Technology for Design of Transport Aircraft

Lecture Notes for MIT Courses

Sem. 1.61 Freshman Seminar in Air Transportation

and

Graduate Course 1.201, Transportation Systems Analysis

Robert W. Simpson

Flight Transportation Laboratory, MIT

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A) Measures of Performance

The common measures of performance for a transport aircraft are listed below:

1. Cruise Performance - Payload (passengers) versus Range (s. miles)
2. Cost Performance - ($/block hour, $/available seat mile)
3. Runway Performance - takeoff and landing distances (feet)
4. Speed Performance - max. cruise speed (mph)
5. Noise Performance - noise footprint size, or peak noise (PNdb)

For a long range transport aircraft, the designer maximizes cruise and cost performance subject to constraints specified for takeoff and landing, speed, and noise performance. If the designer optimizes takeoff and landing performance as for STOL or VTOL transport aircraft, then cruise performance will be less than optimal, and these aircraft will only perform well over short cruise ranges. Introduction of noise constraints into the design of transport aircraft requires good knowledge of the noise generation characteristics of engines and other propulsive devices as a function of size and technology, and like all constraints will cause less than optimal cruise and takeoff and landing performance.

The designer's problem is to create an aircraft design which is matched to some design mission stated in terms of desired or required levels of these measures of performance.

Here we shall discuss the design parameters which determine cruise performance for a conventional subsonic jet transport, and fix other design considerations. We shall assume the aircraft burns climb fuel to reach cruising altitude, and ask ourselves how far the aircraft can carry a given payload at cruising altitude. This simple analysis brings out the major factors in establishing the cruise performance. We shall see how the current state of aeronautical technology determines the current size of transport aircraft, (and therefore its operating cost) and how different sizes of transport are needed to provide the cost optimal vehicle for different
given payload-range objectives.

B) Technology

We have three areas of aeronautical technology, aerodynamics, structures, and propulsion, which keep improving, and which cause newer aircraft to be superior as time goes on. In discussing cruise performance, we will use a single measure for the level of technology in each area.

Areas of Technology

<table>
<thead>
<tr>
<th>Areas of Technology</th>
<th>Measure of Technology Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Aerodynamics</td>
<td>$V(L/D) = \text{speed} \times (\text{lift/drag ratio in cruise})$</td>
</tr>
<tr>
<td>2. Structures</td>
<td>$W_E/W_G = \text{empty weight fraction}$</td>
</tr>
<tr>
<td></td>
<td>= (operating empty weight/gross weight)</td>
</tr>
<tr>
<td>3. Propulsion</td>
<td>SFC = Cruise specific fuel consumption $\left(\text{lbs. of fuel per hour/lbs. of thrust}\right)$</td>
</tr>
</tbody>
</table>

B.1 Aerodynamics Technology

The lift/drag ratio, $L/D$, in cruise for present subsonic aircraft is a number like 16-17, i.e. for every 16 lbs of weight, there is a requirement for 1 lb of thrust. The steady state forces on the aircraft are shown in Figure 1. The aircraft weight $W_G$ equals the lift $L$. Dividing the lift by the $L/D$ ratio gives the drag $D$, which requires an equal thrust, $T$.

While $L/D$ ratios of up to 40 can be obtained for sailplanes at low speeds by using large span, high aspect ratio wings and good airfoil sections, the objective for transport aircraft turns out to be the maximization of the product of speed and $L/D$, i.e. to achieve good $L/D$ values at higher speeds. This objective must be compromised by aerodynamic requirements for takeoff and landing performance which demand a larger wing area than otherwise would be used for cruise.

A plot of values of $V(L/D)$ is given by Figure 2 which shows the
Figure 1  STEADY STATE FORCES IN CRUISE

LIFT $L =$ WEIGHT $W_G$
THRUST $T =$ DRAG, $D$
CRUISE SPEED $V$, MPH
Figure 2  TREND OF V(L/D) FOR TRANSPORT AIRCRAFT

V (L/D) MPH

14000
11500
8500
5750
0

YEAR

PISTON TRANSPORTS

DC-3

DC-6

SUBSONIC JETS

TREND LINE

LFC
SCW

SST
steady improvement for transport aircraft over the past 35 years. These improvements have been developments like laminar flow airfoils, thinner wings, swept wings, higher wing loadings in cruise because of better high lift devices, etc. The supercritical wing section (SCW) and perhaps laminar flow control (LFC) wing are developments which have promise of continuing improvement.

Notice that although the SST has L/D values of only 8, its speed on the order of 1800 mph gives very high values for \( V(L/D) \).

B.2 Structures Technology

Here we use the "empty weight fraction" as a measure of structures technology although it contains other than the weight of the aircraft structure.

We shall use the following, non-standard breakdown of the weight of a transport aircraft:

We define \( W_G \) = takeoff gross weight
\( W_i \) = initial cruise weight
\( W_{Gi} \) = final cruise weight

The total fuel load is divided into:
\( W_F \) = total fuel weight
\( W_{FC} \) = fuel burn in climb
\( W_{FB} \) = fuel burn in cruise
\( W_{FR} \) = weight of fuel reserve

Then
\[
W_{Gi} = W_G - W_{FC}
\]
\[
W_{Gf} = W_G - W_{FC} - W_{FB} = W_{Gi} - W_{FB}
\]
For simplicity, we shall ignore fuel burn in descent, and range during climb, and shall be computing only range in cruise. We shall assume that \( W_{FC} = W_{FR} = 5\% \) of \( W_G \).

We define the operating weight empty, \( W_E \), as made up of:

\[
W_E = W_S + W_{FE} + W_{PP} + (W_{FR})
\]

where
- \( W_S \) = weight of aircraft structure
- \( W_{FE} \) = weight of furnishings and equipment (pilots, seats, galley, toilets, radios, etc.)
- \( W_{PP} \) = weight of power plant
- \( W_{FR} \) = weight of reserve fuel.

Notice that for convenience, we include the reserve fuel in the "operating weight empty" although that is not standard practice.

We define the useful load, \( W_U \), as the difference between the initial cruise weight, \( W_{Gi} \) and \( W_E \)

\[
W_U = W_{Gi} - W_E = W_G - W_{FC} - W_E
\]

The useful load will consist of some combination of payload, \( W_p \) and fuel burn in cruise \( W_{FB} \). We are going to examine the effects of range requirements on the payload fraction, \( W_p/W_G \), which can be achieved. As range is increased, more of the useful load must be devoted to fuel, thereby decreasing the payload fraction.

Typical values of the "empty weight fraction" (without reserve fuel) for current aircraft are given by Table 1. Notice that the empty weight fraction is roughly 50\%, and that lower values are obtained for long haul, large size aircraft, where emphasis is placed upon achieving a low value, and where some economy of scale
TABLE 1. Typical Values of Basic Empty Weight/Max Gross Weight

<table>
<thead>
<tr>
<th>Passenger Aircraft</th>
<th>Empty Weight Fraction</th>
<th>Max. Gross Weight</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>747</td>
<td>.491</td>
<td>110.0</td>
<td>5,790</td>
</tr>
<tr>
<td>DC-10-10</td>
<td>.474</td>
<td>555.0</td>
<td>5,400</td>
</tr>
<tr>
<td>L-1011</td>
<td>.550</td>
<td>426.0</td>
<td>2,878</td>
</tr>
<tr>
<td>DC-8-63</td>
<td>.437</td>
<td>350.0</td>
<td>4,500</td>
</tr>
<tr>
<td>707-320B</td>
<td>.423</td>
<td>327.0</td>
<td>6,160</td>
</tr>
<tr>
<td>727-200D</td>
<td>.552</td>
<td>175.0</td>
<td>1,543</td>
</tr>
<tr>
<td>Trident-3B</td>
<td>.554</td>
<td>150.0</td>
<td>2,430</td>
</tr>
<tr>
<td>Mercure</td>
<td>.557</td>
<td>114.6</td>
<td>1,100</td>
</tr>
<tr>
<td>DC-9-40</td>
<td>.488</td>
<td>114.0</td>
<td>1,192</td>
</tr>
<tr>
<td>737-200B</td>
<td>.538</td>
<td>109.0</td>
<td>2,135</td>
</tr>
<tr>
<td>BAC-111-475</td>
<td>.532</td>
<td>97.5</td>
<td>1,682</td>
</tr>
<tr>
<td>F-28-2000</td>
<td>.557</td>
<td>65.0</td>
<td>1,301</td>
</tr>
<tr>
<td>VFW 614</td>
<td>.656</td>
<td>41.0</td>
<td>1,553</td>
</tr>
<tr>
<td>VAK-40</td>
<td>.570</td>
<td>36.4</td>
<td>807</td>
</tr>
<tr>
<td>Falcon 20T</td>
<td>.607</td>
<td>29.1</td>
<td>641</td>
</tr>
<tr>
<td>DHC-6</td>
<td>.560</td>
<td>12.5</td>
<td>745</td>
</tr>
<tr>
<td>Concorde SST</td>
<td>.44</td>
<td>885.0</td>
<td>4,020</td>
</tr>
<tr>
<td>S-61 helicopter</td>
<td>.62</td>
<td>19.00</td>
<td>275</td>
</tr>
</tbody>
</table>

Freighters

<table>
<thead>
<tr>
<th>Freighter</th>
<th>Empty Weight Fraction</th>
<th>Max. Gross Weight</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>747F</td>
<td>.428</td>
<td>775.0</td>
<td>2,880</td>
</tr>
<tr>
<td>CSA</td>
<td>.425</td>
<td>764.5</td>
<td>3,500</td>
</tr>
<tr>
<td>707-320C</td>
<td>.402</td>
<td>332.0</td>
<td>3,925</td>
</tr>
<tr>
<td>L100-30 (Cl30)</td>
<td>.468</td>
<td>155.0</td>
<td>2,800</td>
</tr>
</tbody>
</table>

(Source: Jane's 1971-72)

-7- x 10^3 lbs. St Miles
may occur for fixed equipment like radios, galley, etc.

The major portion of the empty weight fraction is the structures weight, $W_s$, which is usually 30% of the gross weight. A diagram of the value of the "structures weight fraction" is shown by Figure 3. Since the construction of the DC-3 there has been very few basic changes in structural technology. However, there is considerable promise currently of new developments which use composite materials, and different construction techniques to provide extremely light weight and rigid structures. These are expensive now, but future development work may reduce their costs.

B.3 Propulsion

The specific fuel consumption is given in terms of rate of fuel burned per lb. of thrust for the engine. Here we want the cruise SFC values at cruise altitude and speed. For the early jets, SFC had a value of roughly 1.0 in cruise, which meant that a 10,000 lb. thrust engine would consume 10,000 lbs. of fuel in one hour. For present fan engines, SFC is roughly 0.6, so that only 6,000 lbs of fuel per hour would be consumed by current engines.

Another common measure of propulsion technology is the thrust to weight ratio of the engines, but here we have made it a part of the operating weight fraction as a measure for structur...
<table>
<thead>
<tr>
<th>Engine</th>
<th>Bypass Ratio</th>
<th>Thrust (lbs)</th>
<th>SFC</th>
<th>Mach</th>
<th>Altitude</th>
<th>SFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT3-C</td>
<td>0</td>
<td>13,506</td>
<td>0.77</td>
<td>.69</td>
<td>35000</td>
<td>0.92</td>
</tr>
<tr>
<td>CONWAY</td>
<td>0.6</td>
<td>20,400</td>
<td>0.62</td>
<td>.83</td>
<td>36000</td>
<td>0.84</td>
</tr>
<tr>
<td>SPEY</td>
<td>1.0</td>
<td>9,850</td>
<td>0.54</td>
<td>.78</td>
<td>32000</td>
<td>0.76</td>
</tr>
<tr>
<td>JT9-D</td>
<td>1.03</td>
<td>14,000</td>
<td>0.57</td>
<td>.80</td>
<td>35000</td>
<td>0.83</td>
</tr>
<tr>
<td>JT3-D</td>
<td>1.4</td>
<td>18,000</td>
<td>0.52</td>
<td>.90</td>
<td>35000</td>
<td>0.835</td>
</tr>
<tr>
<td>TFE-731</td>
<td>2.55</td>
<td>3,500</td>
<td>0.49</td>
<td>.80</td>
<td>40000</td>
<td>0.82</td>
</tr>
<tr>
<td>M-45</td>
<td>2.8</td>
<td>7,760</td>
<td>0.45</td>
<td>.65</td>
<td>20000</td>
<td>0.72</td>
</tr>
<tr>
<td>CF-6-6</td>
<td>6.25</td>
<td>40,000</td>
<td>0.34</td>
<td>.85</td>
<td>35000</td>
<td>0.63</td>
</tr>
<tr>
<td>ASTAFAN</td>
<td>6.5</td>
<td>1,5622</td>
<td>0.38</td>
<td>.53</td>
<td>20000</td>
<td>0.63</td>
</tr>
</tbody>
</table>
Figure 3  TREND FOR STRUCTURES WEIGHT FRACTION FOR TRANSPORT AIRCRAFT

CONVENTIONAL ALUMINUM ALLOY STRUCTURE

POSSIBLE EFFECT OF NEW COMPOSITE MATERIALS
Figure 4  TRENDS IN PROPULSION – SFC

- TURBOJETS
- FAN ENGINES
- BPR = 5 ENGINES

CRUISE SFC

YEAR

high bypass ratio fan engines over the initial pure jet engines. This improvement is due to better propulsive efficiencies from the fan, improved component efficiencies for engine components like compressors, turbines, combustors, etc., and higher cycle temperatures due to improved materials and technology in the design and construction of the turbine blades.

C) Determination of Range-Payload Performance

C.1 Short Range Aircraft

Where the fuel burn, $W_{FB}$, is a small fraction of $W_G$, we can assume that $W_G$ remains constant during cruise, or $W_G \approx W_G$. If we define $R$ = cruising range (s. miles),

$m = \text{mileage factor, (s. miles per lb. of fuel)}$

Then $R = m \cdot W_{FB}$

We can express $m$ in terms of $V, T, SFC$:

$m = \frac{V}{T(SFC)} = \frac{\text{s.miles/hr}}{\text{lbs of fuel/hr}} = \frac{\text{s. miles}}{\text{lb. fuel}}$

But from Figure 1, $\frac{T}{W_G} = \frac{D}{L}$, or $T = \frac{W_G}{(L/D)}$

$
\therefore \quad m = \frac{V}{SFC} \cdot \frac{(L/D)}{W_G}
$

Substituting $m$ in (1)

$R = \frac{V(L/D)}{SFC} \cdot \left[ \frac{W_{FB}}{W_G} \right] = r \cdot \left[ \frac{W_{FB}}{W_G} \right]$

where $r$ is called "specific range" (s. miles)

and $\frac{W_{FB}}{W_G}$ is called "fuel burn fraction"
Note: \( r \) has the dimensions of s. miles

\[ r \text{ has the dimensions of s. miles} \]

\[ \text{e.g. if } L/D = 16, \text{ SFC} = 0.6 \text{ lbs. of fuel/hr. per lb. of thrust} \]

\[ V = 550 \text{ mph} \]

Then \( r = \frac{550 \times 16}{0.6} = 14,700 \) s. miles

We shall use these assumed values in later examples.

a) If no payload is carried, then \( W_P = 0 \), \( W_U = W_{FB} = W_{Gi} - W_E \),

then the maximum cruise range, \( R_{max} \)

\[ R_{max} = r \left[ \frac{W_{FB}}{W_G} \right] = r \left[ \frac{W_U}{W_G} \right] = r \left[ \frac{W_{Gi} - W_E}{W_{Gi}} \right] \]

\[ = r \left( 1 - \frac{W_E}{W_{Gi}} \right) \] (3)

So, our structures technology parameter is a strong determinant of the maximum range for a fuelled aircraft. If the "empty weight fraction" can be reduced, it increases the "fuel fraction", or "useful load fraction", and thereby the maximum range.

b) If payload is carried, then \( W_{FB} = W_{Gi} - W_E - W_P \), \( W_G - W_E - W_P \)

and for any given payload

\[ R = r \left[ \frac{W_{FB}}{W_G} \right] \approx r \left[ \frac{W_{G} - W_E - W_P}{W_G} \right] \]

\[ = R_{max} - r \left[ \frac{W_P}{W_G} \right] \] from (3)

where \( \frac{W_P}{W_G} \) is called the "payload fraction".

We can plot the payload fraction against \( R \) in Figure 5.
Figure 5  PAYLOAD FRACTION versus RANGE

PAYLOAD FRACTION
$\frac{W_U}{W_G}$

PAYLOAD FRACTION
$\frac{W_E}{W_G}$

SLOPE = $1/r$

$R_{\text{max}}$ ($r_1$)

$R$, CRUISE RANGE (Statute Miles)
where \[ \frac{W_p}{W_g} = \frac{1}{r} \cdot (R_{\text{max}} - R) \] \hspace{1cm} (4)

At \( R = 0 \), \[ \frac{W_p}{W_g} = \frac{R_{\text{max}}}{r} \cdot \frac{W}{W_g} \] from equation (3)

For this short range case the variation of payload fraction is linear in \( R \), decreasing to zero at \( R_{\text{max}} \). As \( r \) is improved, the payload fraction at any range improves, and \( R_{\text{max}} \) increases. As \( \frac{W_e}{W_g} \) is decreased, \( \frac{W}{W_g} \) is increased which gives higher payload fractions for all ranges.

This simple analysis has been for the short range case where \( W_g \) may be considered as remaining constant over the cruise, or the fuel burn fraction is small for the short range mission.

C.2 Long Range Aircraft

For a long range aircraft, the change in \( W_g \) during the flight cannot be ignored (\( W_g = \) instantaneous gross weight)

e.g. a B-707-300 on a NY to Paris trip

\( W_{G_i} \) out of NY \( \approx \) 315000 lbs

\( W_{G_f} \) at Paris \( \approx \) 230000 lbs

so final weight is 2/3 of initial weight.

Equation 2 still applies over a small increment of cruise so we resort to the calculus which produces a different, more precise formula called the "Breguet Range Equation". Equation (2) becomes

\[ qR = \frac{r}{W_g} \cdot d W_{FB} \]
where \( dR \) = increment of range
\[ d W_{\text{FB}} = -d W_g = \text{increment of fuel burn} \]
\[ = \text{decrease in } W_g \]
\[ \therefore dR = r \left( \frac{-dW_g}{W_g} \right) \]

If the value of \( W_g \) at start of cruise is \( W_{gi} \), at end of cruise is \( W_{gf} \), then we have to integrate from \( W_{gi} \) to \( W_{gf} \) to get the exact formula for \( R \)
\[ R = r \cdot \int_{W_{gi}}^{W_{gf}} \frac{-dW_g}{W_g} = \int_{W_{gi}}^{W_{gf}} \frac{dW_g}{W_g} = r \ln \left( \frac{W_{gi}}{W_{gf}} \right) \] (2a)

If we compare to Equation (2) we see that the specific range is now modified by a logarithmic expression involving the initial and final cruise gross weights;
\[ \frac{W_{\text{FB}}}{W_g} \approx \frac{W_{\text{FB}}}{W_{\text{Gf}}} \] is now replaced by
\[ \ln \left( \frac{W_{\text{Gf}} + W_{\text{FB}}}{W_{\text{Gf}}} \right) = \ln \left( 1 + \frac{W_{\text{FB}}}{W_{\text{Gf}}} \right) \]

a) If no payload is carried, then \( W_p = 0, W_U = W_{\text{FB}} = W_{gi} - W_E \) then the maximum range becomes,
\[ R_{\text{max}} = r \ln \left( \frac{W_{gi}}{W_{Gf}} \right) = r \ln \left( \frac{W_{Gf}}{W_E} \right) = r \ln \left( \frac{1}{W_E/W_{gi}} \right) \] (3a)

As before, if \( W_E/W_{gi} \) is reduced, \( R_{\text{max}} \) will be increased. However since \( W_g \) now decreases as fuel is burned, \( R_{\text{max}} \) is greater in (3a) than from the sample case (3).

For example if \( r = 14,700 \) as before, and \( \frac{W_{\text{FC}}}{W_g} = .05 \), and...
we assume \[ \frac{W_E}{W_G} = 0.60, \quad \frac{W_E}{W_{Gi}} = 0.60 \cdot 0.95 = 0.632 \]

or \[ \frac{W_{FB}}{W_G} = 0.35, \quad \frac{W_{FB}}{W_{Gi}} = \frac{0.35}{0.45} = 0.370 \]

From (3), \( R_{\text{max}} = 14,700 \times 0.37 = 5450 \) s. miles in cruise

From (3a), \( R_{\text{max}} = 14,700 \ln \frac{1}{0.632} = 14,700 \ln (1.58) = 6770 \) s. miles

The correct formula makes a 1320 s. mile difference in \( R_{\text{max}} \).

b) If payload is carried, then \( W_{FB} = W_{Gi} - W_E - W_p \), and the payload becomes

\[ R = r \ln \left[ \frac{W_{Gi}}{W_{Gi}} \right] = r \ln \left[ \frac{W_{Gi}}{W_E + W_p} \right] = r \ln \left[ \frac{1}{W_E/W_{Gi} + W_p/W_{Gi}} \right] \]

If we unlog this expression

\[ \frac{W_E}{W_{Gi}} + \frac{W_p}{W_{Gi}} \]

or payload fraction, \( \frac{W_p}{W_{Gi}} = e^{-R/r} \)

\[ \frac{W_p}{W_{Gi}} = e^{-R/r} \quad \frac{W_E}{W_{Gi}} \quad 4(a) \]

At \( R = 0 \), \( \frac{W_p}{W_{Gi}} = 1 - \frac{W_E}{W_{Gi}} = \frac{W_U}{W_{Gi}} \) as before for short range case

At \( R = R_{\text{max}} \), \( \frac{W_p}{W_{Gi}} = 0 \)

As shown in Figure 6, the payload fraction curve is now a shallow exponential. Near maximum range, the payload fraction becomes very small, and very sensitive to errors in estimating technology measures.
Figure 6  PAYLOAD FRACTION versus RANGE

SLOPE = -1/r  \( e^{R/r} \)

 See BREGUET CURVE

PAYLOAD FRACTION
\( \frac{W_U}{W_G} \)

R, RANGE (STATUTE MILES)
D. Weight-Range Diagram

We can now show the weight breakdown versus design range for a conventional subsonic jet at a given level of aircraft technology. From Figure 7, we see that the payload fraction is strongly dependent on design range.

For a long range aircraft, the payload fraction will be very small, and aircraft payload-range performance will be very sensitive to the values of \( r \) and \( W_E/W_G \) which can be achieved. For example, if \( W_p/W_G \) is 10% for some design range, then every lb. saved in empty weight converts directly to payload, and saves 10 lbs. in design gross weight.

However, for a short range aircraft where \( W_p/W_G \) may be 33%, then every lb. saved in empty weight still converts directly to payload, but saves only 3 lbs. in design gross weight.

Therefore, a critical decision in the design of any transport aircraft is the choice of the full payload-design range point. Once this is selected, we have a good idea of the required aircraft gross weight for a given level of aircraft technology, and consequently, as we shall see, its probable purchase cost and operating cost.

For our example technology, we can compute payload fractions at design ranges from 6000 to 500 s. miles. Table 3 gives the result of applying equation (3a), and quotes typical gross weights for a 50,000 lb. and 100,000 lb. payload, or roughly a 250 and 500 passenger vehicle.
Figure 7  WEIGHT BREAKDOWN versus RANGE

Climb Fuel Burn

Cruise Fuel Burn, $W_{FB}/W_G$

Payload, $W_P/W_G$

Reserve Fuel

Weight for Furnishings, Equipment, Engines

Structures Weight

$W_U = 35\% \text{ of } W_G$

$W_E = 60\% \text{ of } W_G$

Design Range (Statute Miles)
### TABLE 3. SIZING TRANSPORT AIRCRAFT

<table>
<thead>
<tr>
<th>Cruise Design Range (s. miles)</th>
<th>Payload Fraction ($W_p/W_G$)</th>
<th>$W_G/W_P$ (lbs. per payload)</th>
<th>Gross Weight 250 pax or 50,000 lbs. or 100,000 lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>.04</td>
<td>25</td>
<td>$1.25 \times 10^6$ or $2.5 \times 10^6$</td>
</tr>
<tr>
<td>5000</td>
<td>.075</td>
<td>13.3</td>
<td>666,000 or $1.33 \times 10^6$</td>
</tr>
<tr>
<td>4000</td>
<td>.122</td>
<td>8.20</td>
<td>410,000 or 820,000</td>
</tr>
<tr>
<td>3000</td>
<td>.177</td>
<td>5.65</td>
<td>282,000 or 565,000</td>
</tr>
<tr>
<td>2000</td>
<td>.230</td>
<td>4.35</td>
<td>217,500 or 435,000</td>
</tr>
<tr>
<td>1000</td>
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<tr>
<td>500</td>
<td>.317</td>
<td>3.15</td>
<td>158,000 or 315,000</td>
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</table>
E) Payload-Range Diagrams

Having chosen the design range point for a given payload weight, there are two volume decisions which subsequently must be made. First, a fuselage volume must be selected to comfortably house a number of passengers corresponding to the payload, or a cargo load of a given density, or container configuration. Secondly, a fuel tank volume must be selected.

The fuselage volume restriction prevents the addition of passengers or cargo on trips of shorter than design range where the fuel load can be reduced. The fuel volume restriction prevents extending the ranges on trips where less than full payload is being carried. These volume restrictions are shown in Figure 8.

Point A is the design range for full payload. Point B is a point where the fuel tanks are completely filled and a reduced payload is carried. Along the line AB the aircraft operates at full gross weight, and trades off payload and fuel load. Point C is the zero payload range, and the aircraft takeoff weight is reduced from the maximum gross weight as we move along the line BC. Any payload-range point inside the shaded area can be handled by the aircraft by operating at reduced gross weights.

By choosing different volumes, the designer establishes points A and B, and can provide quite different range-payload performance for transport aircraft of constant gross weight as exemplified by the exponential curve which is now dimensional on Y-axis.

-22-
Figure 8  VOLUME RESTRICTIONS ON RANGE-PAYLOAD PERFORMANCE

PAYLOAD, \( W_p \)

DESIGN RANGE FOR FULL PAYLOAD

CABIN VOLUME RESTRICTION

FUEL TANK VOLUME RESTRICTION

ZERO PAYLOAD RANGE

RANGE (STATUTE MILES)
We now have derived one of the two basic diagrams describing transport aircraft performance. It is called the "payload-range" diagram. Payload-range diagrams for various current jet transports are shown in Figure 9. Since smaller aircraft are cheaper to own and operate, airlines buy several kinds of aircraft even at a given level of technology to match their fleet capabilities to their traffic loads on routes of varying distances. Traffic load points should be kept near the outer boundaries of the range-payload diagrams for profitability. This will be shown later using the second basic diagram, the direct operating cost-range curve.

As technology improves, a smaller gross weight airplane can be constructed to provide the same payload-range capability at lower costs. For long range aircraft, these technology improvements can provide spectacular changes in gross weight. For example, if the present cruise engines of SFC = 0.60 did not exist, a transport aircraft of the general size of the B-747 (i.e. the second aircraft in Table 3, Range = 4000 miles, Payload = 100,000 lbs) would increase in gross weight from 820,000 lbs to 1.67 million lbs. if the cruise SFC were only 0.8. One can safely say that the C-5A, B-747, DC-10, L-1011, etc. would not have been built if it were not for the development of this better engine technology. The construction of new engines of smaller thrust will similarly cause new smaller transports to be built in future years to replace the present DC-9 and B-727.
Figure 9  PAYLOAD-RANGE DIAGRAMS FOR CURRENT TRANSPORT AIRCRAFT

REF: FLIGHT, NOV 65, 68, 71
ISA STD, NO RESERVES

0  5  10  15  20  25
DHC-6

100  125  150  175

0  1  2  3  4  5  6  7  8  9
RANGE x 1000 STATUTE MILES

payload x 1000 lb

B-7478
DC-10-30
B-707-320B
B-727-200
DC-9-30
F) Direct Operating Cost

F.1 Effects of Size and Range on Operating Cost

We shall now discuss the second basic diagram describing transport aircraft performance, the direct operating cost curve, or DOC curve. The direct operating costs are made up of crew, fuel, maintenance, and depreciation costs directly associated with operating the aircraft. A fuller discussion of total airline costs is the subject of a separate lecture. In this section we shall make some observations on the effects of aircraft size and range (as determined by technology) on these operating costs.

We shall use a single cost measure, $\text{FC}_{HR}$, the flight operating costs per block hour to show the effects of size as measured by the gross weight, $W_G$, and range as measured by the full payload-design range. Figure 10 shows a typical result of FTL computer design studies for CTOL jet transports. For a level of technology described as 1970 technology, it shows a linear variation of hourly costs with gross weight (or payload size) for a given design range. However, there is also a variation with design range, so that a set of linear rays far out from a zero weight point of 100 $\$/block hour. The hourly costs for current transport aircraft are shown in Figure 10. The rays correspond to a level of technology used in the DC-10 and B-747 aircraft, and good agreement is shown for those aircraft.

The positive intercept at zero gross weight causes an economy of scale as aircraft size is increased for a given design range. We will show this by introducing another basic cost measure, $\text{FC}_{SHR}$, the flight operating cost per seat hour. The variation of $\text{FC}_{SHR}$ as payload is increased (shown for a design range of 1000 s. miles) is given by Figure 11(a). Obviously, there is a significant economy of scale as payload increases from 50 passengers (5.40 $\$/seat hour) to 200 passengers (3.64 $\$/seat hour). Note that the gains are not significant after that size, but there clearly are benefits from introducing
Figure 10  OPERATING COSTS PER BLOCK HOUR versus GROSS WEIGHT AND RANGE

FLIGHT OPERATING COSTS
FCHR
($/BLOCK HR)

AIRCRAFT GROSS WEIGHT (1000 LBS)

RANGE = 1000
(S. MILES)

2000

4000

6000

B-747

BAC-111-400

DC-9-10

B-727-200

B-727-100

DC-9-30

DC-8-50

DC-8-61

B-707-300B

B-737-200

FTL DESIGN STUDIES
ATA-67:
4000 HRS/YR, 12 YRS
1.25 x LABOR

TECHNOLOGY: BPR = 5, SFC0 = 0.23
M = 0.84 AT 25000 FT
FIELD LENGTH, 8000 FT

NOTE: EXISTING AIRCRAFT COSTS FROM CAE,
"AIRCRAFT OPERATING COSTS, 1971"
U.S. DOMESTIC AVERAGE, 1970
Figure 11  EFFECT OF PAYLOAD SIZE ON FLIGHT COSTS PER SEAT HOUR

1970 TECHNOLOGY

$r = 14,000$ STATUTE MILES

$W_p/W_c = 0.28$
Figure 11a  EFFECT OF PAYLOAD SIZE ON FLIGHT COSTS PER SEAT HOUR

1970 TECHNOLOGY
BPR = 5, SFC0 = 0.33
M = 0.84 AT 25,000 FEET
FIELD LENGTH = 8000

ATA-67
4000 HRS/YEAR, 12 YEARS
.25 x LABOR
220 LBS PER PASSENGER

DESIGN RANGE = 1000 STATUTE MILES
Figure 11b  EFFECT OF DESIGN RANGE ON FLIGHT COSTS PER SEAT HOUR

FC$_{SHR}$

CAPACITY (SEATS) 40

80

110

160

DESIGN RANGE (Statute Miles)
larger size aircraft whenever traffic loads warrant their usage.

The variation of $FC_{SHR}$ with design range at constant payload is shown by Figure 11(b). Here as range is increased, there is an exponential growth in $FC_{SHR}$, so that for a given payload size, there are benefits from using the shortest design range vehicle which will perform the task. Figure 11(b) shows the effect of size and range simultaneously, (a crossplot of the 1000 mile design range points actually produce Figure 11(a).) Notice that a smaller, but lesser design range vehicle can be cheaper than a larger, but longer design range vehicle. The cheapest vehicle is the one designed for exactly the payload and range of the transportation task to be performed. Using a larger vehicle is cheaper per seat, but not cheaper per passenger.

F.2 Derivation of DOC Direct Operating Costs ($/available seat mile)

For a given aircraft, we can compute the operating cost per hour, $FC_{HR}$. From this basic cost measure, we can derive the DOC curve in terms of cents per available seat mile versus range. We shall now show this derivation.

First, we must know the variation of block time with range. This is shown in Figure 12 as a linear form, where the slope of the curve is inversely proportional to cruise speed, $V_{CR}$ and the zero distance intercept accounts for taxi time, takeoff and landing times, circling the airport for landing and takeoff, and any delays due to ATC congestion. This curve can be obtained by plotting scheduled times versus trip distance, and Figure 12 shows a typical result.
Figure 12  BLOCK TIMES FOR DOMESTIC SERVICE

OFFICIAL AIRLINE GUIDE
B-727 SCHEDULED SERVICE

$SLOPE = \frac{1}{V_C R} = 0.11 \, d$

BLOCK TIME $T_b$ (minutes)

26 MINUTES

TRIP DISTANCE
Figure 13  BLOCK SPEED VARIATION WITH TRIP DISTANCE

![Graph showing the variation of block speed with trip distance.]
Figure 14 VARIATION OF PRODUCTIVITY WITH TRIP DISTANCE

PRODUCTIVITY $P_{HR}$ (seat-miles/hour)

TRIP DISTANCE

SEATS UNAVAILABLE DUE TO PAYLOAD-RANGE LIMITATIONS

DESIGN RANGE
If we compute block speed, $V_b'$, as trip distance divided by block time, we get the asymptotic curve shown in Figure 13 where at longer ranges, the blockspeed begins to approach the cruise speed.

If we define $P_{HR} = \text{productivity per hour in terms of seat-miles per hour where } S_a = \text{available seats for a given trip, then a curve shown in Figure 14 is obtained. It is proportional to the } V_b' \text{ curve up to the full payload design range point where the number of available seats begins to be reduced causing the aircraft productivity to decrease after that point.}

Now if we divide the hourly cost by the hourly productivity, we obtain the second basic diagram for transport aircraft, the DOC curve (Direct Operating Cost).

$$\text{DOC} = \frac{FC_{HR}}{P_{HR}} = \frac{\$ \text{ /hour}}{\text{seat miles/hour}} = \$ \text{/available seat mile}$$

Since $FC_{HR}$ is a constant, this curve is the inverse of the $P_{HR}$ curve and produces the form shown in Figure 15, where DOC is high for short trips, decreases towards the design range point, and increases thereafter.

If we consider different payloads and ranges for the DOC curve, we see that a 50 seat vehicle is more expensive than a 100 seat vehicle, and a vehicle designed for 1000 miles will be cheaper than one designed for 2000 miles as stated previously.
Figure 15  VARIATION OF DOC WITH TRIP DISTANCE

DOC
cents/available seat-mile

50 SEAT AIRCRAFT

100 SEAT AIRCRAFT

DESIGN RANGE

TRIP DISTANCE

500
1000
2000
Figure 16  VARIATION OF FLIGHT TRIP COST WITH TRIP DISTANCE
Figure 17  VARIATION OF FLIGHT TRIP COST/SEAT WITH TRIP DISTANCE

**FCST**
FLIGHT COST
PER SEAT TRIP
$

100 SEATS

50 SEATS

TRIP DISTANCE

1000

2000
These curves may cross so that a smaller, shorter range vehicle is cheaper at certain ranges than a larger, longer range vehicle.

Because of this hyperbolic shape, it is easier to work with trip cost measures which have a linear form with distance since they are proportional to block time. We define two trip cost measures here:

\[ FC_{AT} = \text{flight cost per airplane trip} = c_1 + c_2d \approx FC_{HR} \cdot T_b \]

where \( c_1 \) and \( c_2 \) are known cost coefficients

\[ FC_{ST} = \frac{FC_{AT}}{S_a} \]

where \( S_a \) = available seats

The form of \( FC_{AT} \) and \( FC_{ST} \) with distance is shown in Figures 16 and 17. After design range, where \( S_a \) is decreasing \( FC_{ST} \) becomes non-linear.

Generally, these trip cost measures are easier to understand and more useful than the DOC curve with its hyperbolic shape. One needs only to compute \( c_1 \) and \( c_2 \) for a given airplane and cruise schedule, and know the variation of available seats with trip distances.

It must be emphasized that because of the strong variation in DOC with trip distance, any value quoted for DOC is meaningless unless accompanied by a value for trip distance. This point is often forgotten by economists, laymen, and inexperienced systems analysts.
G) Profitable Load Diagrams

The two basic diagrams, range-payload and DOC, may be combined to form a "profitable load" diagram if certain major assumptions are made:

1) It is necessary to assume a variation of revenue yield with distance. While a fare formula may be known, yield for a given route is an average net contribution in terms of dollars per passenger computed by taking into account the mix of standard and discount fares, sales commissions, taxes, and perhaps short term, variable indirect operating costs per passenger arising from ticketing, reservations, passenger handling, etc. Here we assume Y is linear with trip distance.

2) It is necessary to assume a variation of total costs, TC with distance, or to ignore allocation of overhead costs and produce a short term profit (or contribution to overhead) diagram. Here we shall assume that short term total operating seats per seat trip, TC_ST have the same linear form as the flight costs, FC_ST.

The usual relationship of Y and TC_ST is shown on Figure 18 where the linear forms cross at some short range. The result is a hyperbolic form for breakeven load decreasing to very low values at design range as shown in Figure 19. As with DOC, any value quoted for breakeven load factor must be accompanied
Figure 18  VARIATION OF TOTAL COSTS AND YIELD WITH TRIP DISTANCE

Y, YIELD

$TC_{ST}$

TOTAL COST/SEAT TRIP

Y - YIELD PER PASSENGER

$TC_{ST}$ - TOTAL COST/SEAT

DESIGN RANGE

TRIP DISTANCE
Figure 19  TYPICAL VARIATION OF BREAKEVEN LOAD WITH DISTANCE

- Design Range
- Trip Distance
- Break-even Load Passengers
by a quoted value for trip distance.

The payload-range and breakeven load curves can now be combined to form a "profitable" load diagram as shown in Figure 20. The shaded areas represent points where a "profit" can be made using the aircraft to carry a given load over this trip distance. If the areas overlap, it is preferable to choose an aircraft where the point lies close to the upper boundary of payload-range limits since it is more profitable. E.g., choose the medium range aircraft for point PQ in Figure 20.

Notice that the profitable load diagram cannot be uniquely associated with a particular aircraft because of its assumptions. It must be associated with an airline and a set of routes since the indirect costs are specific to the airline, and the yield values are specific to a set of routes or city pairs. Thus when profitable load diagrams are shown, these additional data should be quoted.

Notice also that the hyperbolic form of the breakeven load curve is due to the differing slopes of the yield and total cost curves with trip distance. If yields, or fares were proportional to cost over distance, then the breakeven load would be constant with trip distance. Recent fare changes have moved fares much into line with costs by raising the zero distance intercept for coach fares.
Figure 20  PROFITABLE LOAD DIAGRAMS

TRAFFIC LOAD (PASSENGERS)

TRAFFIC ON ROUTE PQ

DISTANCE PQ

TRIP DISTANCE

100

200

LARGE, LONG RANGE AIRCRAFT

AREA OF PROFITABILITY

MEDIUM, LONG RANGE AIRCRAFT

SMALL, SHORT RANGE AIRCRAFT
from $6.00 to $12.00. This provides much lower breakeven loads for shorter distance trips.

H) The Price of Transport Aircraft

As mentioned earlier, the purchase price and therefore depreciation costs are proportional to aircraft size. To demonstrate this Figure 21 shows a plot of current prices against aircraft operating empty weight. A good fit is given by the curve,

\[ P_a = 1.9 \times 10^6 + 66W_E \] $\]

where \( P_a \) = fully equipped market price

\( W_E \) = basic operating weight empty

This correlation does not mean that \( W_E \) is the causative factor in determining the price which a manufacturer will decide to establish for his new product. Competition from existing aircraft, the expected size of the production run, etc. are factors which he considers closely. It is merely interesting to note the correlation with empty weight.

Notice also, that the DEC-6, a simple STOL transport from Canada, and the YAK-40, a new entry in world markets from Russia, are well below the minimum price for conventional transport aircraft from the Western world.
A set of data on prices for current new and used jet transports taken from the weekly editions of Esso's "Aviation News Digest" is given by Table 4. There is considerable variation in unit prices which may be due to various amounts of aircraft spares included with the purchase.
Figure 21  THE PRICE OF CURRENT TRANSPORT AIRCRAFT

SOURCE: FLIGHT MAGAZINE, APRIL 20, 1972
Table 4. ACQUISITION PRICES FOR NEW LONG-RANGE TRANSPORT AIRCRAFT

<table>
<thead>
<tr>
<th>Month of Purchase</th>
<th>Airline Purchaser</th>
<th>Aircraft</th>
<th>Number Purchased</th>
<th>Total Price (Millions of $)</th>
<th>Price/Aircraft (Millions of $)</th>
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Table 4 (cont.) ACQUISITION PRICES FOR NEW MEDIUM AND SHORT-RANGE TRANSPORT AIRCRAFT

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