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THE IMPORTANCE OF DERIVATIVE AIRPLANE PROGRAMS

RESEARCH REPORT

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THE IMPORTANCE OF DERIVATIVE AIRPLANE PROGRAMS

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The mission of the Aerospace Research Center is to engage in research, analyses and advanced studies designed to bring perspective to the issues, problems and policies which affect the industry and, due to its broad involvement in our society, affect the nation itself. The objectives of the Center's studies are to improve understanding of complex subject matter, to contribute to the search for more effective government-industry relationships and to expand knowledge of aerospace capabilities that contribute to the social, technological and economic well being of the nation.

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INTRODUCTION AND SUMMARY

The success of United States commercial airplanes in the world marketplace can be attributed not only to the performance of the basic or initial model, but also to the availability of derivative models that provide improved performance capabilities or satisfy new airline requirements. These derivative models extend and augment the manufacturer's production run. They are a necessary and beneficial part of the air travel system in that they provide both airline and passenger economies that would otherwise not be possible. This paper discusses the developmental history and the relationship of past derivative models to the basic model and outlines the importance of derivatives to all elements of the air transportation system.

Requirements of the airlines result in a demand for airplanes with wide variations in range, capacity and performance characteristics. These requirements are not static, but are continuously changing. Major changes in airline requirements may allow or require new airplane designs while lesser changes may permit a derivative design of the basic airplane model. The choice between a new or derivative design is complex, but in the final analysis it is a choice between the relative cost of a derivative airplane versus that of an all-new design.

The analysis results in the following summary statements:

- Derivative airplane and engine programs are a natural and necessary part of any successful air transport industry development program. They are required in order for a program to be undertaken by a manufacturer and its customers. Also, derivative programs are in the best interests of manufacturers, the traveling public, and the overall national economy.
- Derivative programs provide airplanes and engines which meet the requirements of specific airline markets and provide improvements in capability, performance and efficiency at a lower investment cost for both the manufacturer and the airlines when compared with all-new airplanes.
- To achieve the substantial benefits that derivative airplanes provide commercial aviation, manufacturers must know, before launching a new program, that the regulations to which the airplane is to be designed will be retained throughout the airplane's production life.

THE REQUIREMENT FOR DERIVATIVE AIRPLANES

Figure 1 illustrates six representative derivative choices. From an initial design point or from a subsequent derivative design point, the derivative design requirements may move a reasonable distance in any direction deemed desirable to meet airline requirements. Satisfying passenger capacity or range requirements far removed from the initial design point with a derivative airplane may not be reasonable; a new design airplane may be warranted.

Savings in derivative airplane cost elements extend to all segments of the air transportation system: the manufacturers, suppliers, airlines, and most importantly, the public. The impact of the costs associated with both new design and derivative airplanes are ultimately reflected in the fares paid by the traveling public as well as the rates paid by those that utilize the air cargo and mail services. For this reason costs are a major subject of this paper.

Successful commercial transport airplane programs have included one or more derivative models. Following are important U.S. derivative airplane programs launched since 1945.

1946–1956
- Lockheed Constellation/Super Constellation 049, 649, 749, 1049, 1049C, G, and H, and 1649
- Douglas DC-4, -6, -6A, -6B, -7, -7B, and -7C
- Convair 240, 340 and 440

1956–1959
- Boeing 707-120, -120B, -138B, -220, -320, -320B, -420 and the 720, 720B
- Douglas DC-8-10, -20, -30, -40, -50, -61, -62 and -63

1960–1077
- Boeing 727-100, -200, Advanced 727-200
- Douglas DC-9, -10, -20, -30, -40, and -50
- Boeing 737-100, -200, Advanced 737-200 and -200C
- Boeing 747-100, -200B, -200F, -200C, SR and SP
- Lockheed L-1011-1, -100, -200, -250 and -500
- Douglas DC-10-10, -30 and -40

Figure 1

SOME REPRESENTATIVE DERIVATIVE CHOICES

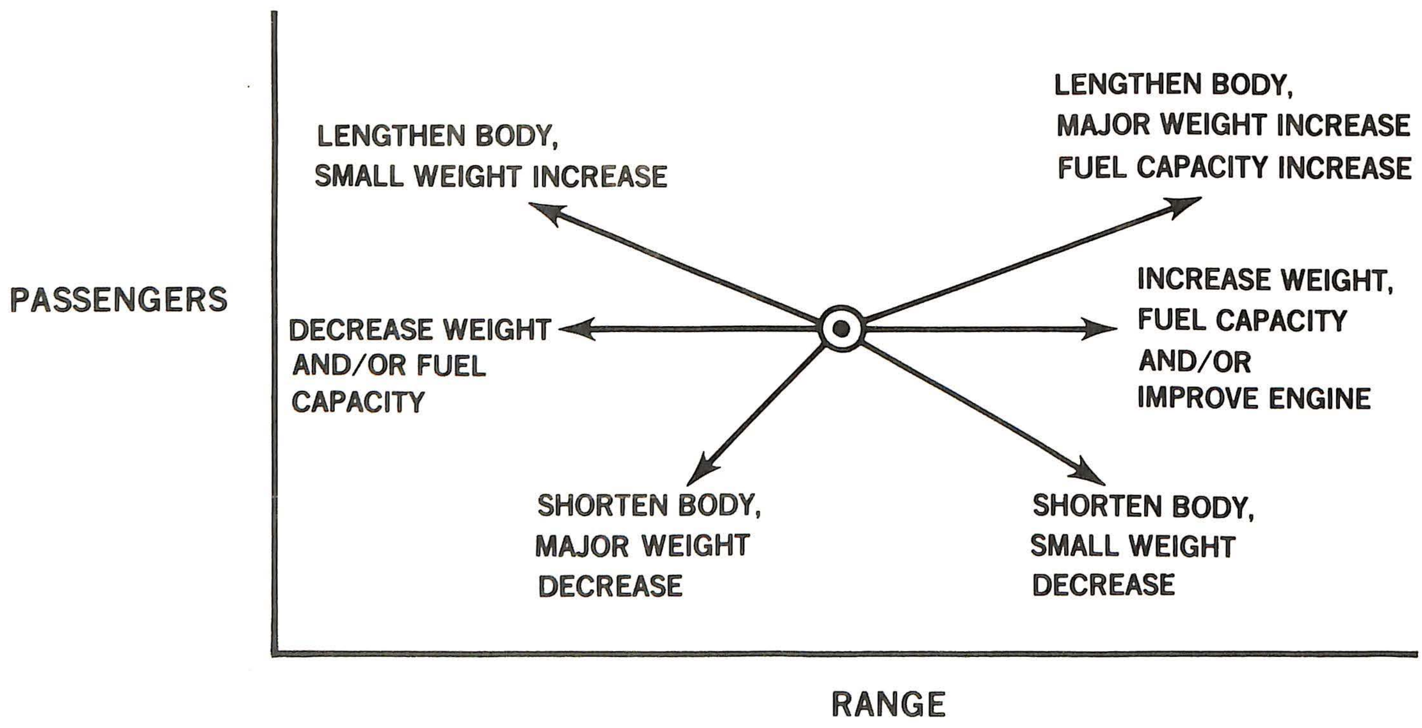


Figure 2

BOEING 707 FAMILY

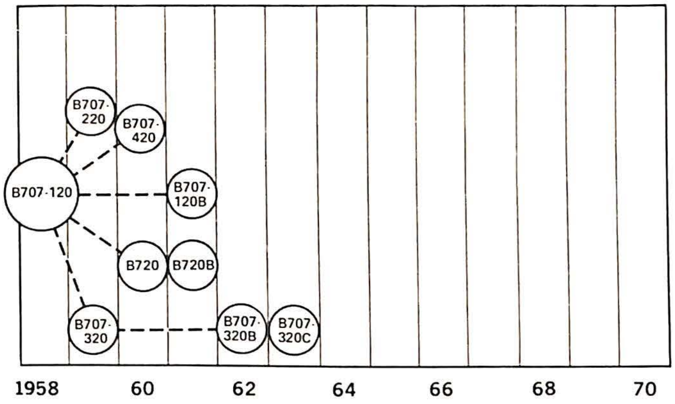
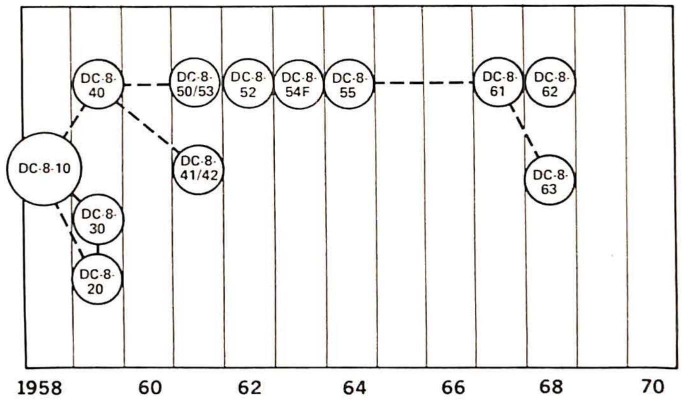


Figure 3

MCDONNELL DOUGLAS DC-8 FAMILY



The "family tree" of the basic B-707 and DC-8 and their numerous derivatives are shown in Figures 2 and 3. Derivatives have been introduced in some programs as late as 10 to 15 years after the original model.

Experience by the manufacturers and airlines has shown that derivative programs are of fundamental importance in making a commercial transport program an economically successful undertaking. Examples of modifications to the basic production model which tailor the derivative to new markets, provide improvements in performance, or meet changing airline requirements, include:

MODIFICATION	OBJECTIVE
Higher gross weight	Greater fuel range and/or increased payload
Longer fuselage	Greater payload capacity, lower unit operating costs
Shorter fuselage	Increased range as a result of lower airframe weight, payload and drag; or, reduced payload capacity requirements; or reduced field length
New or modified wing	Increase range; provide a shorter range derivative; heighten efficiency; better field performance; or reduce noise
Derivative engine	Lower fuel consumption; heighten thrust for higher gross weight; better performance; or reduce noise
Alternate engine	Accommodate airline requirements for lower costs; better field performance; or reduce noise
Nacelles—new or modified	Greater efficiency or reduced noise

Some examples of modifications of basic airplane designs that were made to meet changing airline requirements are shown in Figure 4.

DERIVATIVES—AN ECONOMIC NECESSITY

The fundamental concept of evolving an airplane "family" is an important element in the decision by a manufacturer to launch a new airplane development program, a new engine development program, or virtually any new commercial product. The potential for a family of airplanes is also an important consideration for the airlines when procuring a fleet of new airplanes.

The derivative approach permits the manufacturer to increase the production base and spread the initial development cost over a larger number of units with far less additional investment than that required to develop a completely new model for each new market.

After an initial model of a commercial airplane has been designed, tested, and placed in production, increases in performance can usually be accomplished with a minimum or no increase in structural weight and at a comparatively low cost. This is due to the capability and design margins of the basic airplane being verified during certification and the ability to trade off these capabilities to establish a new balance of performance characteristics to meet revised airline requirements.

Boeing has stated that development costs for the basic B-747 represented a $1 billion investment, which was about twice the net worth of The Boeing Company when the program was launched in 1966. The number

Figure 4

EXAMPLES OF MODIFICATIONS TO BASIC MODEL TO OBTAIN DERIVATIVE AIRCRAFT

	HIGHER GROSS WEIGHT	MORE FUEL CAPACITY	LONGER FUSELAGE	SHORTER FUSELAGE	NEW OR MODIFIED WING	ENGINE DERIVATIVE — MORE POWER	ALTERNATE ENGINES
749 CONSTELLATION	X	X				X	
DC-6B	X	X	X			X	
DC-7	X	X					X
B707-320	X	X	X		X	X	X
DC-8-61	X		X		X	X	
B727-200	X	X	X			X	
B737-200	X	X	X		X	X	
DC-9-30	X		X			X	
DC-10-30	X	X			X	X	
DC-10-40	X	X			X	X	X
L-1011-500	X	X		X		X	
B747-200B	X	X				X	X
B747-SP				X			

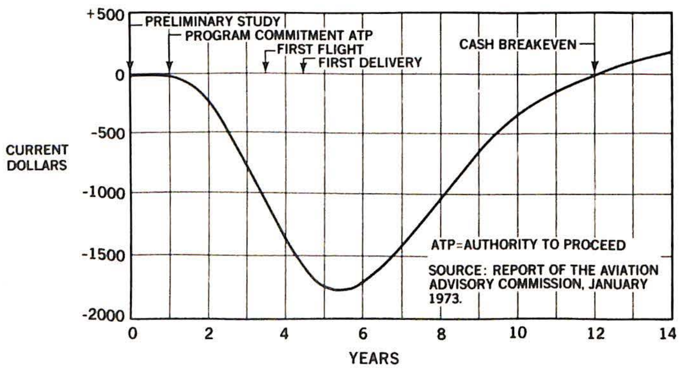
of times any company can or will undertake such a risk is limited, both by its management and by the investment community. Derivative design, where it can meet airline requirements, is clearly an attractive alternative to a new design. Development costs for the 747SP, for instance, involved only about 10 to 20 percent of the investment required for the basic 747.

Cash flow is a major aerospace problem as typified by a representative large new airplane program where cumulative cash flow approaching $2 billion would be required and where over 12 years may elapse before the manufacturer reaches a breakeven point, as shown in Figure 5. Obtaining the capital to support the development and production of a new commercial transport airplane is therefore a major undertaking.

In view of the very large financial investment involved in a new airplane development program, derivative models to meet the changing requirements of the airlines are essential to make new airplane programs economically viable for the air transportation industry. Derivative airplanes are also often less costly for the airlines than new designs.

Figure 5

TYPICAL CASH FLOW CURVE FOR LARGE TRANSPORT AIRPLANE PROGRAM



BENEFITS TO THE AIR TRANSPORTATION SYSTEM

The airlines and their passengers are the principal beneficiaries of the derivative approach to aircraft development. The key benefits are a greater choice of airplane performance characteristics and size to better match specific airline requirements and, therefore, to obtain maximum operating and economic efficiency over the various airline routes.

Achieving an efficient fleet mix is complicated. The airlines must consider many factors including a number of conflicting requirements that must be carefully balanced. Each airline strives to assemble a fleet limited to a minimum number of airplane types with the right combinations of size, range, operating cost, and performance for the needs of its unique route structure. The availability of derivative airplanes greatly widens the choice and provides the best opportunity for achieving an optimum fleet mix.

Price and delivery time are factors of primary concern to the airlines when purchasing airplanes. In general a derivative airplane can be delivered at a lower price and sooner than an all-new airplane of the same capability. The lower price for a derivative airplane results from the manufacturer's broader production base which permits economies of the learning curve and recovery of development costs over a larger quantity of sales. Lower purchase price has a beneficial effect on airline operating costs through lower depreciation as well as lower costs in such areas as financing, spares and insurance.

Further, derivative airplanes provide additional advantages to the airlines when introduced into fleets that include the original basic model. Among these advantages are lower training costs as well as lower introductory and maintenance costs that result from the high degree of commonality between the original and the derivative airplane.

While the airlines and the manufacturers benefit from derivative programs, the ultimate beneficiary is the traveling and shipping public.

TYPICAL DERIVATIVE PROGRAMS

Rather than attempt to provide details on all transport programs with derivative models, two examples, the Boeing 727 and the McDonnell Douglas DC-9, are used to illustrate the evolution of derivatives from the initial production model.

Figure 6 shows the capabilities of the three principal passenger airplanes in the Boeing 727 series. The models entered service as follows: the 727-100 parent in early 1964; the 727-200 about three and one half years later in 1967; and the Advanced 727-200 about four and one half years after the -200, in mid-1972.

Figure 6

MODEL B727 EVOLUTION

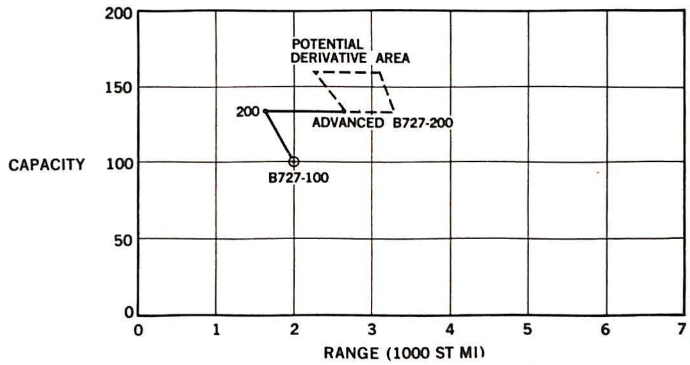


Figure 7 illustrates the simultaneous improvement in passenger capacity and range while, at the same time, seat-mile costs relative to the parent airplane are reduced.

Figure 7

MODEL B727 PROGRAM IMPROVEMENT

	-100	ADV-200	CHANGE (%)
PASSENGERS	100	134	+ 34
RANGE (ST MI)	2,010	2,640	+ 31
ENGINE THRUST (LB AT 84° F)	13,180	16,000	+ 21
RELATIVE SEAT-MILE COST	1.0	0.82	-18

A second example of a derivative program is the DC-9 series. Figure 8 illustrates the evolution of derivatives from the basic DC-9 which was introduced into airline service in 1965. The DC-9-30 entered service in 1967, followed by the DC-9-40 in 1968 and the DC-9-50 in 1975. The DC-9-20, which was developed to meet a specific customer's requirement, entered service in 1969.

Figure 9 shows the simultaneous improvement of the DC-9 family in passenger capacity and range while at the same time achieving reduced seat mile costs compared to the parent airplane.

Figure 8

MODEL DC-9 EVOLUTION

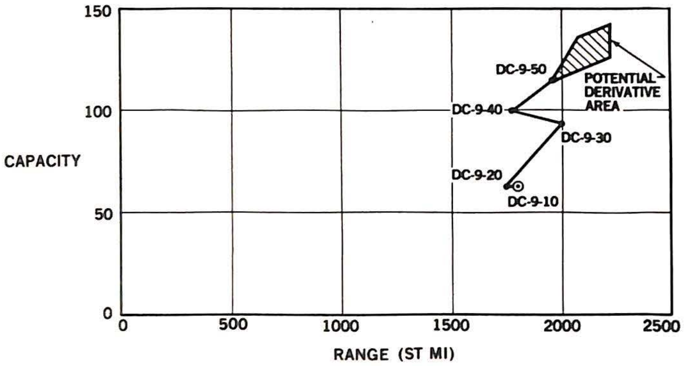


Figure 9

MODEL DC-9 PROGRAM IMPROVEMENT

	DC-9-10	DC-9-50	Δ %
PASSENGERS	72	114	+34
RANGE (ST MI)	1768	1935	+9
ENGINE THRUST (LB AT 84° F)	13,180	16,000	+21
RELATIVE SEAT-MILE COST	1.0	0.85	-15

COMPARATIVE COST OF DERIVATIVES

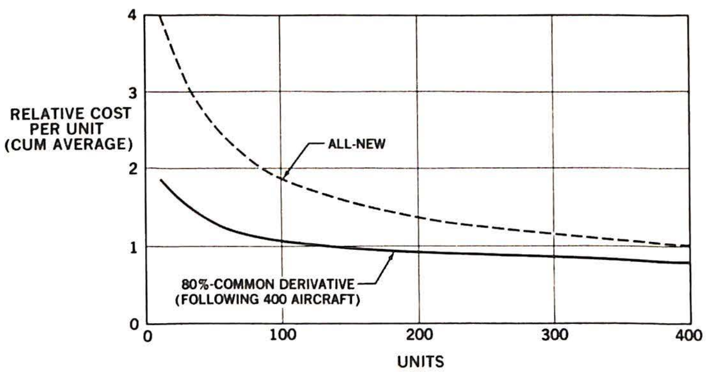
As noted earlier, the development cost of the 747SP was 10 to 20 percent of the investment required to develop the basic 747 airplane. In addition to a lower development cost, there is also a savings in the unit production cost of a derivative airplane since it is further down the learning curve.

A comparison of the cumulative average unit costs of an 80 percent common derivative airplane and an all-new airplane with similar capabilities is shown in Figure 10. Assuming that the derivative program follows a 400-unit production run of the basic airplane, the 100th unit of an all-new airplane program would cost about 75 percent more than a derivative airplane. If 400 units of both alternatives were built, the production cost difference between the all-new and the derivative airplane would still be approximately 30 percent. To justify even a 30 percent increase in unit airplane cost would necessitate a very substantial reduction in operating costs for the new airplane.

Figure 10

AIRFRAME PROGRAM COST COMPARISON

EQUAL AIRFRAME WEIGHTS
CONSTANT DOLLARS



ENGINE PROGRAMS

Not only are derivative airplane programs important, but so are derivative engine programs for many of the same reasons. An example of the application of engine derivatives may be illustrated by tracing the development of the Pratt and Whitney JT8D turbofan engine program. Figure 11 shows the family members of this engine. In addition to the growth in thrust within this family there also have been other design and performance improvements as derivative models evolved to meet specific airline requirements.

As in the case of airplanes, the development cost of a new basic engine has also increased substantially. Hence, engine manufacturers offer derivative versions with higher or lower thrust, improved performance and greater reliability for both derivative and new airplanes.

On the average, it takes about $300 to $500 million and four years to get a new engine certified and into production. Development must continue to provide in-service improvements in performance, reliability, and maintainability; this costs an additional 60 percent of the expenditures to reach initial production. Thus, the total development cost for a new engine could well fall between $500 and $800 million depending upon size, technology availability and potential market.

Experience has shown that the cost of derivative engine models falls between 20 and 50 percent of the new engine cost to reach initial production, depending upon the extent of new technology incorporated. It also takes considerably less time for a derivative engine to reach initial production. Derivative engines also require additional development costs to provide in-service improvements, adding an additional 60 percent to their development costs. Still, a derivative model of a fully developed engine to meet the requirements of the same application as a new engine would be less than half the total cost of that new engine, somewhere between $100 and $400 million. The economic advantages of derivative engines to the U.S. air transportation industry and the traveling public are real and very significant.

Figure 11

JT8D ENGINE MODELS

MODEL	TAKEOFF THRUST (LB)	APPLICATION
-1/-1A/-1B	14,000	B727-100; DC-9-10, -20, -30
-7/-7A/-7B	14,000	B727; B737; DC-9-10, -20, -30
-9/-9A	14,500	B727-200; B737-200; DC-9-30, -40
-11	15,000	B727-200; DC-9-20, -30, -40
-15	15,500	ADV B727-200; ADV B737-200; DC-9-30, -40, -50
-17	16,000	ADV B727-200; ADV B737-200; DC-9-50
-17R	17,400	ADV B727-200

CERTIFICATION AND REGULATORY CONSIDERATIONS

A new aircraft type is designed and certificated to meet the then current air regulations with respect to performance, safety, noise, emissions, and many other considerations.

Airworthiness practice has generally recognized the need for derivative aircraft to be developed and produced under the same regulations by which the original basic model was certificated. However, this practice has not been carried over into environmental regulatory activity. Each time more stringent noise regulations are developed for new aircraft types, pressures begin developing to make them applicable to existing programs. In 1973, the Federal Aviation Administration extended the noise certification standards adopted in 1969 for new aircraft to all aircraft produced after 1974. The International Civil Aviation Organization Committee on Aircraft Noise has recommended new noise requirements more stringent than those of the current Annex 16 for future versions of current aircraft which are powered by engines having a bypass ratio of two or more. This issue is further clouded by regulatory actions of local authorities which place restrictions on aircraft that are not in compliance with the then current noise requirements for new type aircraft.

Since derivative programs are required for a commercial transport project to be economically viable, manufacturers and the airlines must have some assurance before launching a new program that there will not be restrictive regulations appearing later which will make it economically impractical to develop derivatives.

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