Failure	3.27
Both Inboard and Outboard Engine Failure (Same Side)	7.95

These SR increases are approximately 1.5 times the corresponding percentage drag changes shown in Table 1. They presuppose optimum altitude for engine-out flight, and are best case estimates. Conservative constant altitude comparisons would correspond to the lower percentage drag changes previously determined (Table 1).

CONCLUSIONS

Experimental results supported the hypothesis that an optimum bank angle exists for both airplanes, and that this bank angle will reduce drag and increase engine-out specific range significantly. For the Boeing 767, only one type of engine failure was considered. The optimum bank angle, with the increase in specific range achievable in zero sideslip flight, is presented in Table 3.

Table 3**Zero Sideslip Optimum Bank Angles and Percentage Increase in Specific Range for the Boeing 767**

Case	Optimum Bank Angle (Degrees)	Optimum % Increase in SR
Engine Failure	1.12	9.20

Three types of engine failures were considered for the Boeing 747. These were: inboard, outboard, or both inboard and outboard (same side). The optimum bank angles derived for the Boeing 747, with the percentage specific range increase achieved in zero sideslip flight, are presented in Table 4. Incidentally, these values would be applicable to three-engine ferry flight planning.

Table 4

Zero Sideslip Optimum Bank Angles and Percentage Increase in Specific Range for the Three Different Engine Failure Cases for the Boeing 747

Case	Optimum Bank Angle (Degrees)	Optimum % Increase in SR
Inboard Engine Failure	0.46	1.88
Outboard Engine Failure	0.80	3.27
Both Inboard and Outboard Engine Failure (Same Side)	1.88	7.95

The implications of these conclusions influence two distinct areas of flight operations: safety and efficiency.

From the standpoint of safety, flying at zero slip results in minimum drag and maximum specific range for a given cruise altitude. Awareness of these characteristics will benefit the flight crew experiencing one of the rare diversions. The same drag reduction principles apply to optimizing engine-out climb performance, such as at heavy weight following initial takeoff. The many advantages of engine-out, zero slip flight suggest that manufacturers of airplanes and autopilots should investigate feasibility of automated systems. Such systems could more precisely provide optimum zero sideslip bank angles for various failure modes, thrust available, and other flight conditions.

From the economic efficiency standpoint, airplanes and trained crews are capable of achieving the extra engine-out range margins shown above. Hence, with no adverse safety implications, it should be feasible for operators and regulators to reduce the minimum reserve fuel by a related percentage. A

United Airlines (UAL) study showed that it takes fuel to haul fuel (UAL, 1984).

This is especially true on legs of transoceanic length. For example, a Boeing 747-200 on a 4,000 nautical mile flight, with a Take-off Gross Weight of 785,000 pounds would need 210,000 pounds of trip fuel and at least 29,000 pounds of reserve fuel. Because of the demonstrated capability of achieving the extra range margin, Table 2 suggests that the reserve fuel can be reduced about 8%. Therefore, the total reduction in the reserve fuel would be 2320 pounds. The operator could transform this reduction into either more payload or fuel savings. Table 5 shows that a Boeing 747 consumes 35.7 pounds of fuel just to carry 100 pounds of fuel on a 4,000 mile leg. Thus, by reducing the reserve fuel 8%, the resulting fuel savings would be 828 pounds or 127 gallons.

Economic implications worldwide are profound. Awareness of these engine-out optimum range techniques would permit most transoceanic flights to tanker substantially less reserve fuel without increasing risk.

Table 5

Effects of Weight Change on Fuel Burnout

Pounds of Fuel to Carry 100 Pound Increase in Weight Pounds of Fuel Burned to Carry 100 Pounds of Weight				
Nautical Miles	B727	B767	DC-10-30	B747
500	6.6	4.3	4.2	3.9
1000	12.8	8.0	8.6	7.2
2000	26.9	15.7	18.9	15.0
3000		24.0	29.8	24.5
4000			41.5	35.7
5000			53.8	48.8
6000			71.0	68.0

It is suggested that further studies and flight tests be performed in this area by the airplane operators or manufacturers, since they have the equipment and the expertise for a more definitive study. These should be expanded to combine engine-out flight at 10,000-14,000 feet to account for simultaneous loss of an engine and pressurization. Appropriate zero slip bank angles should be made available to flight crews in flight hand books.

Further studies by the operators are suggested to determine the amounts by which the reserve fuel can be reduced in airplanes capable of achieving these increased engine-out range margins. The appropriate government agencies in turn should support studies on the economic and environmental impact of the fuel savings resulting from the reduction of the reserve fuel and corresponding payload improvement.

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