The Effect of Demand on Optimum Launch Vehicle Size

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THE reduction in operating costs associated with increasing vehicle size (economy of scale) is a well-known phenomenon common to both air and space transport vehicles. In order to realize the full effect of this reduction, however, load factor and utilization must remain constant as size increases. This implies a demand increasing as available capacity increases—in effect, an unlimited demand. In the air transportation market demand is usually limited. Hence a wide spectrum of aircraft sizes are available to fit specific market requirements with later configurations tending to lower rather than higher gross weights.

It is interesting to examine the optimum launch vehicle size for both unlimited and limited demands using direct operating cost per pound of payload carried to low earth orbit (LEO) as the measure of effectiveness.

The direct cost per pound in LEO includes a nonrecurring cost (mainly development), a recurring production cost, a recurring refurbishment cost (equivalent to vehicle maintenance), and the cost of fuel. If N vehicles are bulit and each vehicle is reused n times, then the nonrecurring cost, expressed as dollars per pound in orbit, is

$$\frac{C_0}{N} \times \frac{1}{n} \times \frac{\mathrm{WE}}{\mathrm{WL}}$$

where WE is the empty or inert weight, WL is the payload weight, and C_0 is the development cost in \$/lb of inert weight. The average recurring costs are

$$\frac{C_I}{1-p}\,[N(1+nq)]^{-p}\left(q+\frac{1}{n}\right)\frac{\mathrm{WE}}{\mathrm{WL}}$$

where C_I is the cost of the first vehicle in \$/lb and p is defined by the learning curve $C(N) = C_I N^{-p}$. For a 90% learning curve slope, p is 0.15. The refurbishment cost after each reuse is expressed as a fraction q of the production cost. It is assumed that both maintenance labor and spares procurement contribute to learning. Fuel costs are taken as \$0.12 WF for a LH/LOX mix where WF is the fuel weight.

In the absence of statistical information on a representative family of reusable and winged launch vehicles, it will be assumed that costs will follow the trends previously exhibited by commercial transports. For these aircraft, maintenance costs q are substantially independent of weight but have decreased substantially with time.[1] Flyaway costs, on the other hand, would be expected to increase very approximately as the ⅔ power of weight empty WE, and hence C_0 and C_I would be expected to decrease as the ⅓ power of WE. Actual costs, however, have varied widely depending on category. At the lower end of the weight scale, general aircraft have averaged about \$20/lb of WE, and this cost has increased almost directly as weight empty. On the other hand, jet transports have averaged about \$100/lb of WE, this figure remaining substantially independent of weight over the existing spectrum, but increasing appreciably with time at constant dollars. Learning and technological complexity must therefore be considered when predicting flight vehicle costs.

It is probable that for reusable space transports, C_0, C_I, and q will also be substantially independent of weight empty; however results have been presented both for this case and for the case where C_0 and C_I decrease as the ⅓ power of WE. Reference 2 shows additional effects of parameter variation on launch costs.

Reasonable estimates of C_I and C_0 would be, based on the complete space shuttle system with an inert weight of about 500,000 lb:

$$C_I \simeq \$300/\mathrm{lb} \qquad C_0 \simeq \$10{,}000/\mathrm{lb}$$

Figure 1 shows the ratio WE/WL and WF/WL for a family of hypothetical, fully reusable, two-stage launch vehicles with both stages manned and winged. Cargo is assumed to be carried externally, one way to orbit. The improvement in efficiency, as evidenced by the reduction in these ratios with size, is associated with the reduction in fuel tank weight with size, assumed to vary as 0.2 $\mathrm{WF}^{0.90}$, and with the fact that for

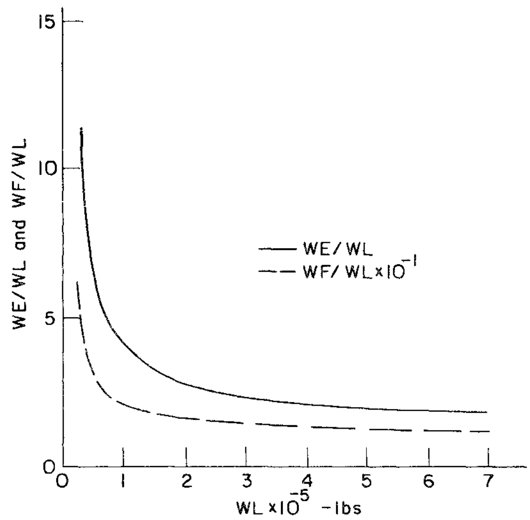

Fig. 1 Ratios of inert weight WE and fuel weight WF to payload weight WL, as a function of WL.

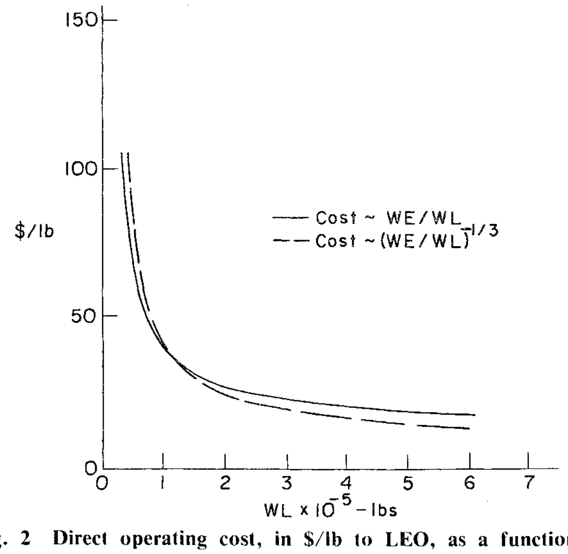

Fig. 2 Direct operating cost, in \$/lb to LEO, as a function of payload weight WL for unlimited demand.

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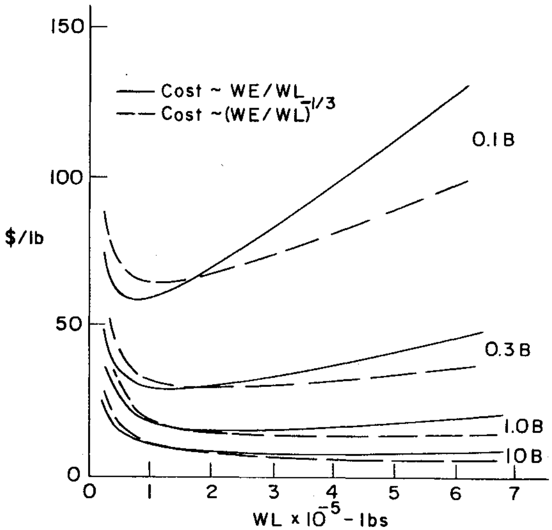

Fig. 3 Direct operating cost, in $/lb to LEO, as a function of payload weight WL for various demands, expressed in billions of pounds to LEO.

a man-rated system fixed equipment associated with environmental control, furnishings, auxiliary power, and avionics are substantially independent of payload weight.

Figure 2 shows the corresponding direct costs for the case of an unlimited demand with $N=20$, $n=100$, and $q=0.01$.

Figure 3 shows the corresponding values for various constant (limited) demands. For these latter cases, N is not fixed but depends on the demand, defined as the total weight to be placed in orbit, or

$$N=\frac{\text{Weight in orbit}}{\text{WL}\times n}$$

Considering a specific example, a satellite solar power (SPS) system may be expected to weigh of the order of 0.1×10^9 or 0.1 billion pounds. A vehicle of about the size of the space shuttle or shuttle derivative, with a payload of about 100,000 lb would appear to be not far from optimum, at least up to a demand level equivalent to the delivery in LEO of ten SPS's. With higher demands some improvement is indicated with the larger vehicles. It is also evident from Fig. 3 that, in addition to the obvious need for reusability, a large demand leading to high utilization of the system is the key to low transportation costs, as has been amply demonstrated by the world air transport systems.

Other factors, contributing more to indirect costs, have influenced the choice of optimum aircraft size. Larger vehicles are dictated by considerations of terminal congestion, both air and landside, while the need for high frequency of services and an even load on ground facilities dictates smaller vehicles. Similar factors may eventually have to be taken into consideration in planning space transportation systems.

In predicting the ultimate cost of near-earth space transportation, it may be noted that the energy required for insertion into LEO is only of the order of four times that required for the round trip by air from Los Angeles to London (LA/LHR/LA) and that the latter trip is available at about $2½/lb, including indirect costs, with a vehicle whose value of WE/WL is also about 5. However, for this system n is of the order of 2000 and q of 0.001. If these figures could be achieved with the postulated space transportation system, the direct cost to LEO would be about $6/lb for 10^{10} lb in orbit, a tonnage that is still only a small fraction of that which the worldwide air transport system delivers yearly. Indirect costs may be expected to raise direct costs by about 50-100%, giving an eventual cost to LEO of about $10/lb.

Concentrating on reducing refurbishment costs q and increasing utilization n, once a suitable configuration has been developed, would therefore appear to be a more promising means of reducing space transportation costs than increasing payload capacity, at least until such time as traffic has increased substantially beyond that envisaged for the next few decades.

References

[1] Miller, R.H., "Some Air Transportation Concepts for the Future," *Journal of the Royal Aeronautical Society,* Vol. 76, July 1973, p. 436, Fig. 7.

[2] Miller, R.H. and Akin, D.L., "Logistic Costs of Solar Power Satellites," IAF Paper 78-186, Dubrovnik, Yugoslavia, Oct. 1978, MIT-SSL Rept. No. 3-78.