ANALYSIS OF FLIGHT PERFORMANCE AND STABILITY OF FAMILY OF TRANSPORT AIRPLANE DESIGNS WITH FUSELAGE COMMONALITIES

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Abstract
Product family concept has been a key aspect in airplane manufacturer long-term strategy. They can make aggressive product differentiation using common product platforms and design commonalities. Airplane configurations can be rapidly modified to meet market demand in time with minimum development cost.

This paper outlines an analysis of various airplanes designed based upon common design concepts. The designs maintain the same geometry of wing and tailplane, the same number and type of exits, and the same number and type of engines. Fuselage is extended by adding frames in front and aft of wing while maintaining the same cross section. For the baseline airplanes, the size of wing and tailplane geometry is optimized for specific seating capacities under the same set of design contraints.

Derivative airplanes are modified from the baseline airplane in which fuselage frames are removed or inserted to obtain the final size of the fuselage, while maintaining the same wing and tailplane geometry as that of the baseline airplane. Analysis would then be carried out on the flight performance, stability and control characteristics of the aircraft. Based on the analysis, design constraints and limitations can be applied to the geometry and design of the derivative airplane.

Introduction
Airplane market has grown at a considerable pace during the past decade. Although it has shown a reduced growth rate for the past few years, the number of aircraft orders continues to increase. Manufacturers have stated concerns about the increased production rates of airplane to keep up with the demand of aviation industry. The number of aircraft orders backlog has kept piling up, since manufacturers are unable to meet the ever-increasing demand.

On the other hand, airlines have difficulties in making available airplanes of the right size at the right time to meet the demand variations in the fluctuative market. The sector market is also growing at a certain rate that the airplane currently available may not be suitable after a number of years. The long interim between the time the airline places the orders and the delivery time makes it even more difficult for airlines to perform fleet planning and timely acquisition of the airplane.

Airplane industry is a high investment venture with low rate of return. The long gestation since airplane conceptual design to mass production and delivery requires costly man-hours and materials. Massive development cost has been a constraint to manufacturers, keeping in mind that the investment will take a long time to be paid back. This situation forces manufacturers to be extremely cautious in taking initiatives for designing and producing a completely new airplane program. One strategy for minimizing development time and cost would be to design the airplane based on existing designs, by modifying designs currently on the market to obtain more operational flexibility, and performance capability in terms of flight range and seat capacity.

Manufacturers have opted to offer families of airplane designs to meet this ever-changing market demand. Product family concept has been a key aspect in Boeing long-term strategy, which is to make aggressive product differentiation using common product platforms and design commonalities. With this design concept, Boeing can vary configurations rapidly and adapt products to meet market demand in time with minimum cost.

The Boeing 737 is the most popular airplane model in Boeing production history. The Boeing 737-100 was first produced in 1968 as the first model in the family. Since then various other models have entered the market in the 100-189 seat category. Each model maintains the same fuselage cross section and keeps commonalities of design as much as possible in order to keep the same type rating. With all-up weights ranging from 52.000 kg. in 737-500, the smallest model currently available, to 70.000 kg in the 737-900, the airplanes cannot keep the same wing, although they still maintain certain level of structural commonalities. Fuselage is extended by adding frames in front and aft of wing while maintaining the same cross section. The same number and type of exit doors are maintained for different number of seats across the variants. For Boeing 737-800NG and 737-900NG, Boeing had to provide an automatic emergency door over the wing to meet FAA's requirement for seat capacity of over 179.

The A320 family [1] is another example of a successful common design concept. The A320 program was launched in 1984 and the first delivery airplane with typical configuration of 150 seats entered service in 1988. Since then variants of this airplane have been offered to airlines. The A321 with 185 seat capacity is a member of the family, in which the fuselage is extended with additional 8 frames (4,26 m) in front of the wing and 5 frames (2,67 m) aft of the wing. Another variant is the 124-seat A319 with shorter fuselage, in which 7 frames are taken out. In terms of geometry, the A319/A320/A321 have many in common. They have same wing and tailplane. Unlike the Boeing 737 family, however, the Airbus variants have different number of exit doors.

The questions would then be how far a design can be expanded without sacrificing performance and safety and with limited penalty on cost and performance. This paper outlines an analysis of various airplanes designed based upon common design concepts. Design analyses are concentrated on the performance and flight stability aspects.

Design Concepts

The commonality concept adopted in this study is similar to the approach in the Boeing 737 family [2]. The design maintains the same geometry of wing and tailplane, the same number and type of exits, and the same number and type of engines. For this reason, the capacity is limited in the range of 70-174 seats in 2-class configuration. The engine candidate is CFM 56-9 with gross thrust of 18.000-22.000 lbs.

The airplane family should be able to fly at least a 1.850 nm. sector without the center fuel tank. The cruise Mach number is 0,78-0,8, with maximum altitude of 41.000 ft. The take-off field length should not exceed 7.000 ft. at sea level and maximum take-off weight condition. The landing field length is no longer than 7.000 ft. at maximum landing weight.

The general arrangement of the airplane family is shown in Figure 1. They have a low wing configuration, with two turbofan engines mounted beneath the wing, a conventional tailplane and tricycle landing gear layout. The center of gravity position is limited to a maximum aft location of 42% MAC in order to maintain the same location of the main landing gear attachment to the wing.

The fuselage cross section is given in Figure 2. The seat arrangement is 4 abreast in the first class, 5 abreast in the business class and 6 abreast in the economy class. It is by far the best seating arrangement that can be obtained for airplane size in this range of capacity. A higher seat abreast would give a very squad fuselage design, i.e. very low fineness ratio, for the lowest capacity airplane. This would result in higher aerodynamic drag and difficulties in the proper arrangement of the wing and landing gear. On the other hand, a lower seat abreast would cause the airplane to be very slim (very high fineness ratio), a design that would result in a controllability problem.

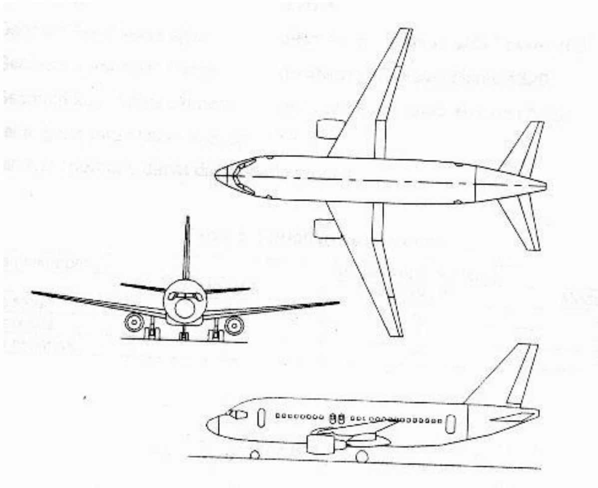

Figure 1 General arrangement of the airplane

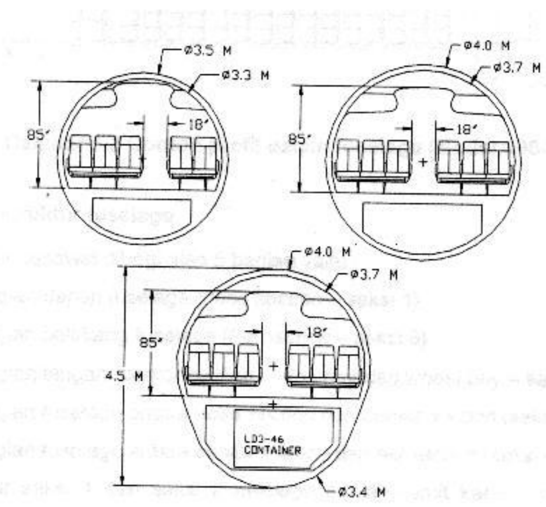

Figure 2 Fuselage cross section

The fuselage is designed to accommodate passengers in two classes. The first class seats are arranged in 38 in. pitch, while the economy class seats are pitched at 32 in., with aisle width of 18 in. Cabin ceiling height is set at 85 in. from the floor, while the fuselage frame is set at 0.12 m. This results in a external diameter of 3,3 m for the 5-seat abreast layout and 3,7 m for the 6-seat abreast layout. A requirement to accommodate LD3-46 containers at the belly compartment can be met by having a double-bubble fuselage cross-section with 4,5 m. height.

Galleys and lavatories are distributed at each end of the cabin to obtain more flexibility in the seating arrangement. With this configuration, each class will have its own galleys and lavatories. The number and size of the lavatory and galley compartment are adjusted according to the number of seats. The number of cabin crew seats is taken as at least one for a maximum of 50 seats. Two passenger doors of at least type I and one type III emergency exits are required by the airworthiness regulations. The size of the doors is the same for all seating configurations. Figure 3 illustrates a typical seating configuration.

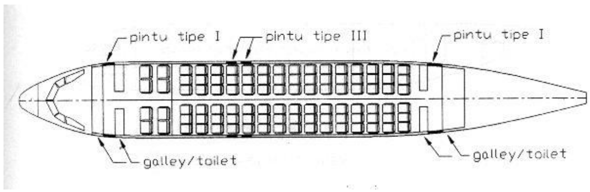

Figure 3 Typical internal arrangement of fuselage.

Structurally, the fuselage is composed of five different sections. Section 1 comprises of the nose part of the fuselage. Section 2 comprises of the constant cross sectional part of the fuselage between the nose section and the center section on which the wing box is installed. Section 3 is composed of the center section, the wing box and the undercarriage wheel bay. Section 5 comprises of the tail aft section of the fuselage, while section 4 is the constant cross sectional portion of the fuselage between section 3 and section 5.

Section 1 is structurally complicated, due to the change of cross sectional shape of the fuselage along the longitudinal axis. There are also a number of cutouts for passenger doors and flight deck windows in this section. The structural design of section 3 is also complex, since it houses the wing box and main undercarriage, whose sizes are depending upon the size and weight of the airplane. The presence of cutouts for exit doors and the longitudinal tapering of the fuselage also require extra care in designing the structure of section 5. Therefore, sections 1, 3, and 5 are taken as fixed with the changes of the fuselage length. Only section 2 and 4 can technically changed to accommodate the variations in seating capacity. This can be done by inserting or removing fuselage frames in these sections. Figure 4 depicts the structural arrangement of the fuselage.

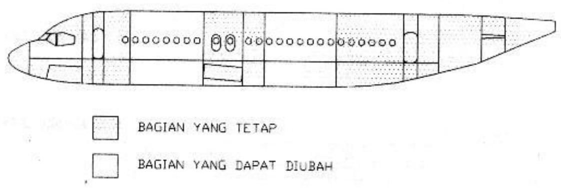

Figure 4 Structural arrangement of the fuselage

Baseline Airplanes

To obtain the right size of wing and tailplane geometry, the airplane designs are optimized for specific seating capacities. The optimized designs are taken as baseline airplanes, from which a family of designs can be derived to meet different seat capacity. Each baseline airplane would then have a certain wing and tail geometry. Derivative airplanes are modified from the baseline airplane in which fuselage frames are removed or inserted to obtain the final size of the fuselage. All derivative airplanes modified from the same baseline will then have the same wing and tailplane geometry as the baseline airplane.

To ease identification of the various configurations, each design is assigned a type code of XYZ-VW. XYZ will typify the baseline airplane, in which the X is the number of seat abreast in the economy class and the YZ is the total number of seats of the baseline airplane. VW is the total number of seats of the individual design. Therefore, the 598-98 airplane is a baseline airplane with a seat abreast of 5 and 98 seat capacity, while the 598-86 is a derivative airplane, derived from the baseline airplane of 598-98 in which several frames are taken out to obtain a final capacity of 86 seats.

Figure 5 illustrates all baseline airplanes with capacity ranging from 74 to 156 seats. Table 1 summarizes the design characteristics of the baseline airplanes.

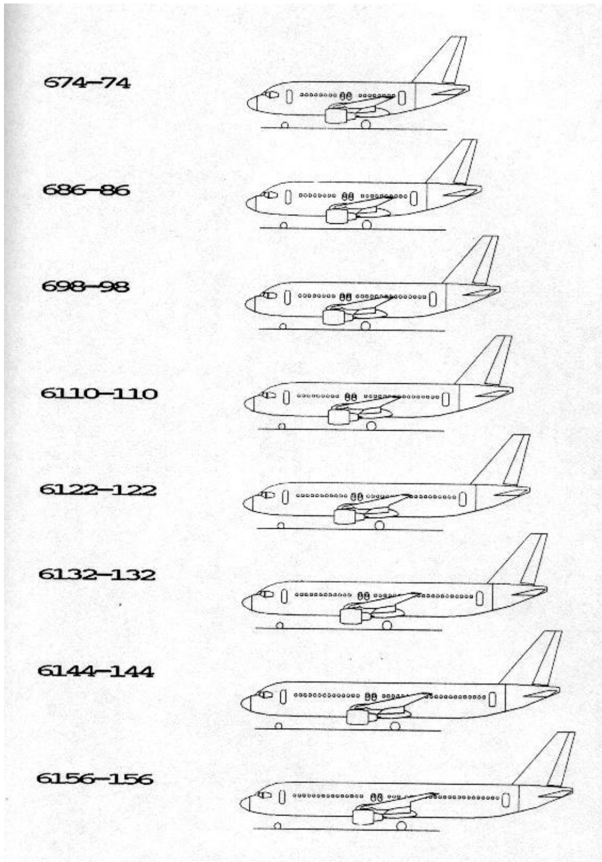

Figure 5 The geometry of baseline airplanes

Table 1 Design characteristics of baseline airplanes

Geometry	Baseline Airplane			
	674-74	686-86	698-98	6110-110
S (sq.ft.)	865,0	895,6	969,6	1020,1
AR_w	8,493	8,602	8,764	8,997

L_f (ft.)	84,97	90,32	97,77	103,1
S_H (sq.ft,)	251,9	267,3	289,9	299,8
AR_H	4,814	4,377	4,255	4,034
S_V (sq.ft.)	234,5	222,9	207,5	213,6
S_H/S	0,291	0,298	0,299	0,294
S_V/S	0,271	0,249	0,214	0,209
MTOW (lbs.)	80.281	86.280	92.957	100.427
W/S (psf)	92,8	96,3	95,9	98,5
$(T/W)_{to}$	0,448	0,417	0,387	0,358

Geometry	Baseline Airplane			
	6122-122	6132-132	6144-144	6156-156
S (sq.ft.)	1113,0	1171,9	1227,3	1270,1
AR_w	9,652	10,082	10,528	10,783
L_f (ft.)	109,9	116,9	122,24	127,85
S_H (sq.ft.)	303,9	313,0	325,8	336,2
AR_H	4,021	4,015	4,005	4,083
S_V (sq.ft.)	234,3	240,2	250,4	253,7
S_H/S	0,273	0,267	0,266	0,265
S_V/S	0,211	0,205	0,204	0,200
MTOW (lbs.)	109.946	118.063	127.425	136.524
W/S (psf)	98,8	100,7	103,8	107,5
$(T/W)_{to}$	0,345	0,35	0,346	0,349

Design Constraints

The airplane will be powered by two CFM56-9 turbofan engines, rated from 18.000 lb. to 22.000 lb. thrust. In order to obtain a good landing gear position, the location of the center of gravity is limited to maximum 42% wing MAC aft.

The take-off and landing field performance is limited to maximum 7.000 ft. The available climb gradient should meet FAR 25 requirements. With two engines operative, it should be at least 0,024 at second segment of the take-off procedure. At approach climb, it should be minimum 0,021.

The handling quality constraints include the static and dynamic stability parameters. They should meet the requirements of FAR 25 [3] and MIL-F-8785C [4]:

- The stick fixed static margin $(X_n - X_{ac})$ should be at least 10% MAC.
- The maneuver margin $(X_m - X_{cg})$ shall be at least the same as the static margin.
- The damping ratio for the phugoid motion ζ_{ph} should be at least zero.
- The short period damping ratio ζ_{sp} at cruise and approach flight condition should be at least 0,15.
- The minimum time to double T_2 for the spiral stability is at least 4 seconds.

Design Analysis

The analysis is carried out using the OPDOT (Optimum Preliminary Design Of Transport Airplane) computer program [5]. The program uses a simplex algorithm to find the optimum solution in the feasible design space. The airplane design module is called to conduct the analysis of the design suggested by the optimizer. There are 53 design constraints embedded in the program, these include flight performance parameters, handling quality criteria, and several sizing factors.

In this report, the analysis will be focussed on the flight performance and stability parameters of the design. These parameters are compared in the selection of the fuselage cross section and the extend of the additional fuselage frames that best fit the overall design to meet the seating capacity requirements.

Fuselage Cross Section

The fuselage cross sectional shape is very much dependent upon the market requirement and the seating capacity. The selection between the 5-, 6- and 6-DB (double bubble) configuration will dictate the final geometry of the fuselage. For the sake of study, an analysis is carried out to have the best seating arrangement for the baseline airplane. Fuselage design is performed using a program code called Fuselage [6].

The 98 seat capacity is selected for this purpose since both the 5- and 6-abreast layout can fit nicely to the capacity in two class configuration. Table 2 depicts a summarized result of the analysis.

Table 2 Summary of Design Parameters

	Airplane Configuration			
	598-78	598-88	598-98	598-108
Add. Frames	-3 -3	-2 -1	0 0	1 2
W_{TO} (lbs.)	80.055	85.259	90.536	96.720

	Airplane Configuration			
	698-74	698-86	698-98	698-110
Add. Frames	-3 -3	-2 -1	0 0	1 2
W_{TO} (lbs.)	80.400	86.502	92.957	99.923

	Airplane Configuration			
	698DB-74	698DB-86	698DB-98	698DB-110
Add. Frames	-3 -3	-2 -1	0 0	1 2
W_{TO} (lbs.)	82.024	88.112	94.424	100.414

Overall, the 598 baseline airplane gives the lowest take-off weight. However, the 698 baseline airplane yields a much better performance and stability qualities. Moreover, the 698 baseline offers a higher maximum seating capacity, 110 seats as compared to 108 seats in the 598 baseline. In any case, the 698DB baseline airplane is the worst. In fact, the 698DB-74, 698DB-88 and the 698DB-110 configuration do not meet the phugoid damping ratio requirement of 0,15 at cruise condition as shown in Figure 6.

The 698 configuration is selected as the baseline for further study. It offers a much roomy cabin than the 598. It has better flight performance and stability, with a penalty of 1% increase in weight and direct operating costs. The maximum lift over drag ratio at cruise condition is also higher at 18,1-18,2 for the 698 baseline, while the 598 only has 17,6-17,8, as shown in Figure 7. The 698 configuration gives a slightly bigger frontal area of the fuselage and a shorter body than the 598, which results in a lower penalty in interference drag. The lifting capability of the wing-fuselage combination is also slightly increased.

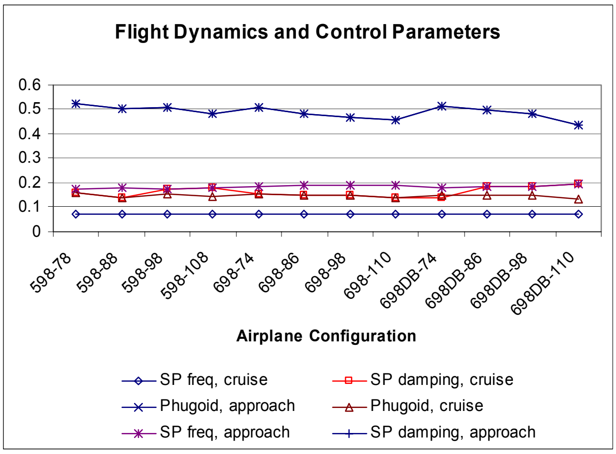

Figure 6 Flight dynamics parameters for various configurations

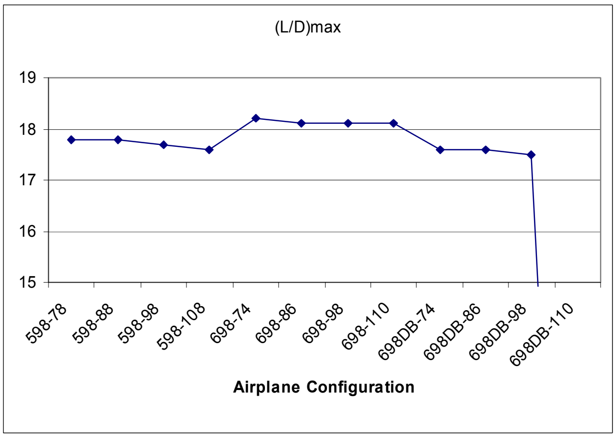

Figure 7 Lift to drag ratio at cruise condition for various configurations

Figure 8 shows that the 698 congifurations offer higher overall stability margins, except for the 686DB-110 configuration, which gives the highest stability margins. The latter configuration, however, does not meet the phugoid damping ratio criteria of 0.15 at cruise condition as mentioned earlier. It also shows that the stability margins are larger in the approach condition than that in the cruise conditions.

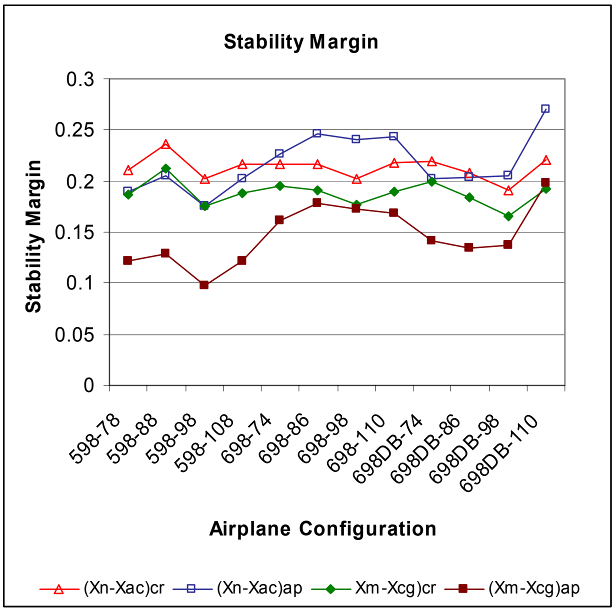

Figure 8 Stability margins for various configurations

Addition and Removal of Fuselage Frames

As mentioned earlier, fuselage length is modified by the addition or removal of fuselage frames in sections 2 and 4, in front and aft of wing. This will result in changes in various areas of design: the position of wing with respect to the fuselage nose, the available underfloor cargo volume in front and aft of wing, the distance of tailplane from the wing, the location of center of gravity (c.g.) and the range of the c.g. movement.

The change of c.g. location would directly influence the handling qualities. Table 3 presents the number of frames added or removed in the sections 2 and 4 of the fuselage that are allowed in order to meet handling quality constraints. It is interesting to note that removing more frames in front of the wing box would give a better stability characteristics. This is due to a larger tail arm for a better control capability in maneuvers. In the 698-74 configuration, for example, the seat capacity can be achieved by either taking out 3 frames each in front and aft of wing (-3 –3) or removing 2 frames in front of wing and 4 frames aft of wing (-2 –4). The (-3 –3) configuration would gives a better stability margin than the (-2 –4), as depicted in Figure 9.

Table 3 The allowable number of frames added or removed

Baseline Airplane	Capacity (seats)			
	74	88	98	110
674	0 0			
686	-1 -2	0 0		
698	-3 -3	-2 -1 -1 -2	0 0	2 1
6110	-4 -5	-3 -3 -2 -4	-1 -2 0 3	0 0

The minus (-) sign indicates removing frames.

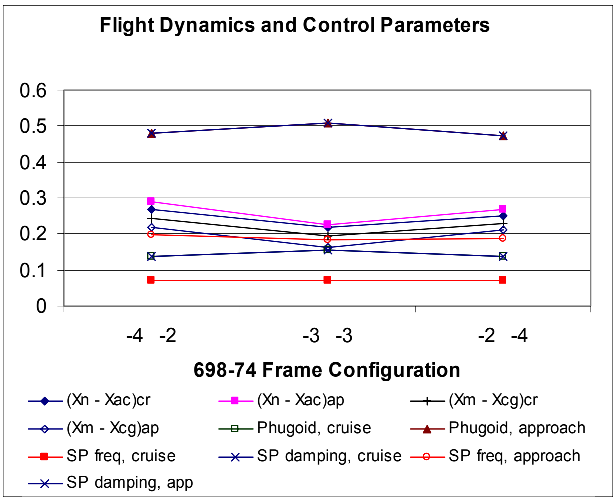

Figure 9 Effect of frame layout on flight dynamics and control parameters

The number of frames removed in section 2 (in front of wing) should, however, be limited since this it will adversely affect the c.g. location. The more the frame removed in this section, the farther aft the c.g. location moves. The most aft c.g. location is obviously restricted by the location of the main landing gear. In the 698-74 design, for example, this criterion is best met by the (-3 -3) configuration. In fact, the (-4 -2) confiruration does not satisfy the design requirement.

Aircraft Performance

Figure 10 shows that the field performance is worse for longer fuselage. For each baseline configuration, adding fuselage frames would result in longer distance in take-off and landing performance. This is undestandable, as the all-up mass increases with the size of the fuselage. The same could be said for the approach speed.

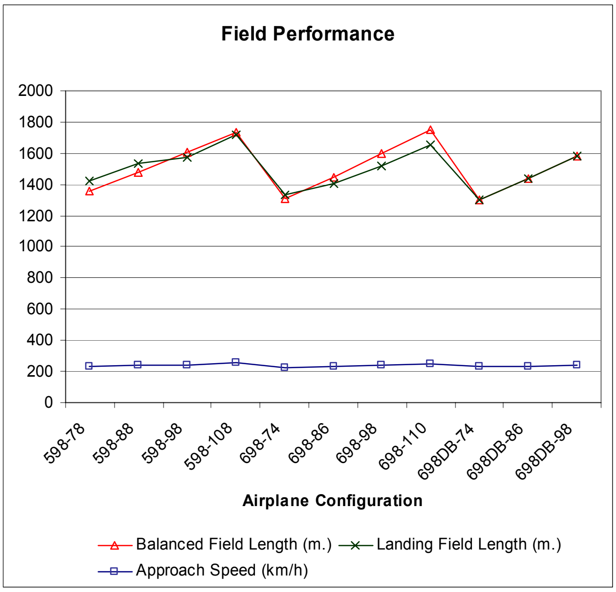

Figure 10 Field performance of various configurations

Concluding Remarks

The study shows that the cross sectional geometry of the fuselage should be selected to maximize the potential of future fuselage stretch in the family. A larger cross section will ensure a better overall performance with increased capacity, while the associated penalty in weight and cost is negligible. It is also found that there is a tendency for removing more frames in front of wing than at aft of wing in order to have a longer tail arm for better handling qualities. For all configurations, the wing size of the baseline airplane is determined by the largest capacity offered.

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