12-1989

Optimized Engine Out Procedures to Extend the Range of Jet Transport Airplanes

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

by
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Thesis Submitted to the
School of Graduate Studies and Research
in Partial Fulfillment of the Requirements for the Degree of
Master of Aeronautical Science

Embry-Riddle Aeronautical University
Daytona Beach, Florida
December 1989

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Charles Richardson, Department of Aeronautical Science, and has been approved by the members of his thesis committee. It was submitted to the School of Graduate Studies and Research and was accepted in partial fulfillment of the requirements for the degree of Master of Aeronautical Science.

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ACKNOWLEDGMENTS

I would like to express my thanks and appreciation to my thesis committee chairman, Dr. Charles Richardson, and to my thesis committee members, Mr. Melville Byington Jr. and Mr. James Lewis, for their advice, assistance and encouragement during the course of my thesis. I would also like to express my thanks to Mr. Charles Eastlake of the Aerospace Engineering Department for his assistance in both the wind tunnel experiments, and his advice on technical matters.

ABSTRACT

Author: Miltos Miltiadous

Title: Optimized Engine Out Procedures to Extend the Range of Jet Transport Airplanes

Institution: Embry-Riddle Aeronautical University

Degree: Master of Aeronautical Science

Year: 1989

The purpose of this study was to develop optimum engine-out procedures for the Boeing 747 and 767 on extended flights that will increase the range of the aircraft in case of engine failure. Theory suggests that an optimum amount of bank angle, that will minimize drag resulting from asymmetric thrust in a multiengine airplane experiencing an engine failure, can be determined. By banking the airplane into the operative engines by that optimum bank angle, the range of the airplane can be improved significantly. Wind tunnel tests of both a Boeing 747 and a 767 model were performed to determine experimentally the increase in range that can be achieved by the zero slip position. By comparing the drag force coefficient obtained at the sideslip position that occurs due to an engine failure with the drag force coefficient obtained at the wings level condition for each airplane, the amount that their specific range will increase was determined.

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Introduction

Until recently, extensive over-water flights were limited, by regulation, to three or four engine aircraft. International Civil Aviation Organization (ICAO) regulations for extended over water flights that are included in Attachment C to Annex 6, Part 1, further state that no airplane may fly on a route where it 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 applies only to four engine airplanes. Unfortunately, ICAO records do not show the origin of this figure and it can only be surmised that it was an empirical rule based upon the capabilities of the airplanes for that period (Mortimer, 1984). The predominant aircraft currently being used in extensive over-water operations is the four engine Boeing 747, because it has a greater flying range and can carry more passengers than most other aircraft.

The Federal Aviation Administration (FAA) has a similar regulation that concerns the operation of twin engine aircraft. The regulation which can be found in part 121 of the Federal Aviation Regulations, states that no airplane may fly on a route where it is more than 60 minutes flying time from a suitable alternate aerodrome after the failure of one engine.

In 1984, however, the rules changed. Based on advisory circular 120-42A that the Federal Aviation Administration (FAA) issued, extended range operations are permitted on routes where the aircraft would be no further than 90 minutes flight time from a suitable airport at single-engine speed. Extended range, two engine aircraft such as the Boeing 767 were approved for extended over-water flights only on certain specific routes that ensure that the aircraft will be able to land within 120 minutes if it experiences an engine problem (O'Lone, 1984).

The new extended range operations of twin engine jets have not been without difficulty. On May 13, 1985, an engine of a Boeing 767 overheated during a step-climb. This led to an engine shutdown and an approximately 2-hour single-engine diversion to Bangor, Maine to avoid marginal weather conditions at the closest airport at Gander, Newfoundland. On June 6, 1985, a loss of engine oil led to an engine shutdown on a Boeing 767 and an approximately 60-minutes single-engine diversion to Keflavic, Iceland, . where the crew executed a single-engine nonprecision approach in marginal weather conditions, because the Instrument Landing System (ILS) at Keflavic was not operative. It should be noted that such an approach is not part of the operator's training syllabus (Howell, 1985).

Statement of the Problem

The purpose of this study is to develop optimum engine-out procedures for the Boeing 747 and 767 on extended flights. These procedures will expand the range of the aircraft in case of engine failure allowing it to reach an aerodrome where the flight crew can successfully execute a safe landing. For the purposes of this study, optimum engine-out procedure is defined as the procedure that should be followed by the flight crew of an aircraft experiencing an engine failure to improve its range performance.

Review of Related Literature

In the case of a multi-engine airplane, the failure of a powerplant does not necessarily constitute a disaster since flight may be continued with the remaining powerplants functioning. However, the performance of a multi-engine aircraft with a powerplant inoperative may be seriously affected for two reasons. Firstly, an asymmetrical thrust condition results when a powerplant fails. This asymmetrical power condition will create a yawing moment on the aircraft which will cause the aircraft to sideslip (Hurt, 1965). This sideslip has two disadvantages. First, it increases the drag that the airplane is experiencing, and second, it decreases the tail fin's angle of attack, adding a weathervaning tendency which compounds the yaw from asymmetric thrust (Byington, 1989). Secondly, if an engine fails during optimum cruise of a turbojet airplane, the airplane must descend to a much lower altitude. The effect of altitude on the range of a turbojet aircraft is of great importance. A decrease in altitude will produce higher inlet air temperature in the operating powerplants which increases the thrust specific fuel consumption. Also, a decrease in altitude requires decreased engine revolutions per minute (RPM) to provide cruise thrust, and the thrust specific fuel consumption increases as the RPM drop below the normal rated RPM. Finally, a decrease in altitude will result in greater density and a lower true airspeed (TAS) for the same amount of thrust (Hurt, 1965).

All of the cited factors seriously affect the performance of a turbojet aircraft, especially its range. In long distance over-water flights, range performance is extremely important when an airplane has an engine failure since it will need to reach an airport suitable for landing.

When an airplane experiences an engine failure, it starts slipping with wings level. Aerodynamic principles indicate that it would be possible to bank the airplane into the operative engine and eliminate the disadvantages caused by this sideslip (Byington, 1989).

Until recently studies performed on this subject related only to light twin-engine aircraft, and none to large transport aircraft. Therefore, very little literature that pertains to this subject is available.

According to the Boeing 747 Operating Manual, when the aircraft experiences an engine failure, it can still cruise successfully, wings level, with the remaining operative engines and land at its original destination. This three-engine wings level cruise will result in severe range penalties. One can speculate that because of these penalties, the aircraft might not reach its destination, since the fuel carried is estimated for a four-engine cruise and not for a three-engine cruise. However, regulatory authorities such as the FAA or ICAO require that each aircraft carry an amount of reserve fuel that will enable it to fly for an additional amount of time in order to safely reach a suitable aerodrome.

Reserve fuel requirements are discussed at some length in part 121 of the Federal Air Regulations (FARs). However, 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 is representative of current airline operational practices (Loftin, 1985).

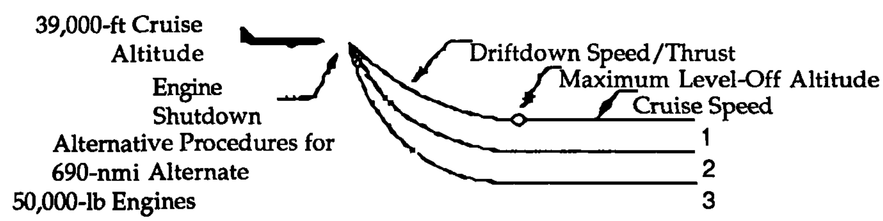
The reserve fuel requirements specified by the ATA for subsonic turbine-powered aircraft employed in international operations are as follows:

1. Fly for 10 percent of trip air time at normal cruise altitude at a fuel flow for end of cruise weight at the speed of 99 percent maximum range.

2. Exercise 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. Descent and land at alternate airport.

In the event of a two engine failure on the 747 or an engine failure on the 767, the Operating Manual of each aircraft states that the crew should initiate a wings level driftdown that will allow them to safely land the aircraft at 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 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).



Standard Day
280,000-lb Gross Weight at Engine Failure

	Driftdown Speed	Cruise Speed After Level-Off	Maximum Continuous Thrust: Level-Off Altitude (ft)	Maximum Continuous Thrust: Time (min)	Maximum Cruise Thrust: Level-Off Altitude (ft)	Maximum Cruise Thrust: 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 an optimum amount of bank angle will minimize drag and assist in counteracting the yawing moment caused by asymmetric thrust in a multi-engine airplane experiencing an engine failure. Therefore, it is hypothesized that by banking the airplane into the operative engine by that optimum bank angle, the range of the airplane can be improved significantly.

Method

Samples

The samples of this study were two aircraft models, one of a Boeing 747 and one of a Boeing 767, used for wind tunnel testing to investigate the hypothesis. The models were manufactured by Pacific Miniatures (PACMIN) which is a subcontractor of the Boeing Aircraft Company. PACMIN produces the models used by Boeing for various projects.

Both models used were exact 1:100 scale models of the two airplanes to ensure that the readings taken during the experiment were as realistic as possible. Also, the models were made of solid fiberglass, allowing them to withstand the forces that will be imposed on them by the wind tunnel during testing.

Instruments

A wind tunnel was used to test the two models. This wind tunnel was manufactured in 1967 by the faculty and students of Embry-Riddle Aeronautical University (ERAU) in Daytona Beach, Florida. It is powered by an eight cylinder engine through an automatic transmission, allowing it to speed up to approximately 100 miles per hour (mph). The test section of the wind tunnel is five feet long, three feet wide, and four feet high. A clamp is used to hold the model aircraft securely in the test section when the wind tunnel is in operation.

The wind tunnel uses a six component force balance designed and built by Aerolab. The force balance measures lift, drag, pitch, yaw, roll, and side force. The output from the force balance goes through an automatic data acquisition and control system manufactured by Hewlett Packard (model

3054C), which converts it from analog to digital and feeds to a Hewlett Packard graphics terminal (model 2848A). The graphics terminal displays graphically the results of the experiment.

Experimental Design

The two models were used to experimentally test the hypothesis. The optimum bank angles and the maximum sideslip angles resulting from an engine-out for the two aircraft were first determined mathematically using aerodynamic principles. When these angles were determined, the two models were tested in the wind tunnel. The increase in drag from the straight and level position to the maximum angle of sideslip was determined. Since the optimum bank angles estimated would result in a zero-slip, minimum drag condition, it was assumed that the drag that would be produced at this condition would approximate the drag produced by the straight and level position. Therefore, the increase in drag determined, is the same as the decrease of drag that would be observed if an aircraft flies at the zero-slip condition as opposed to wings level, when it experiences an engine failure.

The drag force for each aircraft was related to its specific range. Therefore, by comparing the drag force obtained experimentally at the wings level position with the drag force obtained at the maximum sideslip angle for each airplane, the amount by which their specific range will increase was estimated.

Procedure

Each of the two models was fastened on the tare of the force balance in the wind tunnel, utilizing a straight heading, wings level attitude, simulating the cruise condition of the aircraft. The drag force and the side force created at this wings level straight position was measured for both airplanes through the force balance and was displayed on the graphics terminal. The models were then yawed gradually from the straight heading condition to an angle beyond the maximum angle of sideslip that would have been produced by an inoperative engine, in both the positive and negative yaw direction. This operation was conducted at one degree increments. Gradual readings of the drag and the side forces were taken through the force balance and the computer terminal. When the experiment was completed, the graduated readings of the drag and the side force taken were plotted against the yaw angle to observe any trends.

Theory

I. Twin Engine Aircraft

Based on research performed by Byington (1988) for optimizing engine out procedures on multiengine aircraft, it was established that the engine out zero slip bank angle (Φ) for twin engine airplanes depends on the design geometry of each aircraft as well as its thrust to weight ratio as indicated by the following relationship:

$$\Phi = \mathrm{Sin}^{-1} \left\{ \frac{T}{W} \frac{a}{b} \right\} \qquad \text{Equation 1}$$

where T is the thrust (Pounds) that the aircraft is producing, W is the weight (Pounds) of the aircraft, a is the distance (Feet) by which the engine thrust is off-set in an aircraft when one of its engines becomes inoperative (Moment Arm), and b is the longitudinal distance (Feet) between the aircraft center of gravity (CG) and the aerodynamic center of its tail (Byington, 1988).

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

$$\Phi = \text{Sin}^{-1} \left\{ \frac{a/b}{L/D} \right\} \qquad \text{Equation 2}$$

The ratio of L/D was estimated based on the aircraft's best glide ratio, $(L/D)_{max}$. However, it is unlikely that an aircraft 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 approximately equal (Byington, 1988). Thus, since one radian is 57.3 degrees, equation 2 was rearranged to:

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

The sideslip angle resulting from an engine out condition, assuming that the pilot takes no action, can be estimated based on the following equation (Roskam, 1972) :

$$\beta_{max} = \{ \frac{(N_T)}{C_{n_\beta}\ q\ S\ b} \} \qquad \text{Equation 4}$$

where (N_T) is the yawing moments 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 Inch), S is the area of the wings (Square Feet), b is the wing span (Feet), and is the variation of the yawing moment coefficient with sideslip angle (Roskam, 1972).

The dynamic pressure q is given by the following equation:

$$q = \frac{\sigma V^2}{295} \qquad \text{Equation 5}$$

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

$$\beta_{max} = \{ \frac{295\ (T\ a)}{C_{n_\beta}\ \sigma V^2\ S\ b} \} \qquad \text{Equation 6}$$

The thrust produced by the aircraft's operative engine is equal to the total thrust which in turn is equal to the drag produced, thus:

$$T = D = \frac{W}{(L/D)} \qquad \text{Equation 7}$$

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:

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

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

$$\beta_{max} = \{ \frac{295\ (W\ a)}{(0.9\ (L/D)_{max})\ C_{n_\beta}\ \sigma V^2\ S\ b} \}$$ Equation 9

A. Boeing 767

One case was considered for the Boeing 767. The parameters that need to be defined in order to obtain the optimum amount of bank angle that will produce 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, the distance b is equal to 85 feet (Boeing 767, Airport Characteristics - Airport Planning, 1989).

Also, based on Equation 9, the parameters that need to be defined in order to obtain the angle of sideslip that will be produced by an engine out condition are: W, a, $(L/D)_{max}$, C_{n_b}, σ, V, S and b. For large transport aircraft, C_{n_b} is equal to approximately 0.09 (Roskam, 1972). For the Boeing 767-200, S equals 3,050 ft^2 (Lan & Roskam, 1981), b is equal to 156 ft (Boeing 767, Airplane Characteristics - Airport Planning, 1989).

For the purposes of this case, a flight altitude of 39,000 feet is assumed. After an engine failure occurs the aircraft is assumed to level off at an altitude of 27,000 feet, thus, σ is equal to 0.41729. Based on the Boeing 767 Operations Manual long cruise table with one engine inoperative, for an altitude of 27,000 ft and a gross weight 270,000 lbs, V is equal to 492 kts (0.79 Mach).

B. Case 1: Engine Failure

In case of engine failure on the Boeing 767, the line of thrust is displaced from the centerline of the aircraft by a distance a which is equal to 26 feet (Boeing 767, Airplane Characteristics - Airport Planning, 1989).

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

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

Also, equation 6 yields:

$$\beta_{max} = \frac{\{295(270{,}000)(26)\}}{\{(0.9)(17.6)(0.09)(0.41729)(492)^2(3050)(156)\}} = 0.0302 \text{ radians.}$$

Since 1 radian equals approximately 57.3 degrees, the above calculated angle of 0.0302 radians corresponds to 1.73 degrees.

II. Four Engine Aircraft

For a four engine airplane the above equations need to be modified before they are implemented. The items that require modification are the moment arm a' and the thrust T. The moment arm will differ with the type of engine failure, i.e., inboard, outboard or both engines on same side.

A. Inboard Engine Failure

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

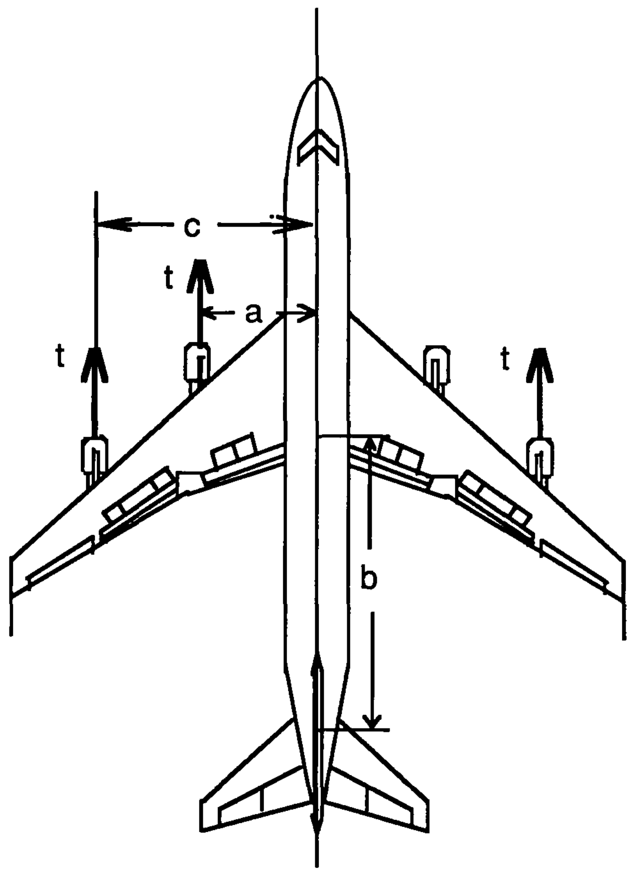


Figure 2. Schematic of an Inboard Engine Failure on a Four Engine Aircraft.

Based on the above, equation 1 was modified to represent an inboard engine failure of a four engine aircraft:

$$\Phi = \mathrm{Sin}^{-1}\left\{\frac{t}{W}\,\frac{a}{b}\right\} \qquad \text{Equation 10}$$

Since, t is only one third of the total available thrust and since the total thrust produced by a four engine aircraft is equal to the drag produced, it can be deduced that $t = D/3$. Also, lift (L) is assumed to be equal to weight (W). Substituting the above relationships in equation 10, the following equation results:

$$\Phi = \mathrm{Sin}^{-1}\left\{\frac{D}{3L}\,\frac{a}{b}\right\} \qquad \text{Equation 11}$$

Equation 11 can be rearranged to:

$$\Phi = \mathrm{Sin}^{-1}\,\frac{1}{3}\left\{\frac{a/b}{L/D}\right\} \qquad \text{Equation 12}$$

The ratio of L/D was estimated based on the aircraft best glide ratio $(L/D)_{max.}$ However, as stated earlier, it is unlikely that an aircraft 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 approximately equal (Byington, 1988). Thus, since one radian is 57.3 degrees, equation 12 was rearranged to:

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

Equation 6 also needs to be modified for this specific case. This can be achieved by substituting t in the place of T. Thus equation 6 becomes:

$$\beta_{max} = \{ \frac{295\ (t\ a)}{C_{n_\beta}\ \sigma V^2\ S\ b} \} \quad \text{Equation 14}$$

As mentioned earlier, for three engines operating, the thrust produced by each of the aircraft's operative engines is equal to the total thrust divided by three, thus:

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

As stated above, the L/D ratio is assumed to be approximately $0.9(L/D)_{max}$ (Byington, 1988). Thus, equation 15 can be modified to:

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

Based on equation 16, equation 14 can be modified to:

$$\beta_{max} = \{ \frac{295\ (W\ a)}{(2.7\ (L/D)_{max})\ C_{n_\beta}\ \sigma V^2\ S\ b} \} \quad \text{Equation 17}$$

B. Outboard Engine Failure

Similarly, for an outboard engine failure the moment arm a' needs to be defined. Since both inboard engines produce equal thrust (t), the resulting moments from these engines are equal and opposite, thus they cancel out. The only other moment left is that created by the remaining operative outboard engine, thus the moment arm is equal to distance c shown in Figure 3.

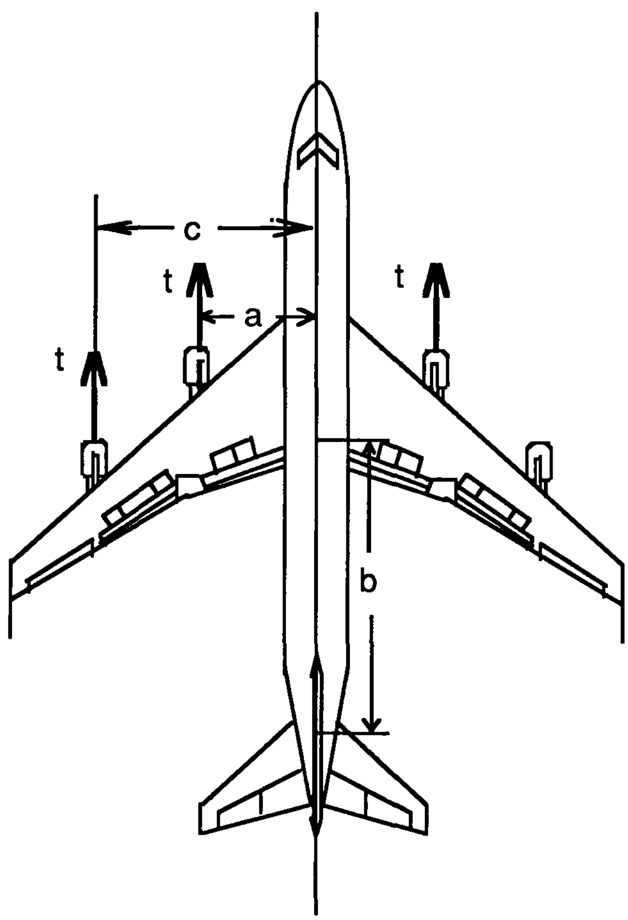


Figure 3. Schematic of an Outboard Engine Failure on a Four Engine Aircraft.

The outboard engine failure case is very similar to the inboard engine failure case, with only the difference of the moment arm distance. Therefore, equations 13 and 17 can be modified for this type of engine failure by substituting the distance c in place of distance a. Thus equations 13 and 17 were modified to read:

$$\Phi = \frac{57.3}{3}\left\{\frac{c/b}{0.9(L/D)_{max}}\right\} = 21.22\left\{\frac{c/b}{(L/D)_{max}}\right\} \qquad \text{Equation 18}$$

$$\beta_{max} = \left\{\frac{295\ (W\ c)}{(2.7\ (L/D)_{max})\ C_{n_\beta}\ \sigma V^2\ S\ b}\right\} \qquad \text{Equation 19}$$

C. 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 . In this case, both inboard and outboard operative engines produce equal thrust (t), thus the resulting moments from these engines are added. The resulting moment arm a' is equal to the sum of the moment arm distances of each operative engine (a and c), thus the moment arm for this case is equal to a+c (see Figure 4).

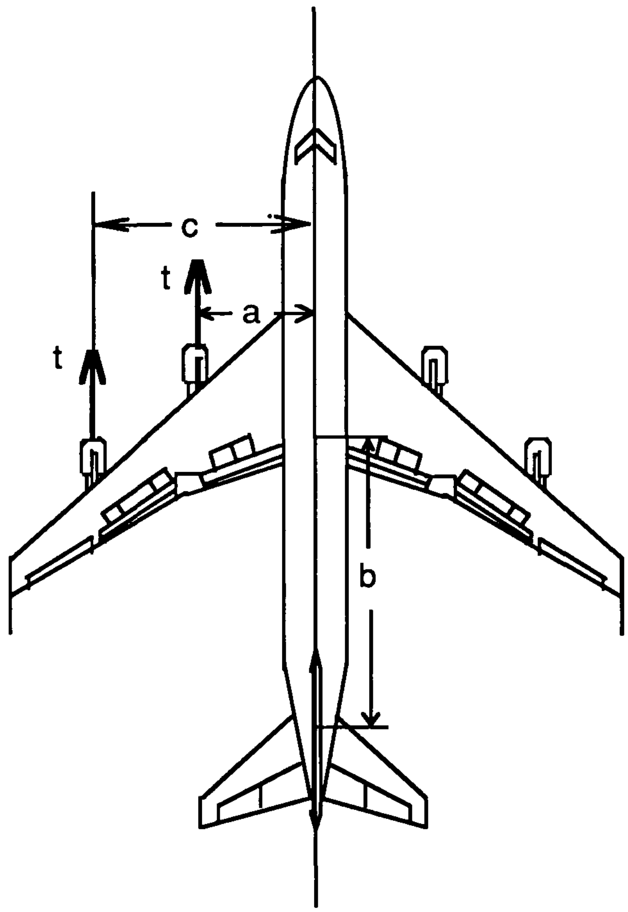


Figure 4. Schematic of Both an Inboard and Outboard Engine Failure (same side) on a Four Engine Aircraft.

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

$$\Phi = \mathrm{Sin}^{-1} \{ \frac{t}{W} \frac{(a+c)}{b} \}$$ Equation 20

Since, t is only one half of the total available thrust and since the total thrust produced by a four engine aircraft is equal to the drag produced, it can be deduced that t = D/2. Also, lift (L) is equal to weight (W). Substituting the above relationships in equation 20, the following equation results:

$$\Phi = \mathrm{Sin}^{-1} \left\{ \frac{D}{2L} \frac{(a+c)}{b} \right\} \qquad \text{Equation 21}$$

Equation 21 can be rearranged to:

$$\Phi = \mathrm{Sin}^{-1} \frac{1}{2} \left\{ \frac{(a+c)/b}{L/D} \right\} \qquad \text{Equation 22}$$

As stated earlier, 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 approximately equal (Byington, 1988). Thus, since one radian is 57.3 degrees, equation 22 was rearranged to:

$$\Phi = \frac{57.3}{2} \left\{ \frac{(a+c)/b}{0.9(L/D)_{max}} \right\} = 31.83 \left\{ \frac{(a+c)/b}{(L/D)_{max}} \right\} \qquad \text{Equation 23}$$

Equation 6 also needs to be modified for this specific case. This can be achieved by substituting t in place of T, and (a+c) in place of a. Thus equation 6 becomes:

$$\beta_{max} = \left\{ \frac{295\ (t\ (a+c))}{C_{n\beta}\ \sigma V^2\ S\ b} \right\} \qquad \text{Equation 24}$$

As mentioned earlier, for two engines operating, the thrust produced by each of the aircraft's operative engines is equal to one half of the total thrust, thus:

$$t = \frac{T}{2} = \frac{D}{2} = \frac{W}{2(L/D)} \qquad \text{Equation 25}$$

As stated above, the L/D ratio is assumed to be approximately $0.9(L/D)_{max}$ (Byington, 1989). Thus, equation 25 can be modified to:

$$t = \frac{W}{((0.9)(2)(L/D)_{max})} = \frac{W}{(1.8)(L/D)_{max}}) \qquad \text{Equation 26}$$

Based on equation 26, equation 24 can be modified to:

$$\beta_{max} = \{ \frac{295\ (W\ (a+c))}{(1.8\ (L/D)_{max})\ C_{n\beta}\ \sigma V^2\ S\ b} \} \qquad \text{Equation 27}$$

D. Boeing 747

Three different cases were considered for the Boeing 747. Based on equation 3 the parameters that need to be defined in order to obtain the optimum amount of bank angle that will produce the zero slip condition are: the $(L/D)_{max}$ and the a/b ratios. Both the $(L/D)_{max}$ ratio and the distance b are assumed to be the same for all three cases. For the Boeing 747-200, $(L/D)_{max}$ equals 17.74 (Lan & Roskam, 1981). Also, assuming a mid center of gravity, the distance b is equal to 105 feet (Boeing 747, Airplane Characteristics - Airport Planning, 1981).

Also, based on Equation 10, the parameters that need to be defined in order to obtain the angle of sideslip that will be produced by an engine out condition are: W, a, $(L/D)_{max}$, C_{n_b}, σ, V, S and b. From these parameters, S and b are the same for all three cases. For large transport aircraft, C_{n_b} is equal to approximately 0.09 (Roskam, 1972), and it is assumed to be constant for all three cases.

For the Boeing 747-200, S equals to 5500 ft^2 (Lan & Roskam, 1981); b is equal to 196 ft (Boeing 747, Airplane Characteristics - Airport Planning, 1981).

For the first two cases, a flight altitude of 35,000 feet is assumed. After an engine failure occurs the aircraft is assumed to level off at an altitude of 31,000 feet, thus, σ is equal to 0.36053. Based on the Boeing 747 operations manual long cruise table with one engine inoperative, for an altitude of 31,000 ft and a gross weight 500,000 lbs, V is equal to 488 kts (0.766 Mach).

For the third case, a flight altitude of 35,000 feet is assumed. After an engine failure occurs the aircraft is assumed to level off at an altitude of 24,000 feet, thus, σ is equal to 0.46416. Based on the Boeing 747 operations manual cruise table with two engines inoperative, for an altitude of 24,000 ft and a gross weight 500,000 lbs, V is equal to 411 kts (0.68 Mach).

E. Case 1: Inboard Engine Failure

In case of an inboard engine failure, since the outboard engines are still producing an equal amount of thrust, the line of thrust is displaced from the centerline of the aircraft to the inboard operative engine.

Therefore, the distance a is equal to 40 feet (Boeing 747, Airplane Characteristics - Airport Planning, 1981).

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

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

Also, equation 17 yields:

$$\beta_{max} = \frac{\{295(500{,}000)(40)\}}{\{(2.7)(17.7)(0.09)(0.36053)(488)^2(5500)(196)\}} = 0.0148 \text{ radians}$$

Since 1 radian equals approximately 57.3 degrees, the above calculated angle of 0.0148 radians corresponds to 0.85 degrees.

F. Case 2: Outboard Engine Failure

Similarly, in case of an outboard engine failure, since the inboard engines are still producing an equal amount of thrust, the line of thrust is displaced from the centerline of the aircraft to the outboard operative engine. Thus, the distance c is equal to 70 feet (Boeing 747, Airplane Characteristics - Airport Planning, 1981).

Substituting the above values into equation 18, it follows that:

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

Also, equation 19 yields:

$$\beta_{max} = \frac{\{295(500{,}000)(70)\}}{\{(2.7)(17.7)(0.09)(0.36053)(488)^2(5500)(196)\}} = 0.0259 \text{ radians}$$

Since 1 radian equals approximately 57.3 degrees, the above calculated angle of 0.0259 radians corresponds to 1.48 degrees.

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

Similarly, in case of both an inboard and outboard engine failure, the line of thrust is displaced from the centerline of the aircraft by a distance equal to the sum of the distances of both operative inboard and outboard engines from the centerline respectively. Thus, the distance (a+c) is equal to 110 feet (Boeing 747, Airplane Characteristics - Airport Planning, 1981).

Substituting the above values into equation 23, it follows that:

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

Also, equation 27 yields:

$$\beta_{max} = \frac{\{295(500{,}000)(110)\}}{\{(1.8)(17.7)(0.09)(0.46416)(411)^2(5500)(196)\}} = 0.0669 \text{ radians}$$

Since 1 radian equals approximately 57.3 degrees, the above calculated angle of 0.0669 radians corresponds to 3.83 degrees.

Analysis

Both models were tested in the Embry-Riddle Aeronautical University wind tunnel according to the experimental design. For every model the following data were collected as a function of the yaw angle: Coefficient of drag (C_d) and coefficient of sideforce (C_h). Also the coefficient of drag (Tare C_d) and the coefficient of sideforce (Tare C_h) of the force balance were measured. By subtracting the Tare C_d from C_d and the Tare C_h from C_h, the Net C_d and Net C_h were obtained.

I. Experimental Results for the Boeing 767 Model

For the Boeing 767 model the data as shown in Table 1 were collected:

Table 1

Experimental Results of the Boeing 767 Model Yaw Test

Yaw Angle (Degrees)	C_d	Tare C_d	C_h	Tare C_h	Net C_d	Net C_h
-5	.2278	.1634	-.05270	-.002217	.0644	-.050483
-4	.2270	.1634	-.04381	-.002217	.0636	-.041593
-3	.2257	.1634	-.04370	-.002217	.0623	-.041483
-2	.2255	.1634	-.03824	-.002217	.0621	-.036023
-1	.2217	.1634	-.02379	-.002217	.0583	-.021573
0	.2208	.1634	-.008241	-.002217	.0574	-.006024
1	.2229	.1634	.01160	-.002217	.0595	.013817
2	.2269	.1634	.02425	-.002217	.0635	.026467
3	.2272	.1634	.04355	-.002217	.0638	.045767
4	.2319	.1634	.04635	-.002217	.0685	.048567
5	.2353	.1634	.06004	-.002217	.0719	.062257

Based on the results shown on Table 1, the net C_d versus yaw angle (see Figure 5), and the Net C_h versus yaw angle (see Figure 6) were plotted.

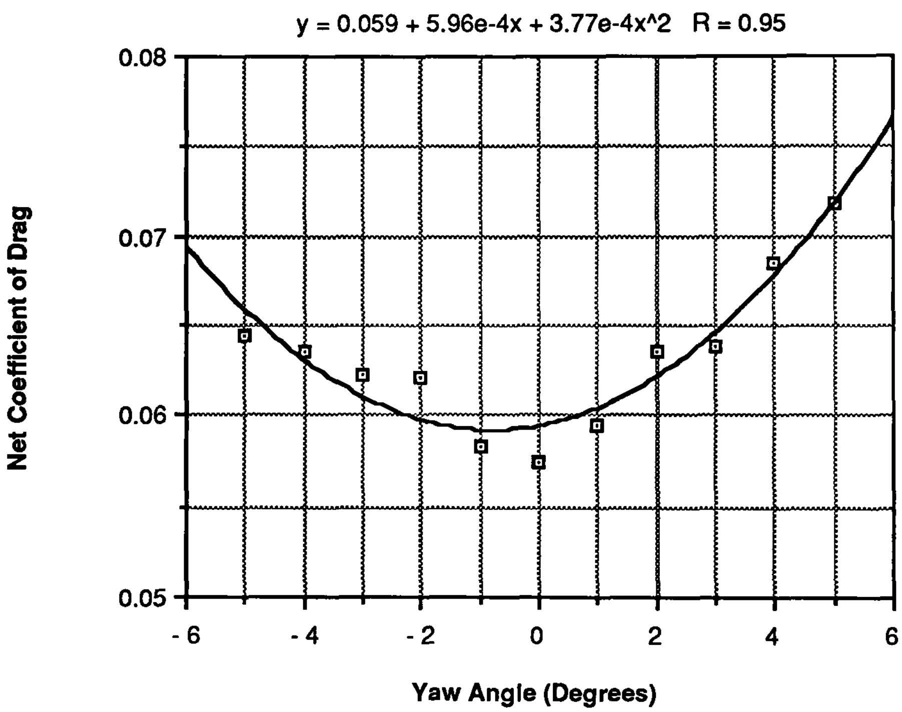


Figure 5. Net Coefficient of Drag Versus Yaw Angle for the Boeing 767 Model

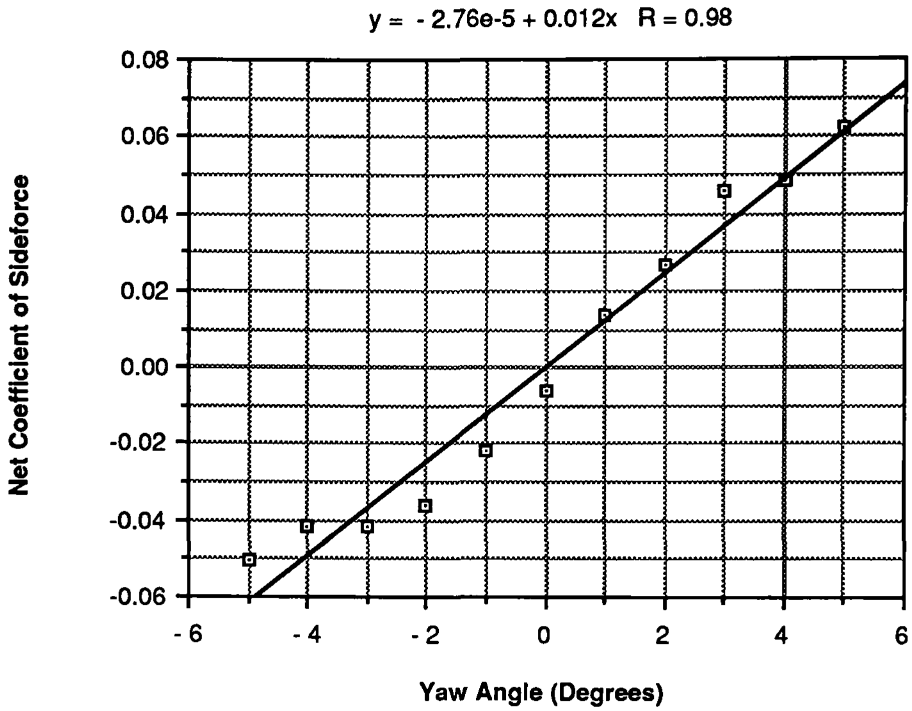


Figure 6. Net Coefficient of Sideforce Versus Yaw Angle for the Boeing 767 Model.

From Figure 5, it can be seen that the drag increases when the aircraft deviates from the zero yaw angle (straight heading), as it was the case with the Boeing 747 model. However, as it was observed before, the drag increase for the positive yaw angle is not symmetrical to that of the negative yaw angles. This lack of symmetry was attributed to the mechanical tolerance of the wind tunnel mounting system and the low Reynolds number that was achieved in the wind tunnel with this scale of a model. Therefore, in order to observe the drag increase that occurs as the aircraft is yawed, the C_d was averaged for symmetrical points so that only one curve was obtained. Table 2 presents the data used for this procedure.

Table 2

Averaging the Net C_d for Symmetrical Yaw Angles for the Boeing 767 Model

Yaw Angle	Net C_d	Yaw Angle	Net C_d	Average C_d
5	.0719	-5	.0644	.06815
4	.0685	-4	.0636	.06605
3	.0638	-3	.0623	.06305
2	.0635	-2	.0621	.06280
1	.0595	-1	.0583	.05890
0	.0574	0	.0574	.05740

Based on Table 2, the Averaged C_d versus the yaw angle was plotted (see Figure 7).

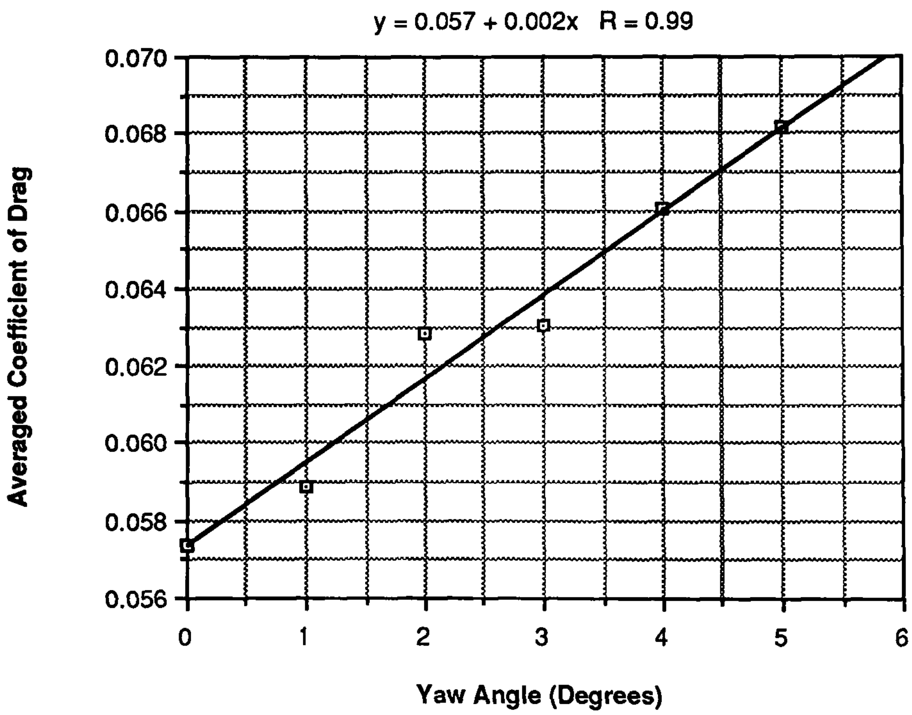


Figure 7. Averaged Coefficient of Drag Versus Yaw Angle for the Boeing 767 Model.

Based on the Boeing 767 geometry, as stated in the theory the a/b ratio that corresponds to an engine failure is 0.30.

As stated above, when an engine failure occurs the a/b ratio is equal to the sideforce (H) over the drag (D) ratio which in turn is equal to the ratio of the coefficient of the sideforce (C_h) to the coefficient of the drag (C_d). Therefore, to get the experimental sideslip angle for the Boeing 767 model, it was necessary to plot the ratio of the C_h to C_d (C_h/C_d) versus the yaw angle (see Figure 8).

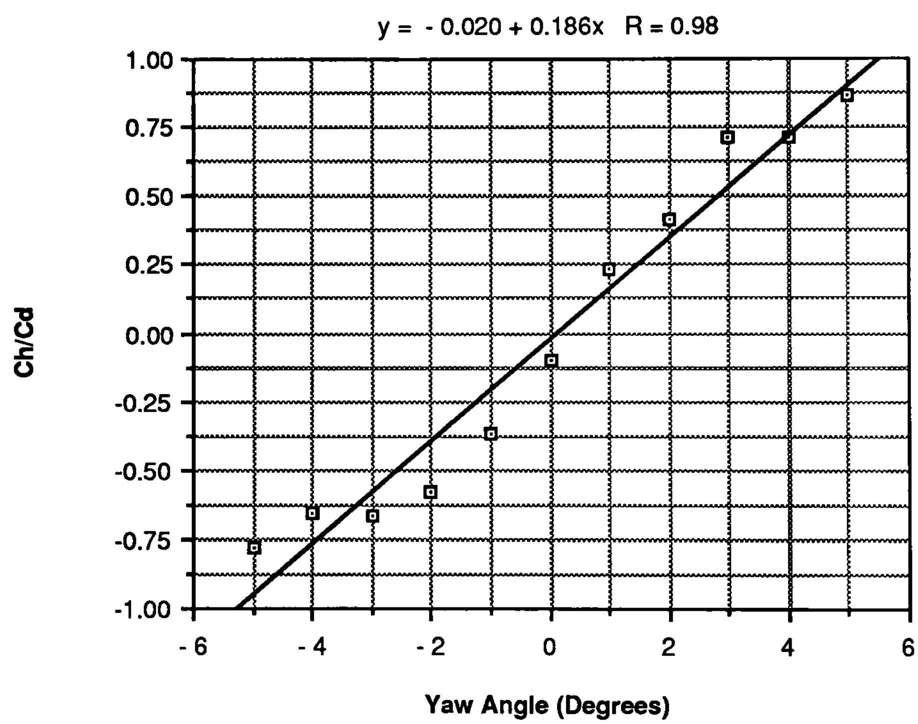


Figure 8. Coefficient of Sideforce over the Coefficient of Drag Ratio (C_h/C_d) Versus Yaw Angle for the Boeing 767 Model.

For $a/b = C_h/C_d = 0.30$, a graphical solution from Figure 8 yields that the sideslip angle produced would be $\beta = 1.72$ degrees.

Based on Figure 7, by substituting the value of the sideslip angle in the equation of the best fit line for the Coefficient of Drag versus Yaw angle, the corresponding coefficient of drag resulting from the simulated engine failure (C_{d1}) was obtained. By dividing the coefficient of drag for the sideslip angle by that of straight and level heading (C_{d0}), the increase in the coefficient of drag was obtained and converted into percentage. The C_{d1}/C_{d0} for the Boeing 767 model was found to be 1.0604, thus the percentage of increase in the C_d corresponding to a failure of a Boeing 767 engine was found to be 6.04 %.

II. Experimental Results for the Boeing 747 Model

For the Boeing 747 model the data shown in Table 3 were collected:

Table 3

Experimental Results of the Boeing 747 Model Yaw Test

Yaw Angle (Degrees)	Cd	Tare Cd	Ch	Tare Ch	Net Cd	Net Ch
5	.1435	.0879	.072430	.001133	.0556	.071297
4	.1406	.0879	.060900	.001133	.0527	.059767
3	.1384	.0879	.037140	.001133	.0505	.036007
2	.1380	.0879	.020510	.001133	.0501	.020396
1	.1379	.0879	.018004	.001133	.0500	.016871
0	.1368	.0879	.002916	.001133	.0489	.001783
-1	.1376	.0879	-.007900	.001133	.0497	-.009033
-2	.1384	.0879	-.007279	.001133	.0505	-.008412
-3	.1387	.0879	-.020210	.001133	.0508	-.021343
-4	.1406	.0879	-.029920	.001133	.0527	-.031053
-5	.1420	.0879	-.047430	.001133	.0541	-.048563

Based on Table 3, the net C_d versus yaw angle (see Figure 9), and the Net C_h versus yaw angle (see Figure 10) were plotted.

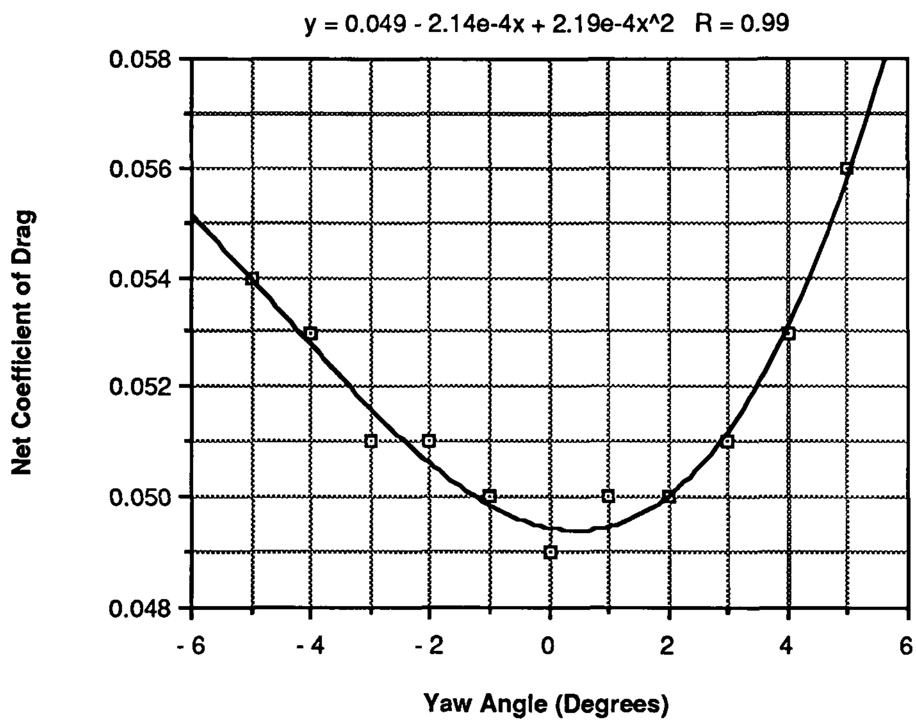


Figure 9. Net Coefficient of Drag Versus Yaw Angle for the Boeing 747 Model.

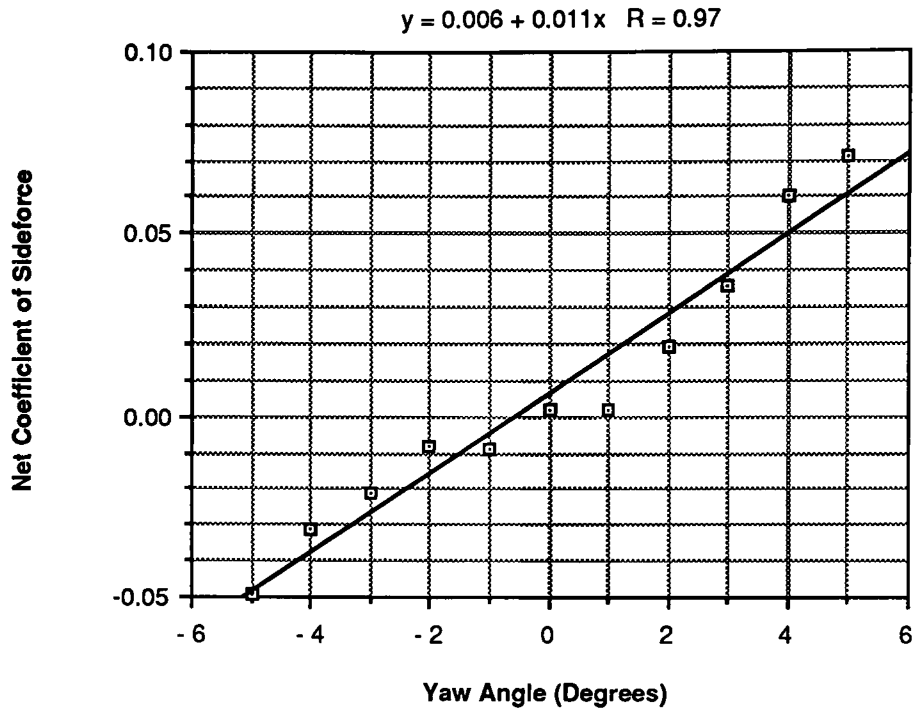


Figure 10. Net Coefficient of Sideforce Versus Yaw Angle for the Boeing 747 Model.

From Figure 10 it can be seen that when the yaw angle is equal to zero, the coefficient of the sideforce has a value of 0.006 instead of zero. It is concluded that a calibration error existed in the experiment, since when the yaw angle is zero, the coefficient of the sideforce should be zero. To account for this calibration error, zero yaw angle was defined to be where the coefficient of the sideforce is equal to zero, which is at a yaw angle of -0.55 degrees. Thus, the yaw angles were corrected by adding 0.55 degrees to each one of them. Table 4 presents the corrected experimental data of the Boeing 747 model.

Table 4

Corrected Experimental Results of the Boeing 747 Model Yaw Test

Yaw Angle (Degrees)	Corrected Yaw Angle (Degrees)	Cd	Tare Cd	Ch	Tare Ch	Net Cd	Net Ch
5	5.55	.1435	.0879	.072430	.001133	.0556	.071297
4	4.55	.1406	.0879	.060900	.001133	.0527	.059767
3	3.55	.1384	.0879	.037140	.001133	.0505	.036007
2	2.55	.1380	.0879	.020510	.001133	.0501	.020396
1	1.55	.1379	.0879	.018004	.001133	.0500	.016871
0	0.55	.1368	.0879	.002916	.001133	.0489	.001783
-1	-0.45	.1376	.0879	-.007900	.001133	.0497	-.009033
-2	-1.45	.1384	.0879	-.007279	.001133	.0505	-.008412
-3	-2.45	.1387	.0879	-.020210	.001133	.0508	-.021343
-4	-3.45	.1406	.0879	-.029920	.001133	.0527	-.031053
-5	-4.45	.1420	.0879	-.047430	.001133	.0541	-.048563

Based on Table 4, the net C_d versus the corrected yaw angle (see Figure 11), and the Net C_h versus the corrected yaw angle (see Figure 12) were plotted.

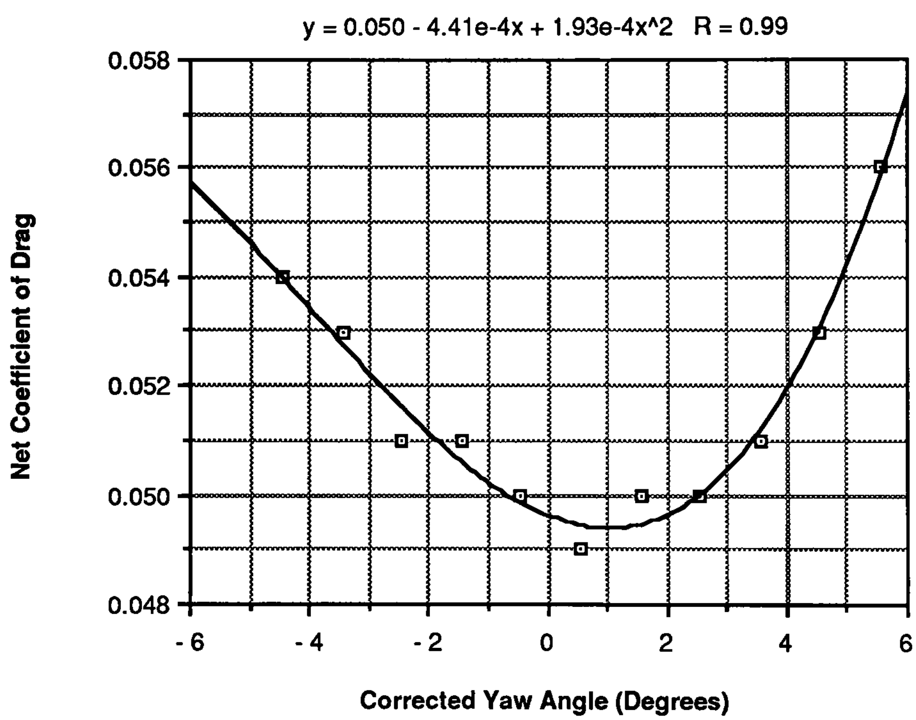


Figure 11. Net Coefficient of Drag Versus Corrected Yaw Angle for the Boeing 747 Model.

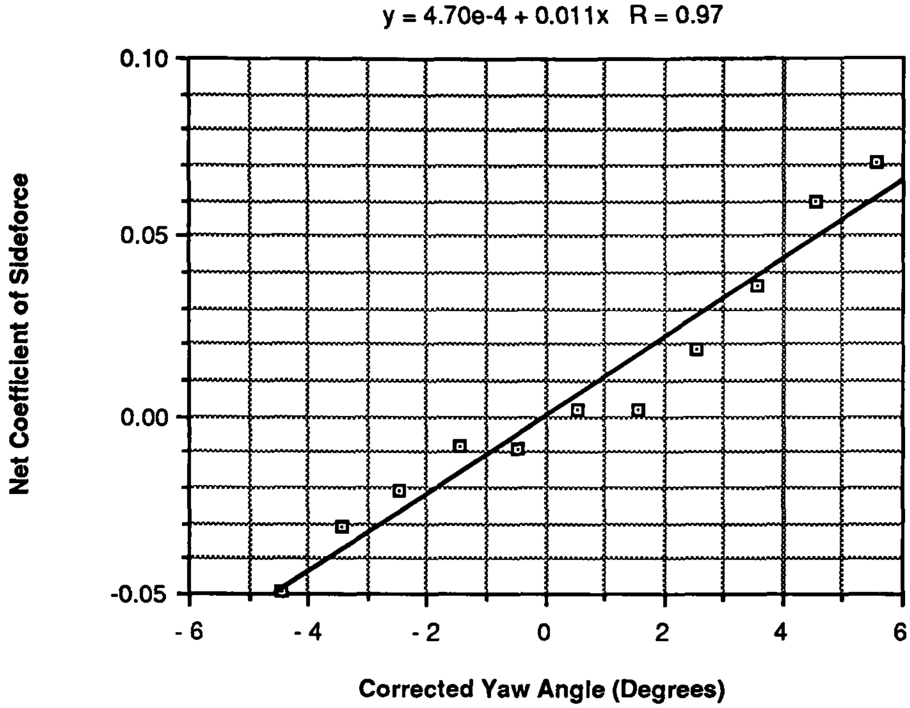


Figure 12. Net Coefficient of Sideforce Versus Corrected Yaw Angle for the Boeing 747 Model.

From Figure 11, it can be seen that the drag increases when the aircraft deviates from the zero yaw angle (straight heading). However the drag increase for the positive yaw angle was not symmetrical to that of the negative yaw angles. This lack of symmetry was attributed to the mechanical tolerance of the wind tunnel mounting system and the low Reynolds number that was achieved in the wind tunnel with this scale of a model. In order to estimate the drag increase that occurs as the aircraft is yawed, the C_d was averaged for symmetrical points so that one curve was obtained. Table 5 presents the data used for this procedure.

Table 5

Averaging the Net C_d for Symmetrical Yaw Angles for the Boeing 747 Model

Yaw Angle	Net C_d	Yaw Angle	Net C_d	Average C_d
5	.0556	-5	.0541	.05485
4	.0527	-4	.0527	.05270
3	.0505	-3	.0508	.05065
2	.0501	-2	.0505	.05030
1	.0500	-1	.0497	.04985
0	.0489	0	.0489	.04890

Based on Table 5, the Averaged C_d versus the yaw angle was plotted (see Figure 13).

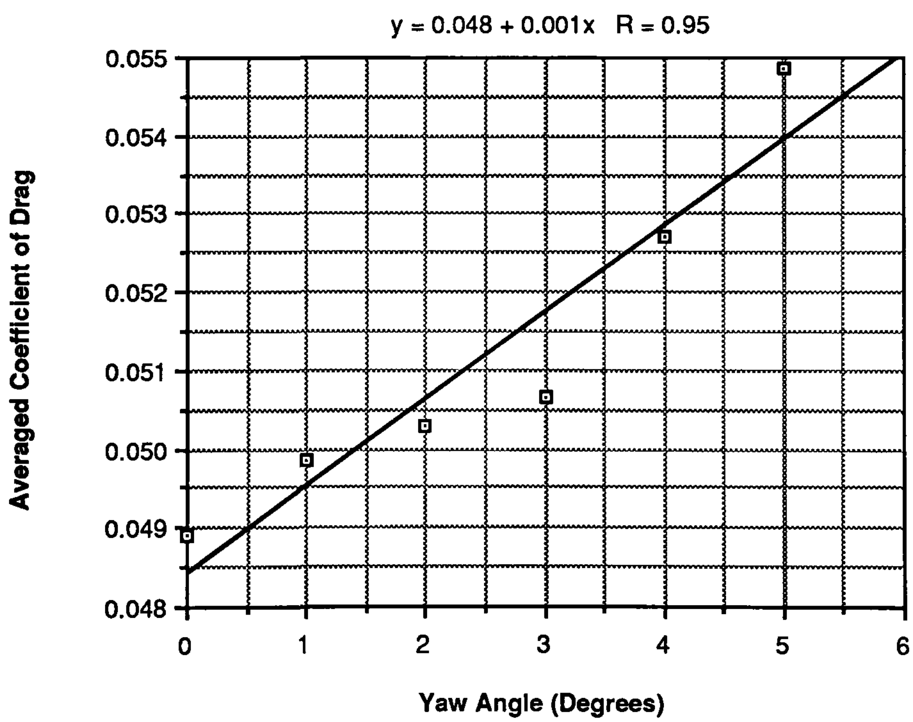


Figure 13. Averaged Coefficient of Drag Versus Yaw Angle for the Boeing 747 Model.

Based on the Boeing 747 geometry there are three different a'/b ratios, where a' is the moment arm corresponding to three different types of engine failure, i.e., inboard engine failure, outboard engine failure, and both inboard and outboard engine failure at the same side, and b is the longitudinal distance between the aircraft center of gravity (CG) and the aerodynamic center of its tail. The a'/b ratios corresponding to the various cases are presented in Table 6.

Table 6

Different a'/b Ratios for the Three Different Engine Failure Cases for the Boeing 747 Model

Case	a'/b Ratio
Inboard Engine Failure	0.13
Outboard Engine Failure	0.22
Both Inboard and Outboard Engine Failure (Same Side)	0.52

When an engine failure occurs the a/b ratio is equal to the sideforce (H) divided by the drag (D) ratio which in turn is equal to the ratio of the coefficient of the sideforce (C_h) to the coefficient of the drag (C_d). Therefore, to get the experimental sideslip angles it was necessary to plot the ratio of the C_h to C_d (C_h/C_d) versus the corrected yaw angle (see Figure 14).

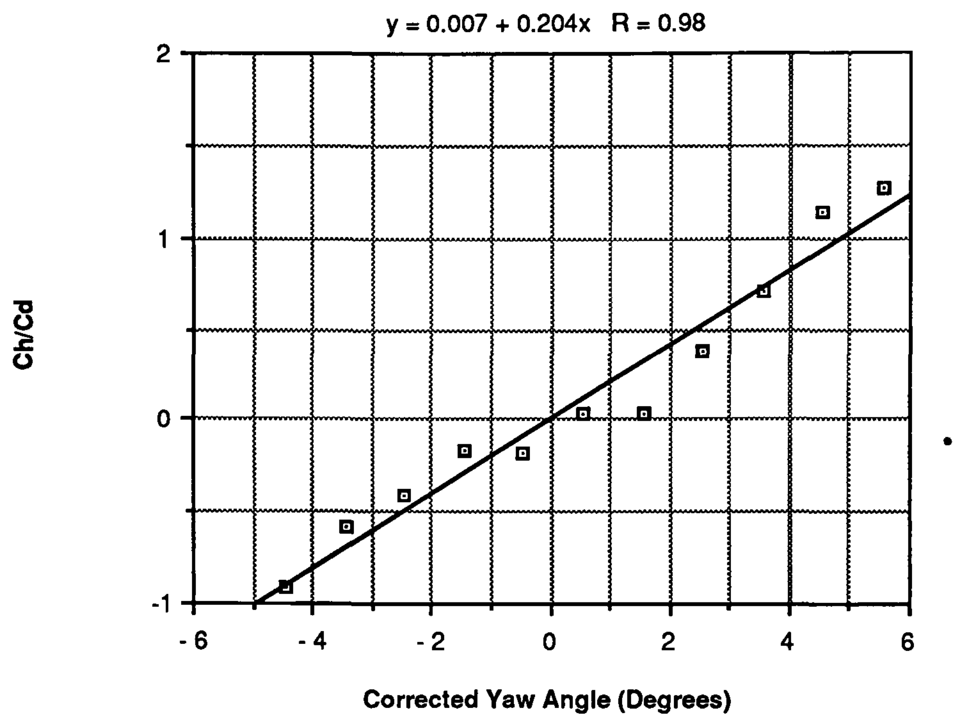


Figure 14. The Coefficient of Sideforce Divided by the Coefficient of Drag Ratio (C_h/C_d) Versus Corrected Yaw Angle for the Boeing 747 Model.

For the case of an inboard engine failure, using $a/b = C_h/C_d = 0.13$, a graphical solution from Figure 12 yields that the sideslip angle produced would be $\beta = 0.60$ degrees. Similarly, the sideslip angles for the other two cases were found and are presented in Table 7.

Table 7

Sideslip Angles Produced for the Three Different Engine Failure Cases for the Boeing 747 Model

Case	Sideslip Angle (Degrees)
Inboard Engine Failure	0.60
Outboard Engine Failure	1.04
Both Inboard and Outboard Engine Failure (Same Side)	2.51

Based on Figure 13, by substituting the three values of the sideslip angles in the equation of the best fit line for the Coefficient of Drag versus Yaw angle, the corresponding coefficients of drag resulting from the simulated engine failures (C_{d1}) were obtained. By dividing the coefficient of drag for the three sideslip angles by that of straight and level heading (C_{d0}), the increases in the coefficient of drag were obtained, and converted into percentages (See Table 8).

Table 8

Percentage of Increase in Drag for the Three Different Engine Failure Cases for the Boeing 747 Model.

Case	C_{d1}/C_{d0}	% Increase in Drag
Inboard Engine Failure	1.0125	1.25
Outboard Engine Failure	1.0217	2.17
Both Inboard and Outboard Engine Failure (Same Side)	1.0523	5.23

III. Relationship of Drag to Specific Range

Specific range (SR) is one of the most important items of aircraft 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:

$$\text{Specific Range} = \frac{\text{Velocity (Knots)}}{\text{Fuel Flow (Pounds per hour)}} \qquad \text{Equation 28}$$

Therefore, in order 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), then FF is proportional to drag. Relating TAS to drag is somewhat more complicated. TAS is proportional to SMOE, which is equal to the inverse of the square root of the density ratio (σ). Therefore, TAS is proportional to $1/\sqrt{\sigma}$. However, thrust available (Ta) may be assumed approximately proportional to σ. Assuming that thrust available is equal to drag at maximum altitude and maximum continuous thrust, then drag is proportional to σ. Therefore, TAS is 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 was obtained:

$$SR = \frac{TAS}{FF} = C\left(\frac{1}{\text{drag}\sqrt{\text{drag}}}\right) = C\,(\text{drag})^{-3/2} \qquad \text{Equation 29}$$

where C is a constant of proportionality.

Based on the above relationship, if the SR of the aircraft after an engine failure occurs (SR_1) is divided by the SR of the aircraft at the zero slip position which is approximated by the SR of the aircraft with all engines operating (SR_0), then the constants of proportionality cancel out, and the following relationship results:

$$\frac{SR_1}{SR_0} = \frac{(\text{drag after engine failure})^{-3/2}}{(\text{drag before engine failure})^{-3/2}} \qquad \text{Equation 30}$$

The wings level drag after engine failure, however, is proportional to the coefficient of drag at the sideslip angle that occurs because of the asymmetric thrust (C_{d1}), and the wings level drag is proportional to the coefficient of drag for the straight and level position (C_{d0})

$$\frac{SR_1}{SR_0} = \frac{(C_{d1})^{-3/2}}{(C_{d0})^{-3/2}} = \frac{(C_{d0})^{3/2}}{(C_{d1})^{3/2}}$$ Equation 31

In order to obtain the percent increase in SR that will be produced by banking the aircraft to the zero slip position, equation 31 had to be inverted.

$$\frac{SR_0}{SR_1} = \frac{(C_{d1})^{3/2}}{(C_{d0})^{3/2}}$$ Equation 32

By substituting the value of $C_{d1}/C_{d0} = 1.0604$, obtained from testing the Boeing 767 model, into equation 32, the percentage of increase in SR for the Boeing 767 was found to be equal to 9.20 %.

For the Boeing 747 model, Table 5 presents the ratio of C_{d1}/C_{d0} along with the percentage of increase in the coefficient of drag for the three different engine failure cases that can result on a Boeing 747. Table 9 presents the C_{d1}/C_{d0} ratio for the three different types of failure.

Table 9

C_{d1}/C_{d0} Ratios for the Three Different Engine Failure Cases for the Boeing 747 Model

Case	C_{d1}/C_{d0}
Inboard Engine Failure	1.0125
Outboard Engine Failure	1.0217
Both Inboard and Outboard Engine Failure (Same Side)	1.0523

By substituting the above ratios of C_{d1}/C_{d0} in equation 32, the total increase in SR for the Boeing 747 was obtained (see Table 10).

Table 10

Total Percentage of Increase in Specific Range for the 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

Conclusions

Despite the fact that this study tested two small scale models of the Boeing 747 and 767 in a low speed wind tunnel, the results of the study supported the theory that an optimum bank angle exists for both the Boeing 747 and the Boeing 767 that will significantly increase their specific range in case of a engine failure. Therefore, the results of this study supported the research hypothesis, that by banking the airplane into the operative engines or engine by that optimum bank angle the range of the airplane improves significantly.

For the Boeing 767 only one type of engine failure was considered. The optimum bank angle derived for the Boeing 767, along with the percent increase in specific range that can be achieved by configuring the aircraft in the zero slip position, are presented in Table 11.

Table 11

Optimum Bank Angles and Percentage of Increase in Specific Range for the Boeing 767

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

For the Boeing 747 three types of engine failures were considered. Those are: inboard, outboard, or both inboard and outboard (same side) engine failure. The optimum bank angles derived for the Boeing 747, along with the percentage of increase in specific range that can be achieved by configuring the aircraft in the zero slip position, are presented in Table 12.

Table 12

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

Case	Optimum Bank Angle (Degrees)	% 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

Based on research performed by Byington (1988) for optimizing engine out procedures on multiengine aircraft, it was established by flight testing three light piston twin aircraft that by configuring the aircraft in the zero slip position, a drag reduction in the range of four to eight percent was achieved. Byington's results tend to validate the results of this study.

There are two different areas of flight operations that the results of this study might affect. These areas are: safety and economy.

From the safety point of view, by configuring the aircraft into the zero slip position, the specific range can be increased, thus providing the aircraft with the extra distance needed to reach a suitable aerodrome in certain extreme incidents.

Also, since it was proven that both twin-engine and four engine aircraft can achieve an increase in specific range by configuring the aircraft in the zero slip position, the regulations concerning how long the aircraft can sustain flight under engine failure conditions may be modified to accommodate the range increase. This will result in increasing the existing flight time limits that exist in both the ICAO and the FAA regulations, thus minimizing the incidents where the rules needed to be bent as in the cases mentioned in the introduction of this paper.

The various aircraft manufacturers should also review the concept of banking the aircraft into the zero slip position to improve its range performance. Based on the results, it may be feasible to modify the autopilot to sense the engine failures and configure the aircraft in the zero slip position automatically.

From the economic point of view, since the aircraft are capable of achieving the extra range margin, it may be feasible for the operators and the regulators to reduce the onboard reserve fuel by a certain percentage. Based on a study that United Airlines (UAL) performed on aircraft performance for economical operation, it was proven that it takes fuel to haul fuel (UAL, Study on Aircraft Performance for Economical Operation, 1984). 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 29,000 pounds of reserve fuel. Assuming that, because of the aircraft capability of achieving the extra range margin, Table 10 suggests that the reserve fuel can be reduced by 8 percent. Therefore, the overall weight reductions in the reserve fuel would be well over a ton (2320 pounds). The operator can transform this weight reduction into either more payload or fuel savings. From Table 12 it can be seen that a Boeing 747 consumes 35.7 pounds of fuel to carry 100 pounds of fuel. Thus, by reducing the reserve fuel by 8 percent the resulting fuel savings would be 828 pounds or 127 gallons of fuel. If the small percentage of the reserve fuel is eliminated from all the flights throughout the world, the resulting cumulative fuel savings would be tremendous.

It is suggested that further studies be performed in this area by the aircraft manufacturers since they have all the technical means and the expertise for a more extensive study. Furthermore, the manufacturers may have the opportunity to flight test the actual aircraft under study in order to obtain actual flight data on the subject. For aircraft that are still under design, it is suggested that the manufacturers conduct a similar study in order to obtain the value of the optimum bank angle that would configure the aircraft in the zero slip condition, and include that value along with the necessary engine out procedures in the Pilot Operating Handbook.

Also, further studies should be performed by the aircraft operators in order to determine the exact percentage by which the reserve fuel can be reduced, since the aircraft are capable of achieving the extra range margin. The proper government agencies in turn, should perform studies on the economic and environmental impact of the fuel savings that would result from the reduction of the reserve fuel.

Table 12

Effects of Weight Change on Fuel Burnout

	LBS. OF FUEL TO CARRY 100 LB. INCREASE IN WEIGHT / LBS. OF FUEL BURNED TO CARRY 100 LBS. OF WEIGHT									
NAUT. MILES	B737	STD B727	B727S	ADV B727	DC8-71	DC8F	B767	DC-10	DC-10-30	B747
100	1.0	1.2	1.4	2.0	1.2	1.9	1.2	1.1	1.3	1.8
200	2.0	2.2	2.9	3.1	2.0	2.6	2.0	1.8	2.0	2.2
300	3.1	3.5	4.0	4.2	3.0	3.3	2.8	2.6	2.7	2.7
400	4.1	4.8	5.3	5.6	4.0	4.0	3.5	3.1	3.4	3.3
500	5.1	5.9	6.7	6.6	4.9	4.8	4.3	4.1	4.2	3.9
600	6.0	7.0	8.0	8.0	5.8	5.7	5.0	4.9	5.0	4.5
700	6.8	8.2	9.3	9.1	6.7	6.7	5.8	5.8	5.8	5.2
800	7.8	9.4	10.5	10.3	7.6	7.6	6.5	6.0	6.7	5.8
900	8.6	10.6	11.9	11.5	8.6	8.7	7.3	7.4	7.7	6.5
1000	9.6	11.7	13.3	12.8	9.5	9.7	8.0	8.2	8.6	7.2
1100		12.9	14.5	14.1	10.5	10.7	8.8	9.1	9.6	7.9
1200		14.1	16.0	15.5	11.4	11.8	9.5	9.9	10.5	8.6
1300		15.2	17.3	16.8	12.3	12.9	10.3	10.6	11.5	9.4
1400		16.3	18.8	18.1	13.2	14.0	11.1	11.7	12.5	10.1
1500		17.5	20.3	19.4	14.2	15.2	16.3	12.6	13.6	10.9
1600		18.8	21.7	20.8	15.2	16.3	12.6	13.5	14.7	11.7
1700		19.9	23.0	22.3	16.2	17.5	13.3	14.4	15.7	12.5
1800		21.1	24.5	23.8	17.1	18.6	14.2	15.3	16.8	13.3
1900		22.4	25.8	25.3	18.1	19.9	14.9	16.2	17.8	14.2
2000		23.4	27.4	26.9	19.1	21.0	15.7	17.3	18.9	15.0
2100		24.7	28.9	28.7	20.1	22.3	16.4	18.3	20.0	15.9
2200		25.9	30.0	30.5	21.1	23.5	17.3	19.1	21.1	16.8
2300		27.0	32.0	32.3	22.1	24.8	18.1	20.2	22.1	17.7
2400				35.3	23.1	26.0	18.9	21.0	23.2	18.6
2500					24.1	27.5	19.7	22.0	24.3	19.5
3000					29.5	34.8	24.0	26.7	29.8	24.5
3500					35.5		29.2		35.6	29.9
4000					42.2				41.5	35.7
4500					50.7				47.6	42.0
5000									53.8	48.8
5500									62.4	59.0
6000									71.0	68.0

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