Chapter 4

Estimation of wing loading and thrust loading - 10

Lecture 18

Topics

4.15.3 Characteristics of a typical turboprop engine

As noted earlier, in this engine, a major portion of the output is available at the propeller shaft (SHP) and a small fraction through the jet thrust (T_j). Hence, the output is represented as:

$$THP = \eta_p \, SHP + (T_j V_\infty /1000) \quad (4.138)$$

where, SHP = shaft horse power available at propeller shaft in kW,η_p = propeller efficiency and T_j = jet thrust

The total output of a turboprop engine, also called 'Equivalent shaft horse power (ESHP)', is defined as :

$$ESHP = SHP + \{T_j V_\infty / (0.8x1000) \} \quad (4.139)$$

Note : (i) For the purpose of defining ESHP, the value of η_p is taken as 0.8 in Eq.(4.139). The ESHP and SHP are in kW.

(ii) Equation (4.139) would not be able to account for the contribution, to ESHP, of the thrust produced when the flight velocity (V) is zero or the static condition. In this case and when V < 100 knots (or 185 kmph), the convention is to define ESHP as follows (Ref.1.20, chapter 14).

$$ESHP = SHP + (T_j / 14.92) \quad (4.140)$$

where, ESHP and SHP are in kW and T_j is in N.

For example, a turboprop engine developing SHP of 746 kW and jet thrust of 503 N, under sea level static condition, would have :

ESHP = 746 + (503/14.92) = 780 kW.

Characteristics of a typical turbo-prop engine are shown in Fig.4.21. It is observed that the power output increases with flight speed. This increase is due to two factors viz. (a) the mass flow through the engine ($\dot{m} = \rho A_i V_i$; A_i and V_i being the area of intake, and the velocity at the intake) increases with flight speed and (b) the pressure rise due to the deceleration of the flow in the inlet diffuser also increases with flight Mach number.

Figure 4.21 also shows the influence of ambient temperature on power output. It is observed that there is a significant fall in ESHP as the ambient temperature rises.

From the curves regarding fuel flow rate in Fig.4.21, the BSFC can be obtained at various speeds and altitudes as:

BSFC = (Fuel flow/hr) / ESHP

Remark:

Reference 1.18, Appendix E.3 gives performance curves for a large turboprop engine with sea level static power of 6500 HP. It may be noted that the 'Sea level static power' is the engine output at sea level at zero velocity. Reference 3.4, chapter 6 gives characteristics of an engine of around 1700 HP.

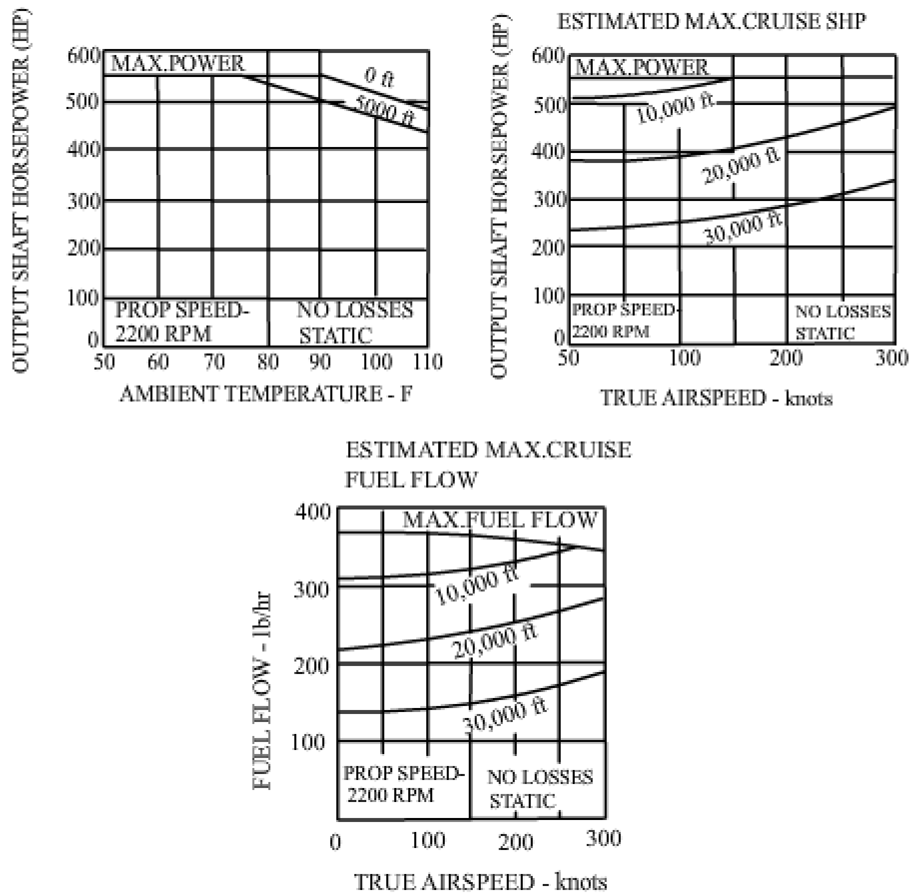

Fig.4.21 Characteristics of PT6A-25 turboprop engine

(Adapted from Brochure of Pratt & Whitney Canada Corp. 1000, Marie-Victorin, Longueuil Quebec J4G 1A1, Canada © Pratt & Whitney Canada Corp. Reproduced with permission)

4.15.4 Characterisitcs of a typical turbofan engine

In the early turbofan engines the thrust output used to remain fairly constant with flight speed. In the modern turbofan engines the performance at low speeds and low altitudes (up to about 5 km) has been improved so that the ratio of the sea level static thrust and that (thrust) in high speed-high altitude flight is much higher than the early turbofan engines. The 'Sea level static thrust' is the engine output at M = 0 at sea level. Higher sea level static thrust helps in reducing the distance required for take-off. Figure 4.22 shows the variations of thrust with Mach number at different altitudes for an engine with bypass ratio of 4.9. The figure also shows the values of the specific fuel consumption (TSFC).

Remark:

Chapter 9 of Ref.1.14 gives the performance, in terms of non-dimensional parameters, for engines with bypass ratios of 3, 6.5, 8 and 13. The curves are also presented for take-off rating, climb rating and cruise rating. It may be added that the 'Take-off rating' is the engine output which can be availed for about 5 min. The engine can be run at 'Climb rating' for about half an hour and at 'Cruise rating' for long periods.

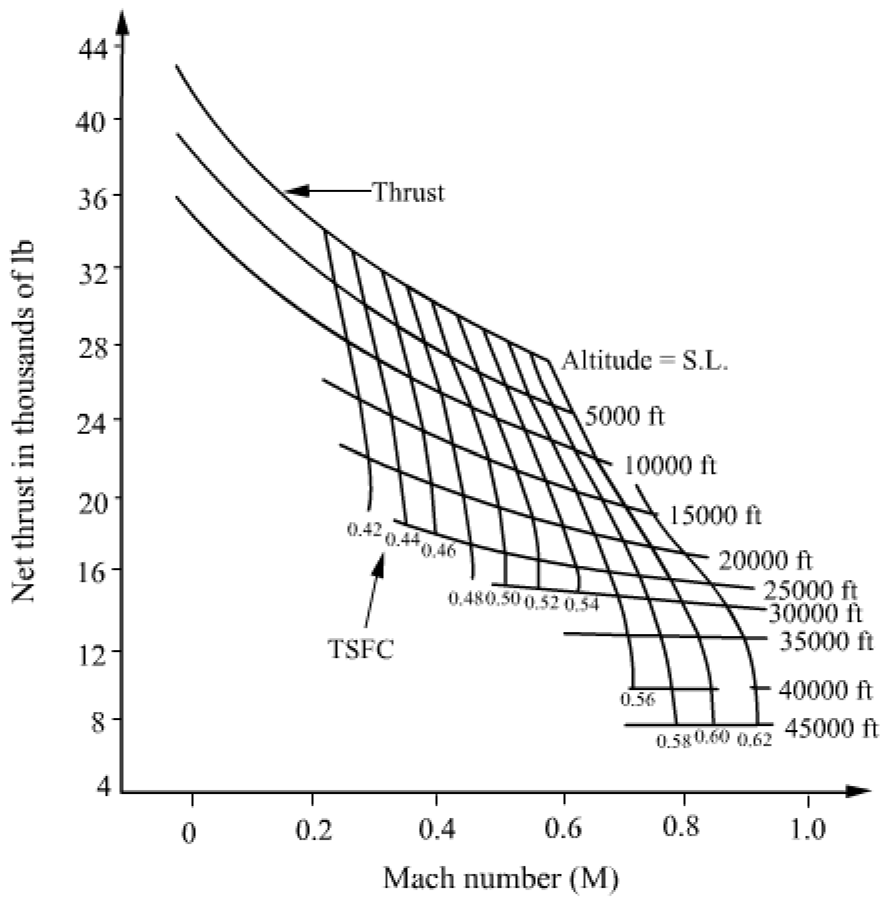

Fig.4.22 Characteristics of Pratt and Whitney PW4056 turbofan engine - maximum cruise thrust
(With permission from Pratt and Whitney, East Hartford)

4.15.5 Characterisitcs of a typical turbojet engine

The characteristics of a supersonic turbojet engine are shown in Figs.4.23a to d. It is observed that at subsonic speeds the thrust is fairly constant, but it increases considerably at supersonic speeds. This rise is due to increased ram pressure in the intake, as a result of the deceleration of the supersonic flow. The Mach number at which the peak value of thrust occurs depends on the design of the engine.

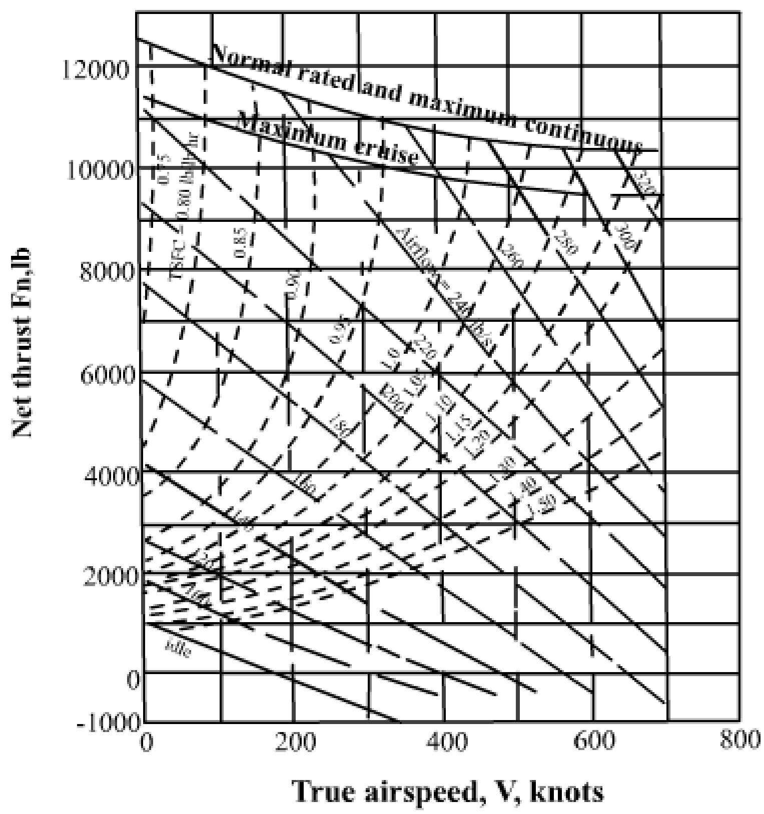

Fig.4.23a Characteristics of Pratt and Whitney JT4A-3 turbojet engine (estimated thrust, TSFC, and airflow) under standard atmospheric condition and 100% RAM recovery. h = sea level (With permission from Pratt and Whitney, East Hartford)

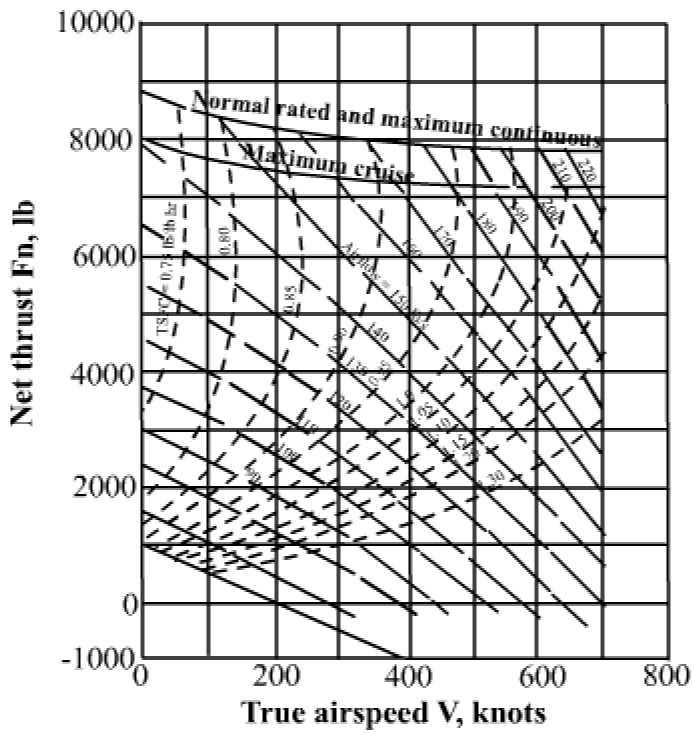

Fig.4.23b Characteristics of engine in Fig.4.13a, h = 15000 ft
(With permission from Pratt and Whitney, East Hartford)

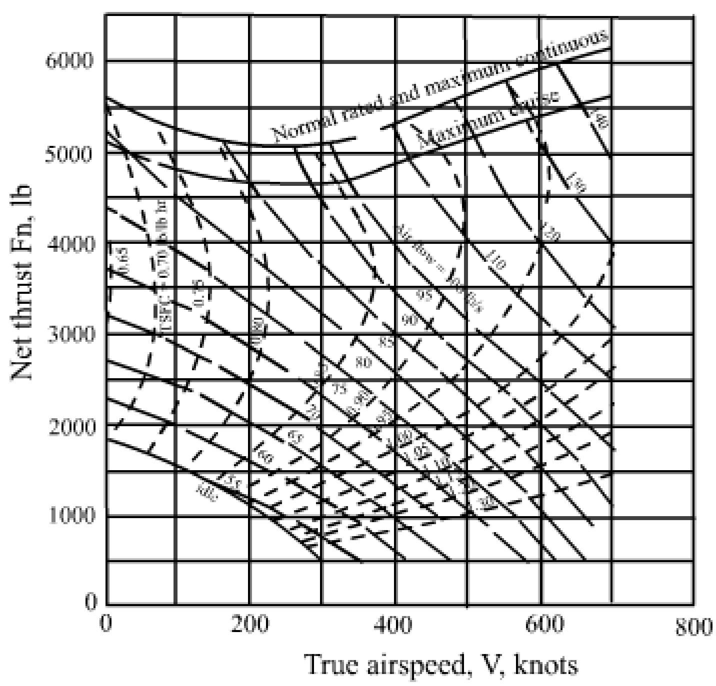

Fig.4.23c Characteristics of engine in Fig.4.13a, h = 30000 ft
(With permission from Pratt and Whitney, East Hartford)

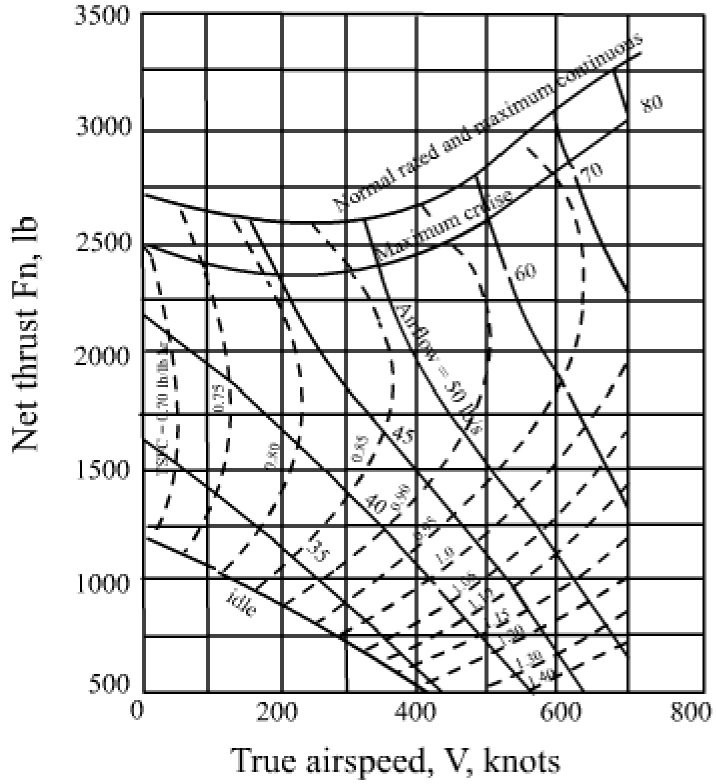

Fig.4.23d Characteristics of engine in Fig.4.13a, h = 45000 ft

(With permission from Pratt and Whitney, East Hartford)

Remarks:

i) In Figs. 4.23 a to d the true airspeed is given in knots;one knot is equal to 1.852 kmph. Further, the speed of sound at h = 0, 15000' , 30000' and 45000' is respectively 661, 627, 589 and 574 knots.

ii) Bypass supersonic turbofan engines are also being considered for supersonic flight. Reference 1.18, gives, in Appendix E, typical curves for an engine with sea level static thrust of 30000 lb (133 kN). Similarly Ref.1.16, chapter 8 also presents curves for an engine with 33000 lb (146.3 kN) sea level static thrust. Figures 4.23a to d also indicate the values of specific fuel consumption (TSFC) and the air flow rate.

iii) Figure 4.18b shows an after burner duct between the turbine exit and the entry of the nozzle. The same figure also shows the fuel spray bars and the flame holder. An after burner is used to increase the thrust output for a short duration. When the fuel is burnt in the after burner, the temperature of the gases goes up and the thrust increases, when these gases subsequently expand in the nozzle. However, the specific fuel consumption also goes up considerably and the after burner operation is resorted to only for a short duration like during take-off or transonic acceleration.

4.16 Deducing output and SFC of engines where these characteristics are not available directly

The detailed information about engine performance (i.e. variations with altitude and flight velocity of the thrust (or power) and TSFC (or BSFC) is generally available only in a limited number of cases. To get the performance of an engine with other rating, scaling of the available data is carried out. For this purpose, the values of thrust(or power) of the engine, whose characteristics are known, are multiplied by a suitable factor which will bring the output of the existing engine equal to the output of the desired engine. It is assumed that the SFC values will be the same for the two engines. This kind of scaling is generally applicable for outputs within ± 25% of the output of the known engine (Ref.1.16, Chapter 8).

4.17 A note on choice of engines for different range of flight speeds

The topic of choice of engine for different types of airplanes is briefly covered in this section. Some salient points are mentioned to conclude the discussion on engines.

The following five criteria are used to select a power plant for a specific application.

1.Overall efficiency (η_0) : This quantity is the product of (a) thermodynamic cycle efficiency (η_t) (b) combustion efficiency (η_c) (c) mechanical efficiency (η_m) and (d) propulsive efficiency (η_p). The thermodynamic efficiency depends on the thermodynamic cycle on which the engine operates. The details regarding estimation of η_t are available in books on thermodynamics. However, it is of the order of 40 to 50%. The combustion efficiency and mechanical efficiency would be around 95%. The propulsive efficiency of the propeller and gas turbine engines have been described in subsections 4.14.7, 4.14.8 and 4.15.2. It has been pointed out there that η_p depends on flight speed or Mach number.

The specific fuel consumption (SFC) is an indication of the overall efficiency. Based on Ref.1.18, chapter 3, it can be mentioned that the piston engine-propeller combination would have lowest SFC for Mach number (M) upto about 0.3. The turboprop engine would have lowest SFC in the range of Mach number from 0.3 to 0.6 which may extend to $M \approx 0.7$ with the use of a transonic propeller. The high bypass ratio turbofans have lowest SFC between for $M \approx 0.7$ to 1.0 and the low by-pass ratio ones between $M \approx 1$ to 1.6. Turbojets are more suited for $M \approx 1.6$ to about 3.5 and ramjets later upto $M \approx 8$. It may be recapitulated that a ramjet engine requires another powerplant to bring it to Mach number of about 1.5.

2. Variation of thrust (or power) with flight speed and altitude: The shaft horse power of a piston engine does not change significantly with flight speed. Consequently, the thrust output of this engine decreases significantly with flight speed or Mach number. The output of a turbofan engine decreases with Mach number, especially at low altitudes (Fig.4.22). The thrust of a jet engine is fairly constant at subsonic speeds but increases considerably at supersonic speeds (Fig.4.23 c & d). As regards the effect of flight altitude Eq.(4.105) shows that for a piston engine $\left(P/P_{sl}\right) = \sigma^{1.1}$ where, σ is the density ratio and the suffix 'sl' denotes a quantity at sea level.For a turboprop engine (from Ref.4.1, chapter 3), $\left(P/P_{sl}\right) \approx \sigma^{0.7}$. From Ref.1.15, chapter 3, (T/T_{sl}) for turbofan and turbojet engines is also roughly proportional to $\sigma^{0.7}$.

3. Weight of the engine: The weight of the engine contributes to the gross weight of the airplane and hence it should be as low as possible.This quantity is indicated by the ratio W_{pp}/T or W_{pp}/BHP, where W_{PP} is the weight of the power plant. This ratio depends on the type of engine and the engine rating; it (ratio) decreases as the rating increases. Based on data in Ref.1.21, it can be mentioned that the weight per unit BHP for a piston engine is around 9 N / kW for an engine with a rating of around 150 kW and about 6 N/kW for a rating of around 500 kW. For a turboprop engine W_{PP}/ESHP is around 2.9 N/kW for rating of 500 kW, 2.3 N/kW for a rating of 2500 kW and 1.4 N/kW for a rating of

7500 kW. For a turbofan engines the ratio W_{PP}/T could be around 0.25 N/N for a rating of around 100 kN and about 0.15 N/N for a rating of about 250 kN.

4. Frontal area: The frontal area of an engine contributes to the parasite drag of the airplane. Hence, a lower frontal area is a desirable feature of the engine. For a given output the piston engine-propeller combination generally has the highest frontal area. Turboprop, turbofan and turbojet follow in the decreasing order of the frontal area.

5.Other considerations : Gas turbine engines have mechanical simplicity as compared to a piston engine. However, gas turbine engines are costlier than the piston engines as some of the components of the gas turbine engines operate at higher temperature and RPM. This requires special materials and fabrication techniques.

Keeping these factors in view, the different types of engine are used in the speed range/application as given in Table 4.4.

Type of engine	Speed / Mach number range	Application – airplanes Categories
Piston engine-propeller combination	Upto 300 kmph	General aviation, trainer, agricultural and sports.
Turboprop	250 to 600 kmph; upto 750 kmph with advanced propeller	Short and medium range transport/cargo, aerial survey, feeder liner and executive transport.
Turbofan	M from 0.7 to 1.0	Medium and long range transports, cargo, maritime patrol, executive transport, jet trainer.
Turbojet	M from 1 to 3	Trainers, supersonic transport, fighter, interceptor, bomber.
Ramjet	M from 2 to 8	Intended for hypersonic transport.

Table 4.4 Speed range and applications of different types of engines

Example 4.21

After having chosen a turboprop engine, the designer comes across a new engine which has a 5% lower SFC but is 10% heavier. How does one assess the suitability or otherwise of the new engine?. Assume that the fuel fraction is 0.15 and the installed weight of the engines is about 5% of the gross weight of the airplane.

Solution :

The suitability can be checked by obtaining the influence of the change of engine on the gross weight.

Let,

W_{01} = gross weight of airplane with the new engine

W_{02} = gross weight of airplane with new engine

Further,

$$W_{01} = W_{pay} + W_{crew} + \frac{W_{pp1}}{W_{01}} W_{01} + \frac{W_{f1}}{W_{01}} + W_{otheritem}$$

$$\text{Or } W_{01} = W_{pay} + W_{crew} + W_{otheritems} + \frac{W_{pp1}}{W_{01}} W_{01} + \frac{W_{f1}}{W_{01}} W_{01}$$

$$\text{Or } W_{01} = C + \frac{W_{pp1}}{W_{01}} W_{01} + \frac{W_{f1}}{W_{01}} W_{01}$$

$$\text{Or } W_{01} = C + 0.05\, W_{01} + 0.15\, W_{01}$$

$$\text{Or } W_{01} = \frac{C}{1 - (0.05 + 0.15)} = 1.25\,C$$

For the airplane with the new engine :

$$\frac{W_{pp2}}{W_{02}} = 0.05 \times 1.1 = 0.055$$

$$\frac{W_{f2}}{W_{02}} = 0.15 \times 0.95 = 0.1425$$

$$\text{Hence, } W_{02} = C + 0.055\, W_{02} + 0.1425\, W_{02}$$

$$\text{Or } W_{02} = \frac{C}{1 - (0.055 + 0.1425)} = 1.2461\,C$$

Thus, the gross weight would be slightly lower with the new engine. If the cost of fuel is also considered, the new engine with lower fuel consumption is even better.