78-100

Distributed Load Aircraft Concepts

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This paper presents distributed load aircraft design concepts that have as a major goal the significant increase in payload from reduction of the bending moments that are responsible for a large percentage of the structural weight. The judicious use of advanced technology, including composite structure and digital control of active control surfaces for gust alleviation, flutter suppression, and maneuver load control, all contribute to reductions in bending moments to achieve significantly lower structural weight fractions. The paper is based on a performance and economics study of a 2.8×10^6-lb gross weight distributed load freighter. The results show significant potential improvements in energy conservation and operating economics when compared to today's aircraft.

I. Introduction

SINCE the advent of the jet engine and the swept wing, airplane performance has been improved primarily by advancements in engine performance. The next potential technical breakthrough in airplane performance appears to be either aerodynamic by means such as laminar flow control, or structural, resulting in lower empty weight, assuming other system elements remain reasonably unchanged.

This paper presents distributed load aircraft concepts designed to reduce significantly the bending moments which are responsible for a large percentage of the structural weight. In designs for very large airplanes, the wing weight can be reduced by placing all of the payload in the wing so that a close match is obtained between aerodynamic loading and mass loading.

Distributed load technology is aimed at the 1995 time period. The judicious use of this advanced technology, including composite structure and digital control of active control surfaces for gust alleviation, flutter suppression, and maneuver load control, all contribute to the reduction in bending moment. The resulting structure, when applied to a constant chord wing, tends to be lighter and less costly due to less structural mass and use of simplified shapes.

The performance and economics of a 2.8×10^6-lb gross weight distributed load freighter (DLF) design, such as the Boeing 759-211, is examined. The data for this aircraft configuration were generated during a NASA/Air Force funded program. The background data have been accumulated over several years of Boeing IR&D effort and the results show significant potential improvements in fuel consumption and operating economics when compared to today's aircraft.

The comparative data presented in this paper use a current wide-body freighter as a base to provide a recognized standard rather than using an advanced technology conventional design which would be difficult to define within the scope of this paper. Therefore, many differences are found between the airplanes compared, including size, technology, and configuration. However, the comparisons should be useful in indicating the magnitude of performance improvement available in the future.

II. Sources of Potential Improvements

Two equations express the desirable properties of an airplane configuration. The Breguet range equation is an expression of the efficiency of the vehicle. The Direct Operating Cost plus Airplane Investment Cost (DOC + AIC) equation expresses the economic potential of the airplane. An examination of these equations will reveal the sources of potential improvements in airplane design.

$$\text{Range} = V\frac{L}{D}\frac{l}{\text{SFC}} \times \ell n\left[\frac{\text{OEW} + \text{Payload} + \text{Block Fuel} + \text{Reserves}}{\text{OEW} + \text{Payload} + \text{Reserves}}\right]$$

$$\text{DOC} + \text{AIC} = fn \times \frac{k_1(\text{Block Fuel})\text{ Fuel Price} + k_2(\text{OEW})\text{A/P Price \$/lb OEW}}{(\text{Payload})\text{Range}}$$

Where V is airplane velocity, L/D is lift-to-drag ratio, SFC is specific fuel consumption, OEW is operational empty weight, DOC is direct operating cost, AIC is airplane investment cost, and A/P is airplane.

If it may be assumed for the moment that velocity, L/D, and specific fuel consumption are held constant, the parameters affecting both the performance and economic efficiency of the airplane may be expressed as fractions of takeoff gross weight. The reserves, for practical purposes, may be seen as an addition to the OEW. OEW, payload and block fuel are found in both the performance and economic equations and improvement in OEW will automatically increase the payload. At the same time, it has the potential to reduce airplane cost. This strong effect of OEW on fuel efficiency and airplane cost is the reason for examining configurations which may lead to a low OEW fraction and high payload fraction.

The parameters that influence L/D are friction drag and induced drag. Friction drag is addressed by reducing wetted area, eliminating excrescences, optimizing the fineness ratio of the airplane, and observing area rule considerations at the higher Mach numbers. The induced drag portion is largely dependent on span and span load distribution and varies inversely with aspect ratio. The velocity term has been greatly improved with the advent of the jet engine and wing sweep. The trade between L/D and Mach number is addressed by using high-speed airfoil technology that is well understood and is being exploited. The specific fuel consumption term is being improved continually but will reach a plateau as the limits of pressure ratio and turbine inlet temperature are reached.

This paper discusses ways of improving the weight elements of the Breguet range equation and of the economic equation. The weight of a structure is greatly influenced by the loads that the structure is required to carry. The introduction of

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composites and material improvement will reduce the empty weights, but the potential improvements to date have been less than 25%. Also, the theoretical potential is highly influenced by design details. Fuel reserves become significant as the empty-weight fraction is reduced, especially for long-range airplanes which have a small payload fraction. The use of advanced communications and navigation equipment with automatic all-weather landing capability can eliminate the alternate-field portion of the fuel reserve requirement.

The airplane cost equation has, for this discussion, two aspects: the direct operating cost (DOC) and the airplane investment cost (AIC). DOC reflects efficiency, fuel price, and airplane price; and AIC is a function of airplane cost. The DOC + AIC equation may be written using many of the same terms that are found in the range equation (block fuel, payload, and OEW). The constants in the equation represent factors such as crew size, utilization, maintenance factors, and insurance.

Figure 1 shows the bending moments distribution for the major structural components of a conventional wide body freighter configuration. It may be noted that although a portion of the fuel and empty weight of the airplane is distributed in the wings, the body and payload of the airplane are supported at the wing/body junction point near its center of gravity. The bending moments build up as a result of support at that point. Superimposed on Fig. 1, the bending moments of the distributed load airplane have been normalized to the span of a conventional wide body freighter, indicating the relative magnitude of the moments when the loads are fully distributed.

Standard physical scaling laws require that as any given configuration is scaled geometrically, the load is a function of scale squared. Bending moment is a function of scale cubed and the integral of the bending moment is a function of the scale to the fourth power. Since gross weight is a function of scale squared, the scale laws for the integral of the bending moment (which is proportional to structural weight), divided by the airplane gross weight, is a function of scale squared (see Fig. 2). Figure 3 is a plot of the area under the bending moment curves for the whole airplane, normalized to gross weight (psi/lb) as a function of gross weight. Several airplanes of various gross weights are plotted on the chart. The arrows on Fig. 3 at each airplane type are oriented to a scale squared slope. Various configurations have different areas under the bending moment curve as a function of the degree of dead weight bending relief from the nacelles and fuel and also as a function of body length and wing aspect ratio and sweep. The 759-211 would have a value of over 250 psi/lb if a conventional configuration were designed at that size. A value of this magnitude would complicate the structural design and would also be quite heavy. When structure is designed for strength requirements, any increase in bending moments will result in an increase in structural weight. Likewise, any reduction in bending moment will result in a reduction in structural weight. As the bending moment curves are reduced, the limits of weight reduction are reached at a minimum gage wing structure. Some of the wing weight is invested in structure that is not affected by bending moment. Therefore, only a portion of the area under the bending moment curve represents wing structural weight.

The criteria for designing the structure of a distributed load wing are being evolved. If the inertia loads of a distributed load airplane have been perfectly distributed, there will be no net bending moments resulting from those loads. In practice, the structure requirements will be affected by the performance of the control system and also by unavoidable loads such as those due to runway crown. The conventional critical load conditions due to flight loads are all susceptible to the influence of the control system. The definition of the structural loads must be obtained by an interdisciplinary approach which includes the use of active flight critical control hardware that is sufficiently reliable to limit the magnitude of all of the loads encountered in flight and maneuver. Considerable additional work will be required to develop suitable criteria for distributed load configurations.

III. Characteristics of the DLF

Figure 4 is an artist's conception of a typical distributed load aircraft. It is estimated that this airplane could enter service in the 1995 time period. The freight market by the end of the century is expected to be about 115 billion revenue ton miles per year, which is 8 times the current freight market. The airplane is loaded and unloaded through wing tips, using automatic container handling terminals to sort and convey the 8×8×20-ft intermodal containers to the airplane. The wing tips open, as shown in Fig. 5, to allow rapid simultaneous loading of the four bays. The cargo handling system is designed to permit a 30-min turnaround for the airplane. The airplane permits an average utilization of 14 hours a day. It is expected for part of the cycle that around-the-clock utilization will be achieved by using quick-change landing gear and engine nacelle features, together with an onboard system management and diagnostic capability.

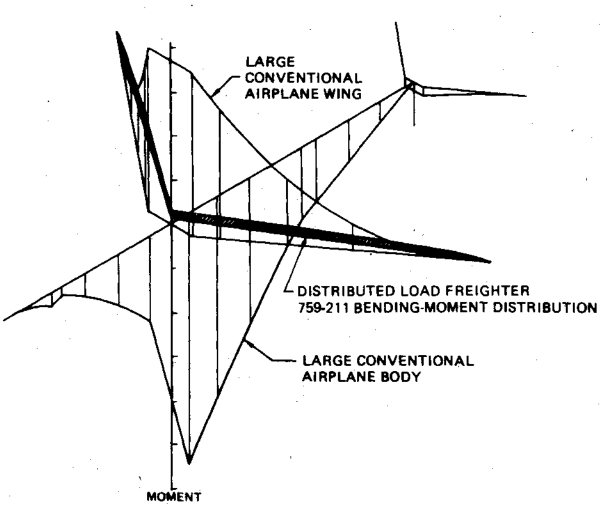


Fig. 1 Bending-moment distribution comparison

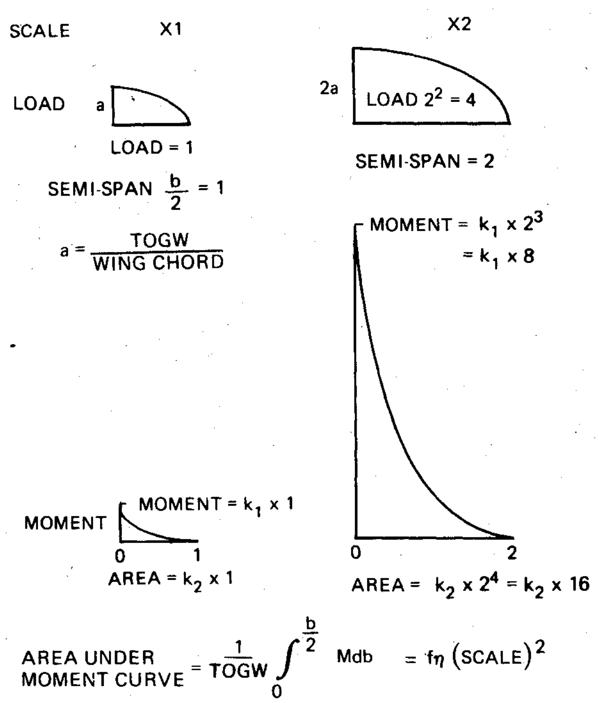


Fig. 2 Description of scaling laws.

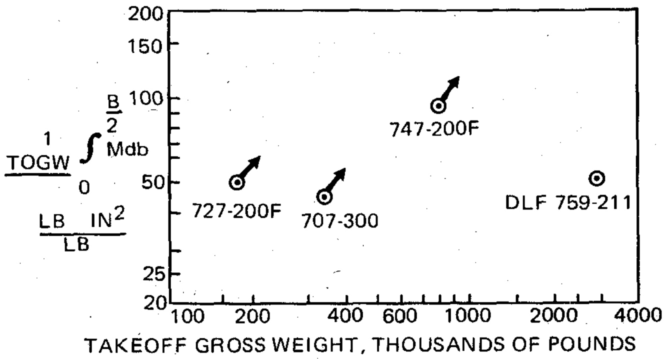


Fig. 3 Total area under ultimate bending-moment curves.

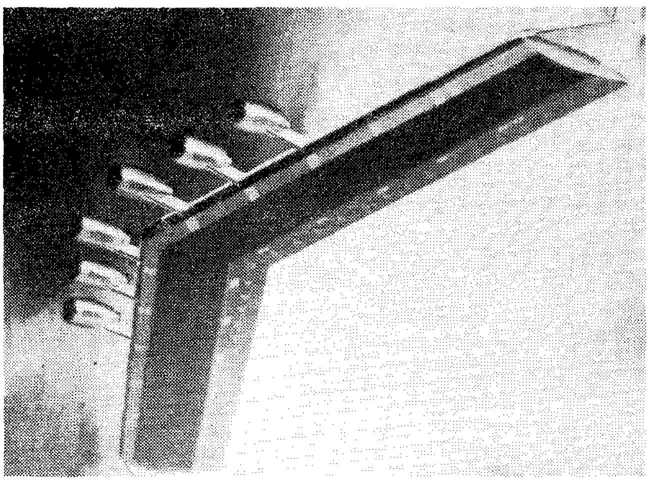


Fig. 4 Distributed load freighter.

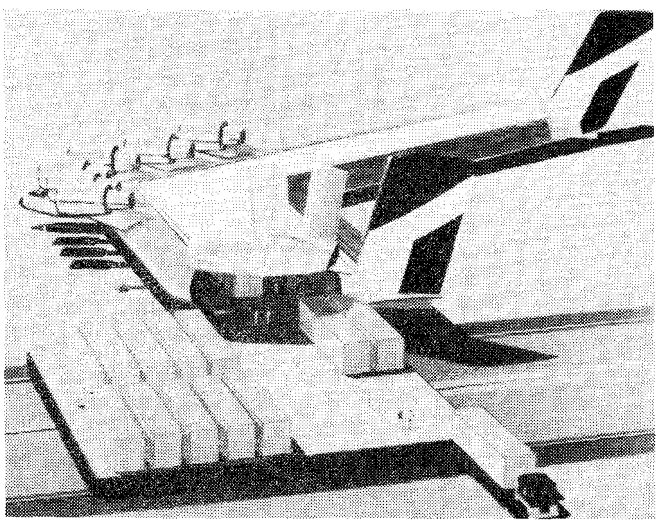
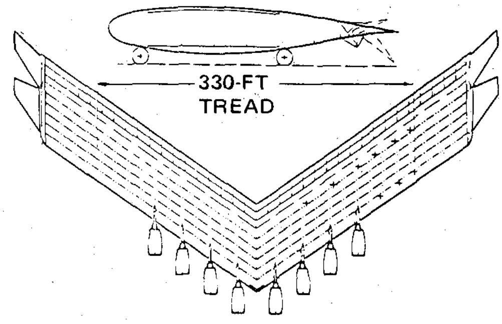


Fig. 5 Cargo loading through the wing tips.

Distributed load freighters that have been studied are extremely large airplanes, with wing spans up to 2½ times greater than the largest aircraft currently in operation. Multiple landing gears are necessarily distributed along the span to preclude concentrated loads that would be incompatible with the minimum gage structure. Specialized airports with runways as wide as 500 ft are needed to accommodate this type of an airplane. The takeoff field length required for the DLF, however, is less than that for conventional freighters because of the low wing loading. A global air transportation system employing this aircraft would require several "hub" airports at specific locations throughout the world.



Range	3600 nmi
Payload (gross)	1,400,000 lb
TOGW	2,828,650 lb
OEW	832,200 lb
Wing area	40,731 ft^2
Basic aspect ratio	4,902
Effective aspect ratio	7,868
Wing span (total)	503 ft
Sweep	35°
t/c	0.16
Cruise Mach	0.85
Engines: BPR	9.5
SLST	84,500 lb

Fig. 6 Boeing model 759-211 design.

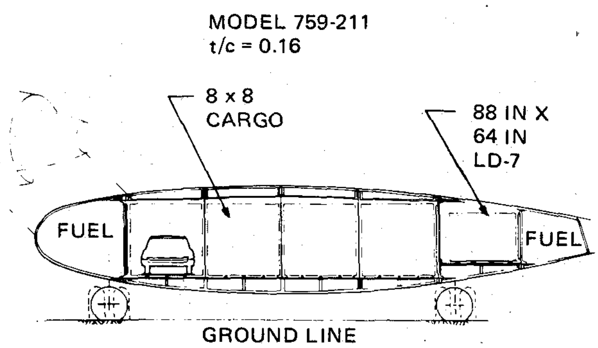


Fig. 7 Distributed load freighter wing cross section.

Figure 6 shows the general arrangement of the Boeing 759-211. This design has a gross weight of 2.8×10^6 lb, a range of 3600 miles, and carries 104 $8\times8\times20$-ft containers for a total payload weight of 1.4×10^6 lb at Mach 0.85. Because the combined landing gear tread is 330 ft, the required runway width is 430 ft. The wing loading is only 70 psf, and the thrust requirements are 84,500 lb per engine, which is in accordance with engine growth predictions for the 1995 time period.

Takeoff rotation for large swept flying wings poses a difficult landing gear arrangement problem. If the airplane is to rotate before lift-off, the landing gear must be long enough to permit clearance of the wing tips. The landing gear is not only heavy but results in concentrated loads which are not readily introduced into a distributed load structure. The ability to achieve lift-off without rotation is an important consideration in configuring a distributed load airplane. The 759-211 uses ground effects for lift-off and its flaps are fully deflected. The control system is fully active and programmed so that as soon as the airplane has lifted off, rotation is accomplished and a new flap trim position is automatically achieved. This results in a second-segment climb gradient that is most favorable with respect to field length and airport noise.

Figure 7 shows a cross section of a distributed load flying wing. Cargo is distributed between front and rear spars to make efficient use of the volume of the wing cross section. Fuel is carried in the leading and trailing edges.

The wing structure consists of over 300 identical ribs made of bonded graphite epoxy honeycomb on 30-in. spacing. The wing surfaces consist of graphite epoxy honeycomb made in continuous 103-in. wide planks. The planks are 1.5-in. thick and 260-ft long, and are joined at the airplane centerline. The shear loads are carried by honeycomb front and rear spars. Tension ties between the upper and lower surfaces provide reaction for pressurization and airloads. The additional space aft of the 8×8 cargo container area is sufficient for an LD-7 container or for automobile transport. The LD-7's are spaced so that the aft landing gear may be retracted between the containers, but when the gears are extended the containers are free to move to the end of the wing for loading and unloading. The engine nacelles are mounted between the same fuel bulkheads that form the wheel wells, permitting common local structure to be use for both landing gear loads and engine loads. The constant chord wing, the highly repetitive structural details, the lightweight gages, and the lack of fastenings all combine to make a structural concept so simplified that the airplanes should be produced at a relatively low cost. The thickness ratio of the wing is 16% normal to the leading edge. The leading-edge tanks are protected from bird strike by a high deformation aluminum honeycomb leading-edge construction over the forward part of the fuel tank. Much of the fuel is carried in the trailing-edge tanks, the leading-edge tanks serving the function of feeder tanks. The airplane is balanced with a nominal c.g. at 40% of the mean aerodynamic chord.

To maintain good span load distribution on the ground, 24 identical landing gear units, each similar in size to the 747 nose gear, are distributed along the front and rear spars. This placement is a good landing gear arrangement with favorable weight. The landing gear retracts vertically and is stowed in the leading and trailing edges between fuel tanks. The landing gear is steerable to permit crosswind landings.

The low ground clearance is an advantage in handling cargo. The cargo deck height is 60 in. The engines are located over the wing in order to achieve the benefits just described. Engine thrust-augmented lift results in favorable lift and pitching moment effects in the low-speed region. The over-wing blowing was shown through analysis to have a negligible effect at cruise speeds.

IV. Control Systems

The 1995 time period will probably see the universal application of digital controls and fly-by-wire or fiber optics. Large airplanes with the multisegmented controls will be very difficult to connect to the pilot by means of mechanical control systems, so the use of advanced controls technology is an integral part of the distributed load concept. An essential function of flight controls will be to regulate flight loads at all times and, as such, the controls will become as important to the airplane as the primary structure itself. Achieving the integration of flight controls and structures by 1995 is a challenging goal for the flight controls discipline.

The design calls for a two-man crew. Essentially all of the airplane operations required for both control of the systems and the airplane itself will be handled by four independent digital computers. Each computer will be able to diagnose failures in any other computer and to reprogram essential elements to restore computer operation.

The stability and control of swept wing airplanes is very similar to that of any other configuration. The airplane must be balanced and it must have enough control power to execute the required maneuvers. The use of full-span controls in addition to the tip fins must result in enough control over the existing variables to provide a satisfactory solution to every flight condition.

The control surfaces function both as flaps and primary flight controls. The wingtip fins provide directional and engine-out control. Operated together, they function as both a redundant pitch control and as side force generators. The airplane with this system is capable of direct lift control, permitting a flat landing attitude. The large span makes it

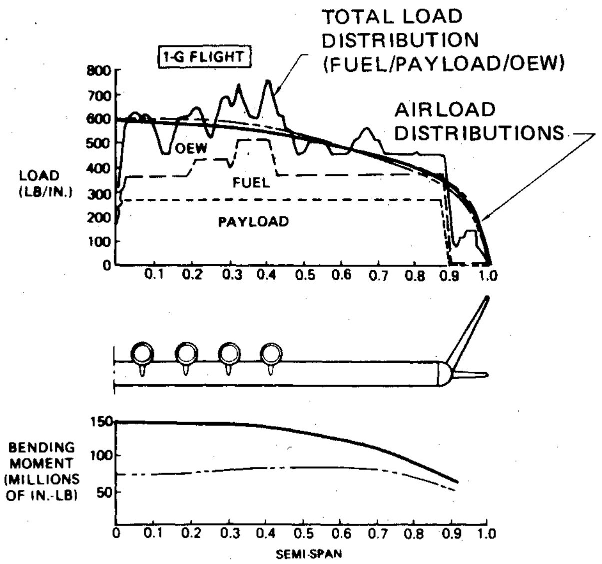


Fig. 8 Span load distribution model 759-211.

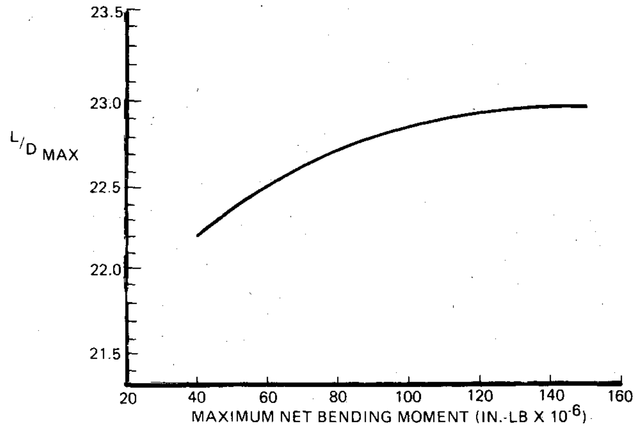


Fig. 9 Lift-dependent drag as a function of maximum net bending moment.

desirable to land at very small roll angles, and it is probable that a tight control on roll will be maintained automatically during landings. It is assumed that the airplane will have a Category III landing system, which should eliminate the requirement for an alternate field, and thus the alternate field reserves for airplanes with this capability also should be eliminated.

V. Span Load Distribution

Figure 8 shows the span load distribution for the model 759-211. The payload, for purposes of this diagram, is uniform. The fuel load is shown above the payload. The empty weight fraction is then added to the payload plus fuel. Two airload distributions are shown to the proper scale and the resulting bending moments are shown in the curves immediately below. The figure shows the strong influence of airload distribution on bending moment and the importance of the tip fins in producing an efficient spanwise airload distribution. The simple rectangular planform that houses the payload is not nearly as efficient as a more tailored planform in producing the elliptical load distribution. The tip fins carry the required lift to increase effective aspect ratio from 4.9 to 7.9. This results in significant improvements in L/D without a significant penalty on wing bending moment.

Whereas normal airplane configurations with tapered wings require considerable twist to prevent tip stall, the rectangular wings on distributed load airplanes will have lower section lift coefficients at the tip. Therefore it is possible to build the

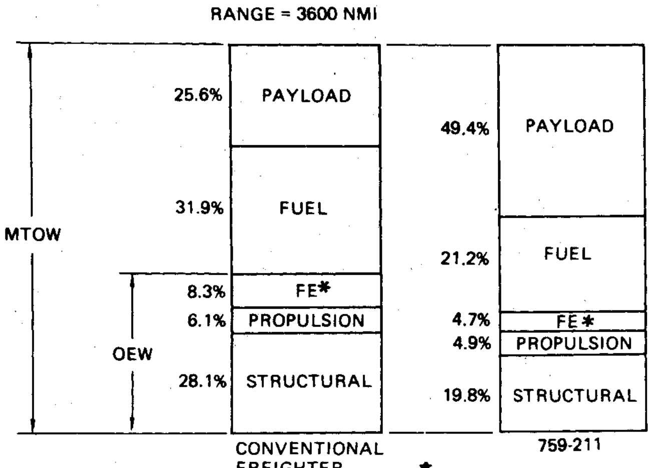


Fig. 10 Weight distribution comparison.

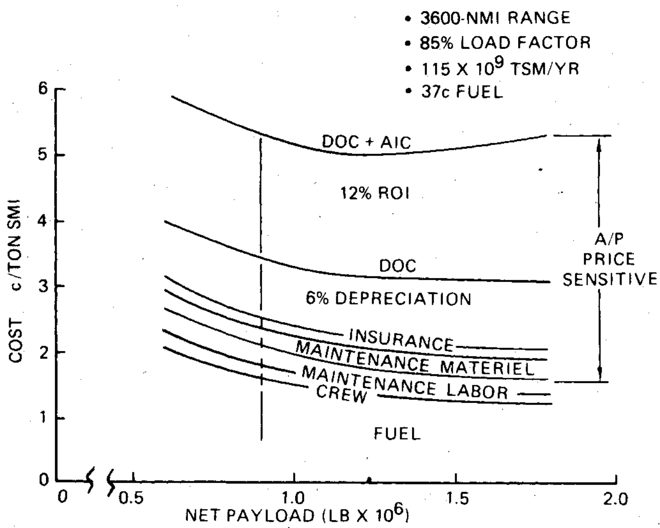


Fig. 11 Operating cost breakdown, distributed load freighters.

basic wing box without twist and to control the span load distribution with relatively small deflections of the control surfaces.

The use of wingtip fins, or winglets, on conventional tapered wings has a much smaller aerodynamic impact than using tip fins on a rectangular planform. The tapered wing has a relatively short chord on which to mount wingtip fins, and as a result, has limited capability to support fins beyond a certain size. A rectangular planform, on the other hand, has ample space and strength at the tip to support the fins, and the selection of the tip fin size is still an open configuration decision.

Figure 9 shows the relationship of L/D (as influenced by induced drag) to bending moment as a function of the span load distribution. An optimum L/D can be achieved with relatively small bending moments. The span load distribution may be governed by the control system to provide the airplane with an optimum span load within the structural capabilities of the wing.

Figure 10 shows the weight breakdown comparison between a conventional wide-body freighter and the 759-211. It demonstrates that the 759-211 has a lower OEW fraction, a lower fuel fraction, and a large payload fraction.

It should be noted in this comparison, and in those that follow, that 20 to 30 years separate the technologies of today's freighters and distributed load freighters. A comparison of the current wide-body performance with airplanes designed 15 years earlier would show similar large changes.

Conventional Freighter	3600	14900	.44	.23	.28	.05
759-211	3600	18744	.29	.49	.19	.02

$$\text{Range} = V\,\frac{L}{D}\,\frac{1}{SFC}\,\ln\left(\frac{\text{OEW}+\text{Payload}+\text{Block Fuel}+\text{Reserves}}{\text{OEW}+\text{Payload}+\text{Reserves}}\right)$$

$$\text{DOC}+\text{AIC}=\text{fn}\left[k_1\frac{(\text{Block Fuel})\,\text{Fuel Price}}{(\text{Payload})\,\text{Range}}+k_2\frac{(\text{OEW})\,\text{A/P Price \$/lb}}{(\text{Payload})\,\text{Range}}\right]$$

Conventional Freighter	5.58+1.78	(1.22)	(1.91)
759-211	2.75+1.55	(.38)	(.59)

Fig. 12 Cost equations comparison.

VI. Limiting Cost Factors

When airplanes as large as the 759-211 are built and a fleet has relatively few airplanes, investment cost will have a strong influence on the selection of airplane size. Figure 11 shows the result of a parametric study of distributed load freighters.

When airplane size is increased, fuel cost and maintenance labor are reduced. Crew costs are reduced because the crew size is held constant with airplane size. A parallel may be seen in the shipping industry where large supertankers are being built to take advantage of the economies of scale. However, according to the airplane price sensitive parts of the plot in Fig. 11, the improvement in performance is outweighed by the airplane cost parameters. Therefore, airplanes larger than the 759-211 would be less efficient. Trade studies based on the normal DOC formulas do not take adequate account of the airplane investment cost. When added to the depreciation, insurance, and maintenance material, they completely offset the improvements in performance and result in an airplane size selection controlled by airplane price sensitive parameters.

It is important, therefore, to develop adequate cost-estimating procedures for airplanes that are not in the historic cost data base. Fortunately, the structure of distributed load airplanes is very simple compared to conventional configurations, allowing fairly detailed structural designs to be developed and costed to form an adequate cost data base.

The airplane investment cost parameter in the DOC + AIC formula is influenced by the overall design of the configuration. Because of constant section geometry, there are many repetitive structural details and the simplified arrangement can result in relatively few highly loaded joints. The uniform bending moments in the structure may be handled by long, practically constant-section structural elements that are joined at the airplane centerline. The low bending moments of this configuration may be carried by relatively light gages. In many instances, minimum gages are established by other factors such as hail damage and servicing requirements. These long, light, uniform structures are easily adapted to automation. Manufacturing estimates for this design show a part card count significantly lower than for conventional wide-body freighters in spite of the fact that the DLF is several times larger.

VII. Airplane Performance

If we examine the range equation and the cost equations in Fig. 12, and compare the advanced technology of the 759-211 design with a current wide-body freighter, we note that the range factor ($V \times L/D \times$ SFC) has been improved by 26%. A small improvement in velocity and a considerable improvement in L/D has been achieved. It is estimated that there will be a 25% improvement in specific fuel consumption by 1995. The OEW fraction has been improved 52% and the block fuel is greatly influenced by the improved L/D, SFC, and OEW. The reserves are much smaller because of the use of automatic landing systems. The result is an increase in the

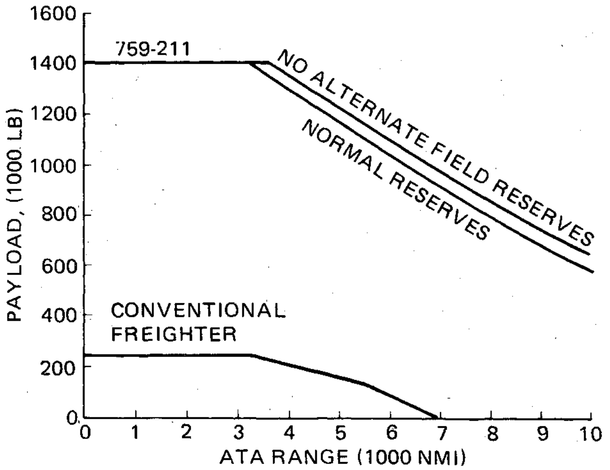


Fig. 13 Payload/range comparison, 759-211 vs conventional freighter.

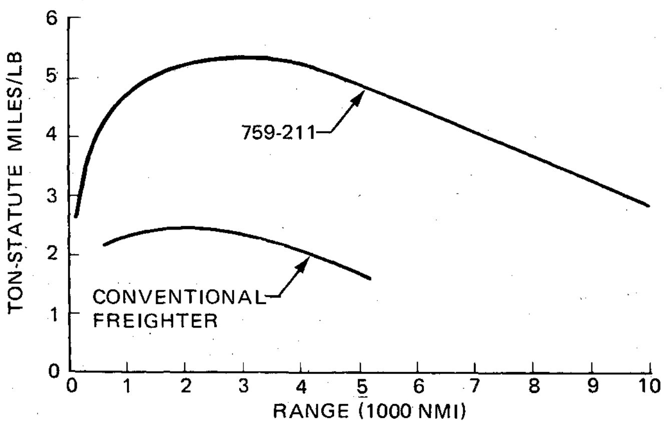


Fig. 14 Effect of range on fuel efficiency.

payload-to-OEW ratio from 52% for the conventional freighter to 169% for the 759-211.

The weight fractions defined in the range equation may be evaluated in the economic equation. The ratio of block fuel to payload and OEW to payload are shown in parentheses below the economic equation. The improvement in these parameters is significant. There is a 51% reduction in DOC and a 15% reduction in AIC, or an overall economic improvement of 42%. (Note that k_1, k_2, and the airplane price per pound do not remain constant for the two configurations.)

Figure 13 compares the 759-211 and conventional freighters on payload range curves, and it shows the incremental performance available through the elimination of the alternate field reserve. The curve also shows the extreme ranges available when at lower payload values.

Figure 14 shows the effect of range on fuel efficiency of a conventional wide-body freighter. A better than 2 to 1 improvement is achieved. At a 5,000-mile range, the figure is increased to almost 3 to 1.

Figure 15 compares the DOC of a conventional wide-body freighter with that of the 759-211. One noteworthy feature of these data is the extremely flat curve as range increases.

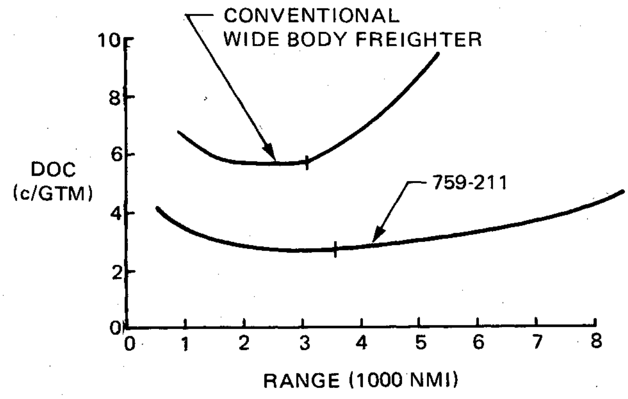


Fig. 15 Economic comparison, 759-211 vs conventional freighter (fuel at 37¢/gal.).

Studies to date have narrowed to a configuration type that should be competitive in the freight market of the future. These studies have been limited to rigid cases; the effects of aeroelasticity on the configuration are not known. The degree of bending moment control available is also part of the aeroelastic study and will determine what strength and stiffnesses are required. Aeroelastic studies currently underway are encouraging. They indicate that the weight penalties for the aeroelastic factors may not be large and the upper limits to size are still undefined.

The minimum size (about 1.5×10^6 lb gr wt) that is effective with full distributed load configurations is limited by the density of the payload. The 8×8 container is about the minimum size to provide adequate wing loading. For smaller airplanes, other designs will be needed.

VIII. The Future of DLF Technology

Distributed load technology has progressed to the point where it may be established as a configuration option to be considered for the 1995 time period. Feasibility of ground effect takeoff and landing and some structural concepts for large lightweight construction have been achieved.

To further confirm and optimize distributed load configurations, several developmental factors need immediate study. They include the following: aerodynamic optimization of thick airfoils, aeroelastic studies to determine the limits to airplane size, control studies to determine the degree of bending moment control available, improved cost estimating techniques for low quantities of vehicles, and other configuration arrangements to reduce bending moments of smaller airplanes. All competitive ideas will be judged ultimately on the basis of the improvements to the range and DOC + AIC equations that have been considered, and each successful configuration concept must achieve improvements of varying degrees on most elements of the equations.

Acknowledgment

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