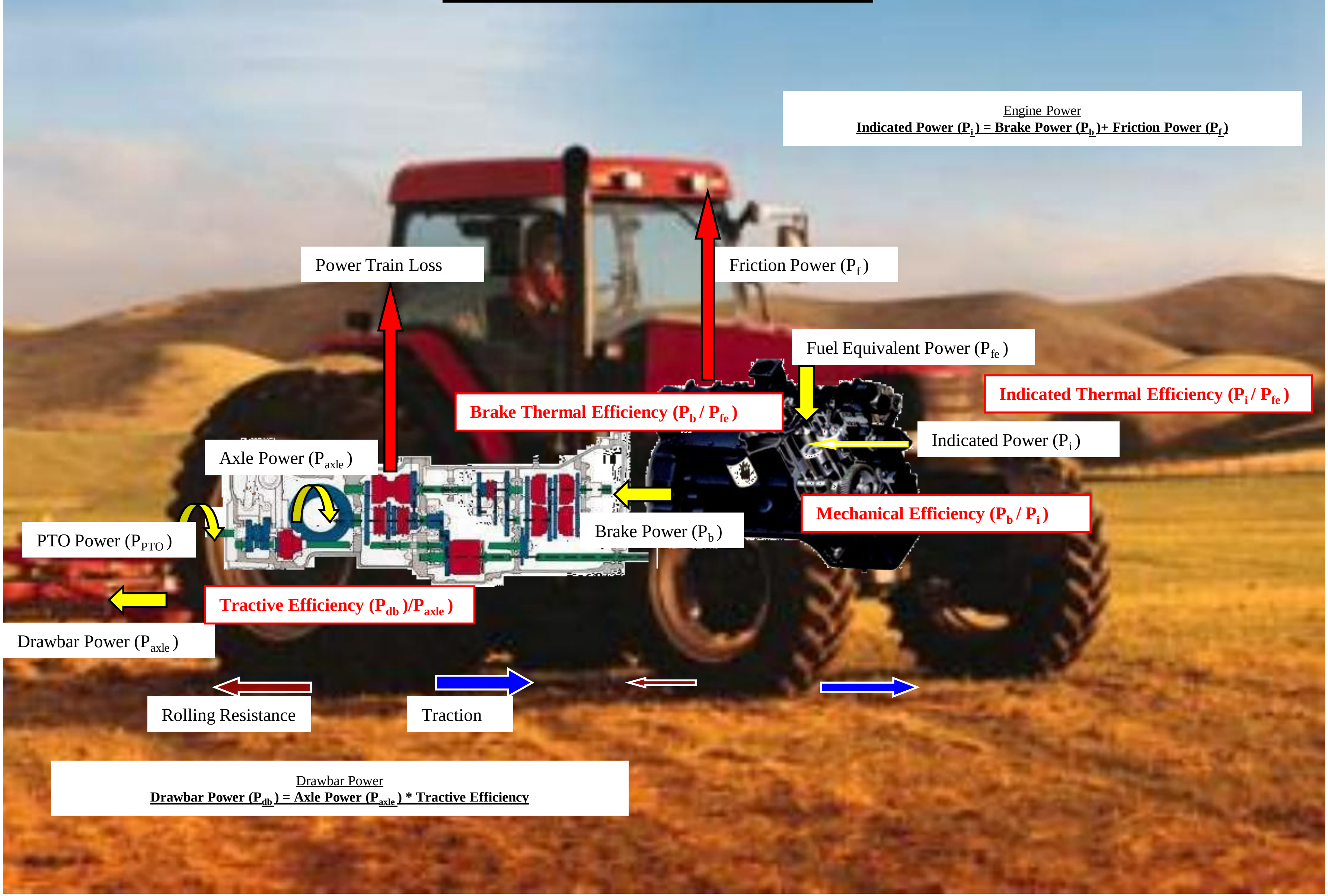
Tractor Power Flows



Force, Torque, Work and Power

Fundamental Units

	Metric (SI) Units	English Units
Time	seconds (s)	seconds (s)
Length	meter (m)	foot (ft)
Temperature	Celsius (^oC)	Fahrenheit (^oF)
(Absolute)	Kelvin (^oK)	Rankin (^oR)
Mass	kilogram (kg)	Slug (hardly ever used)

Derived Units

Force	Newton (N) (1 N = 1 kg.m/s^2)	pound force (lb_f) (1 lb_f = 1 slug.ft/s^2)
Work/Energy	Joule (J) (1 J = 1 N.m)	foot pounds (ft-lb) Conversion: 1 BTU = 778 ft-lb
Power	Watt (W) (1 W = 1 N.m/s)	Horsepower (Hp) Conversion: 1 Hp = 550 ft-lb/s or 1 Hp = 33,000 ft-lb/min

Force, Torque, Work and Power

Force: Force = Mass * acceleration

Metric (SI) Units, (N)

Force (N) = 1 (kg) * 1 m/s^2

1 N = 1 kg.m/s^2

English Units, (lb_f)

Force (lb_f) = 1 (slug) * 1 ft/s^2

1 lb_f = 1 slug.ft/s^2

Work / Energy: Work = Force * Distance

Metric (SI) Units, (J)

Work (J) = 1 (N) * 1 m

1 J = 1 N.m

English Units (ft-lb)

Work (ft-lb) = 1 (lb) * 1 ft

1 (ft-lb) = 1 ft-lb

Note: For English units energy is often given in British Thermal Units (BTU)
1 BTU is equivalent to 778 ft-lb of work

Power: Power = Work/Time = Force * Distance / Time

Metric (SI) Units, Watt (w)

Power (w) = 1 (J) per second

1 w = 1 J/s

English Units, (Hp)

Power (ft-lb_f/s) = 1 (ft-lb) per second

1 ft-lb_f/s = 1 ft-lb/s^2

1 Hp = 550 ft-lb/s^2

Power

Power is the rate of doing work

Metric (SI) Units, (watts, W)

P = Work/time (N.m/s = J/s = W)
P = Force * distance/time = Force * velocity (N*m/s = N.m/s = J/s = W)

Normally given in kilowatts (kW) 1 kW = 1000w

English Units, (Horsepower, Hp)

P = Work/time (ft-lb/s = ?? Hp)
P = Force * distance/time = Force * velocity (lb*ft/s = ft-lb/s = ?? Hp)

Normally given in Horsepower (Hp). 1 Hp = 550 ft-lb/s
or 1 Hp = 33,000 ft-lb/min

Power (Hp) = [Force*distance/time (lb*ft/s)] / [550 (lb*ft/s per Hp)]

Torque and Power (Metric)

Torque (T) = Force (F) * Lever Arm (L)

	Metric (SI) Units	English Units
Torque	N.m	ft.lb

Torque and Power

Torque =Force*Lever Arm
=F*L

Work per revolution =Force*Distance
=F * (2π*L)

Work per revolution = Torque * 2π = 2π*T (N.m/rev or ft.lb/rev)

Metric Units, (watts, W)

Work per Revolution = 2π*T (N.m/rev)

Power (W) = Work / Time
= Work per Revolution (N.m/rev) * Revolutions per minute (rev/min)
= [2πTN (N.m/rev * rev/min)]/ [60 (sec/min)]
= 2πTN/60 (N.m/s)
= 2πTN/60 (W)

Power is normally given in kilowatts (kW)

Power (kW) = 2πTN/60,000 (kW)

Power (kW) = 2πTN/60,000 (kW)

Torque and Power (English)

Torque (T) = Force (F) * Lever Arm (L)

	Metric (SI) Units	English Units
Torque	N.m	ft.lb

Torque and Power

Torque =Force*Lever Arm
=F*L

Work per revolution =Force*Distance
=F * (2π*L)

Work per revolution = Torque * 2π = 2π*T (N.m/rev or ft.lb/rev)

English Units, (Horsepower, Hp)

Work per Revolution = 2π*T (ft.lb/rev)

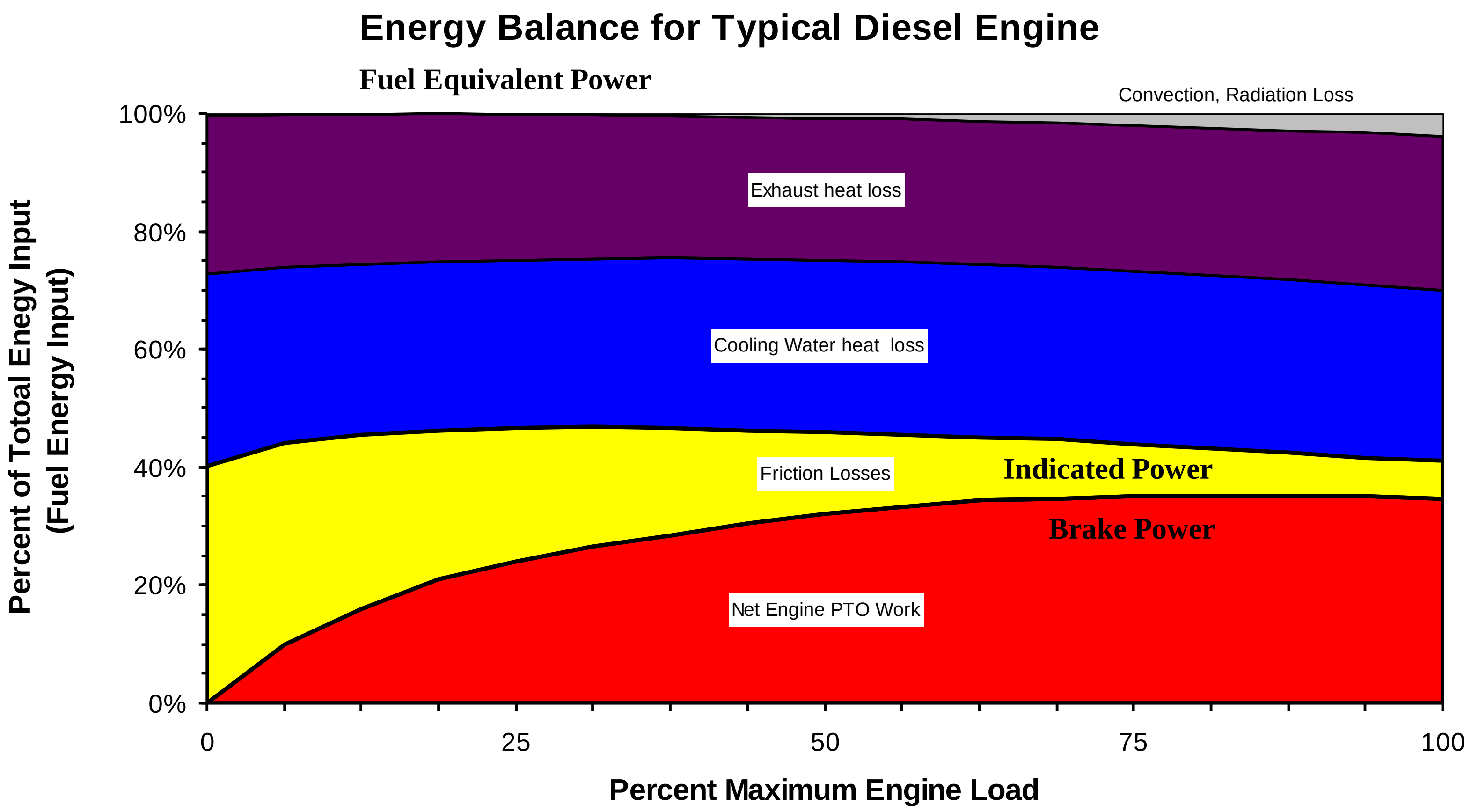
Power = Work / Time
= Work per Revolution (ft.lb/rev) * Revolutions per minute (rev/min)
= [2πTN (ft.lb/rev * rev/min)]/ [60 (sec/min)]
= 2πTN/60 (ft.lb/s)
= 2πTN/60 (ft.lb/s)

Power is normally given in horsepower (Hp) Note: 1 Hp = 550 ft.lb/sec

Power = [2πTN/60 (ft.lb/s)] / [550 (ft.lb/sec per Hp)]
= 2πTN/(60*550) Hp
= 2πTN/33,000 Hp

Power = 2πTN/(33,000) Hp

Power (Energy) Flows in an Engine



Engine Power Flows

- Fuel Equivalent Power, P_{fe}
  - Power if 100% of energy in fuel was converted to usable power
- Indicated Power*, P_i
  - Power generated at the Piston by the Otto(gasoline), Diesel or Dual cycle
    - Indicated power can not be measured directly, however the pressure in cylinder can
    - Cylinder Pressures used to calc. **Indicated Mean Effective Pressure (IMEP)**
    - IMEP is related to Indicated Power
  - Indicated Thermal Efficiency (e_{it}) = Indicated Power / Fuel Equivalent Power
- Brake Power, P_b
  - Power generated at the flywheel of the engine
    - Brake power is measured directly (Torque), however the brake pressure cannot be measure directly
    - Brake Power is used to calculate **Brake Mean Effective Pressure (BMEP)***
  - Brake Thermal Efficiency (e_{bt}) = Brake Power / Fuel Equivalent Power
  - Mechanical Efficiency (e_m) = Brake Power / Indicated Power
- Friction Power, P_f
  - Friction Power = Indicated Power - Brake Power
    - Friction power can be “measured” directly, by recording the friction (or motoring) (Torque) require to turn the engine a particular speed without combustion
    - Friction Power is used to calculate **Friction Mean Effective Pressure (FMEP)***

Indicated (Power/Torque/MEP) = Brake (Power/Torque/MEP) + Friction (Power/Torque/MEP)

$$e_{bt} = e_{it} * e_m$$

Engine Power Flows

Fuel Equivalent Power (P_{fe})

Energy per unit time (Power) consumed by the engine

Fuel Equivalent Power = Fuel Consumption * Higher Heating Value

Metric (kW)

P_{fe} (kW) = HV (kJ/kg) * M_f (kg/hr) / 3600 (s/hr)

= HV * M_f / 3600 (kW)

HV = Heating value of the fuel (kJ/kg)

M_f = Fuel Consumption (kg/hr

English (Hp)

P_{fe} (Hp) = [HV (BTU/lb) * M_f (lb/hr)* 778 (ft.lb/BTU)] / [60 (min/hr) * 33,000]

= HV * M_f / [60*33000] (Hp)

= HV * M_f / 2545 (Hp)

HV = Heating value of the fuel (BTU/lb)

M_f = Fuel Consumption (lb/hr)

Engine Power

Indicated Power (P_i)

Power transferred to the Piston due to combustion of fuel.

Indicated Mean Effective Pressure

Steady Pressure applied to piston during expansion stoke

Metric (kW)

P_i = Force * Distance / Time (Force = Pressure * area)

= [IMEP (kN/m^2)*A_p(cm^2)*L(cm)* 10^{-6} (m^3/cm^3)] / [Time]

= [IMEP * A_p * L (kJ)] / [Time] (Time = rev. cycle / rpm)

= [IMEP * A_p * L (kJ)] * N (rev/min) / [rc (cycle/rev) * 60 (sec/min)]

$$P_i \text{ (kW)} = [IMEP*L*A_p*N*n] / [rc*60*10^6]$$

IMEP = Indicted Mean Effective Pressure (kPa), L = Stroke Length (cm), A_p= Piston Area (cm^2)

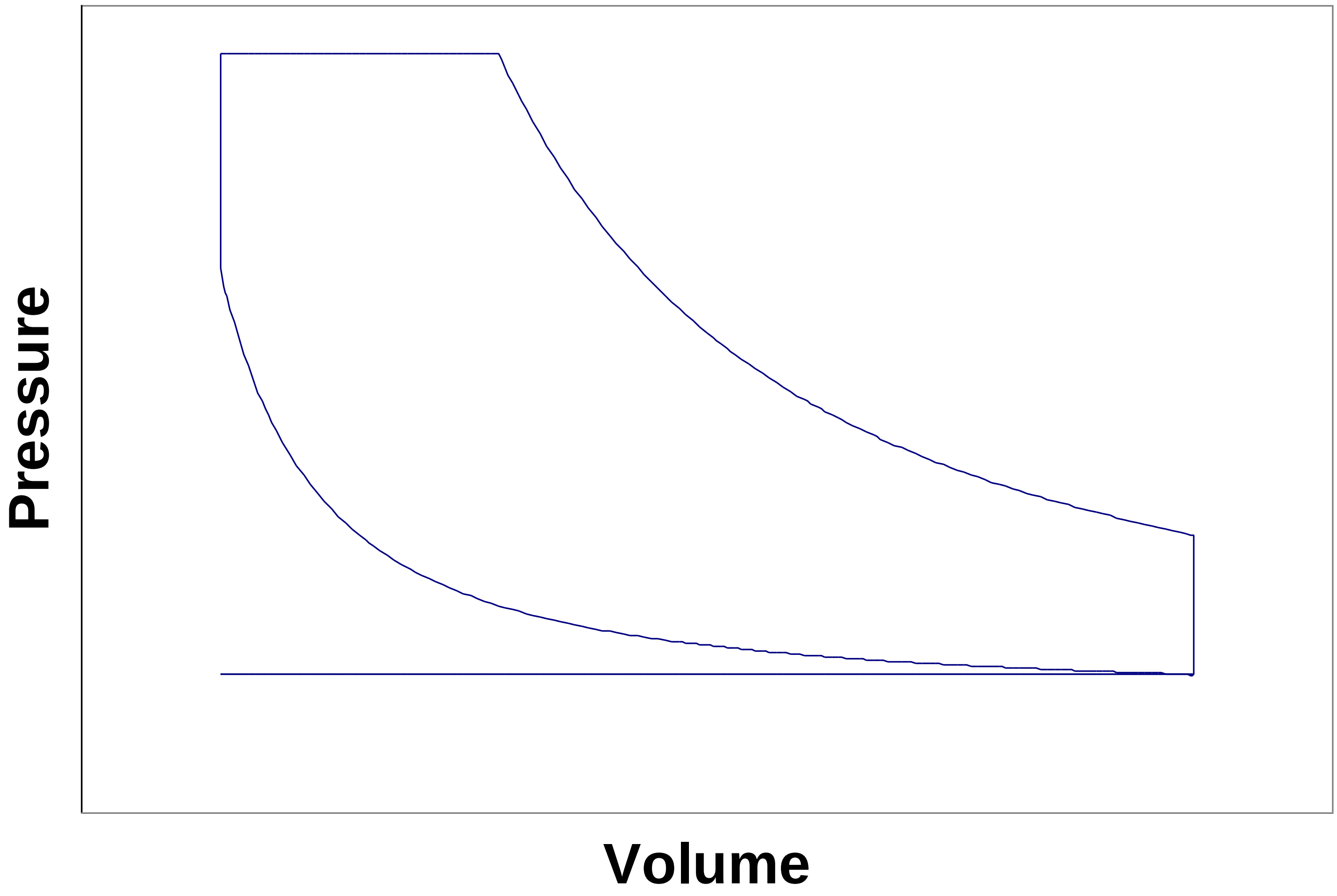
N= Engine Speed (rpm), n= number cylinders, rc = revolutions per cycle

$$P_i \text{ (kW)} = [IMEP*D*N] / [rc*60*10^3]$$

IMEP = Indicted Mean Effective Pressure (kPa), D = Displacement (Liters, L), N= Engine Speed (rpm),

rc = revolutions per cycle (two stroke rc=1, four stoke engine rc = 2)

Mean Effective Pressure



Engine Power

Indicated Power (P_i)

Power transferred to the Piston due to combustion of fuel.

Indicated Mean Effective Pressure

Steady Pressure applied to piston during expansion stoke

English (Hp)

P_i = Force * Distance / Time (Force = Pressure * area)

= [IMEP (psi)*A_p(in^2)*L(in)* 1/12 (ft/in)] / [Time]

= [IMEP * A_p * L/12 (ft-lb)] / [Time] (Time = rev. cycle / rpm)

= [IMEP * A_p * L/12 (ft-lb/cycle)] * N / [rc] (cycles/min)

= [IMEP * A_p * L/12 * N / [rc] (ft-lb/min)

= [IMEP * A_p * L/12 * N / [rc *33,000] (Hp)

$$P_i \text{ (Hp)} = [IMEP*L/12*A_p*N*n] / [rc*33000]$$

IMEP = Indicted Mean Effective Pressure (psi), L = Stroke Length (in), A_p= Piston Area (in^2)
N= Engine Speed (rpm), n= number cylinders, rc = revolutions per cycle

$$P_i \text{ (Hp)} = [IMEP*D/12*N] / [rc*33000]$$

IMEP = Indicted Mean Effective Pressure (psi), D = Displacement (in^3), N= Engine Speed (rpm),
rc = revolutions per cycle (two stroke rc=1, four stoke engine rc = 2)

Increase Indicated Engine Power

$$P_i\,(kW) = [IMEP*D*N] / [rc*60*10^3]_{(metric)}$$

IMEP = Indicted Mean Effective Pressure (kPa), D = Displacement (Liters, L), N= Engine Speed (rpm),
rc = revolutions per cycle (two stroke rc=1, four stoke engine rc = 2)

- Increase Engine Speed
    - Friction ??
    - Dynamic Forces
- Increase Displacement
    - Size
- Increase Mean Effective Pressure
    - Compression Ratio
        - Auto ignition, Fuel Quality
        - Cylinder Pressures
    - Increase Air Charge (Turbocharger / Intercooler)
    - Increase Fuel

Brake Power

Brake Power (P_b)

Power available at the flywheel

Determined from Engine Torque

Can be used to calculate Brake Mean Effective Pressure

- Metric Units, (watts, W)

  $$P_b\ (kW) = 2\pi TN/60{,}000\ (kW)$$

  $$P_b\ (kW) = [BMEP*L*A_p*N*n] / [rc*60*10^6]$$

  $$P_b\ (kW) = [BMEP*D*N] / [rc*60*10^3]$$

- English Units, (Hp)

  $$P_b\ (Hp) = 2\pi TN/(33{,}000)\ Hp$$

  $$P_b\ (Hp) = [BMEP*L/12*A_p*N*n] / [rc*33000]$$

  $$P_b\ (Hp) = [BMEP*D/12*N] / [rc*33000]$$

Increasing Engine Brake Torque

- Metric Units, (watts, W)

  $P_b = 2\pi TN/60{,}000 = [BMEP*D*N] / [rc*60*10^3]$

  Therefore :

  $2\pi TN/60{,}000 = [BMEP*D*N] / [rc*60*10^3]$

  Torque = $= [BMEP*D] / [rc*2\pi]$

- English Units, (Hp)

  $P_b = 2\pi TN/(33{,}000) = [BMEP*D/12*N] / [rc*33000]$

  Therefore :

  $2\pi TN/(33{,}000) = [BMEP*D/12*N] / [rc*33000]$

  Torque = $= [BMEP*D] / [rc*2\pi *12]$

- **Increase Brake Torque**
  - **Increase Displacement**
  - **Increase BMEP** **(Note: BMEP = IMEP - FMEP)**
    - **Increase IMEP**
      - **Increase CR, Fuel Delivery, Turbo charging**
    - **Decrease FMEP**
      - **Decrease auxiliary losses**
      - **Reduce pumping losses**
      - **Decrease friction (reduce engine speed)**

Torque Shaping Theory (metric)

$$T_b = T_i - T_f$$

$P_i = 2\pi TN/60{,}000$

$P_i = P_{fe} * e_{it}$ $\quad$ $P_i = e_{it} * mf*Hg/3600$

$T_i = e_{it} * m_f*H_g/3600 * 60000/ 2\pi N$

$$\mathbf{T_i = [(e_{it}\, H_g)/(0.06\pi)] * [\, m_f /2N\,]}$$

$P_f = 2\pi TN/60{,}000$

$P_f = [FMEP*D*N] / [rc*60*10^3]$

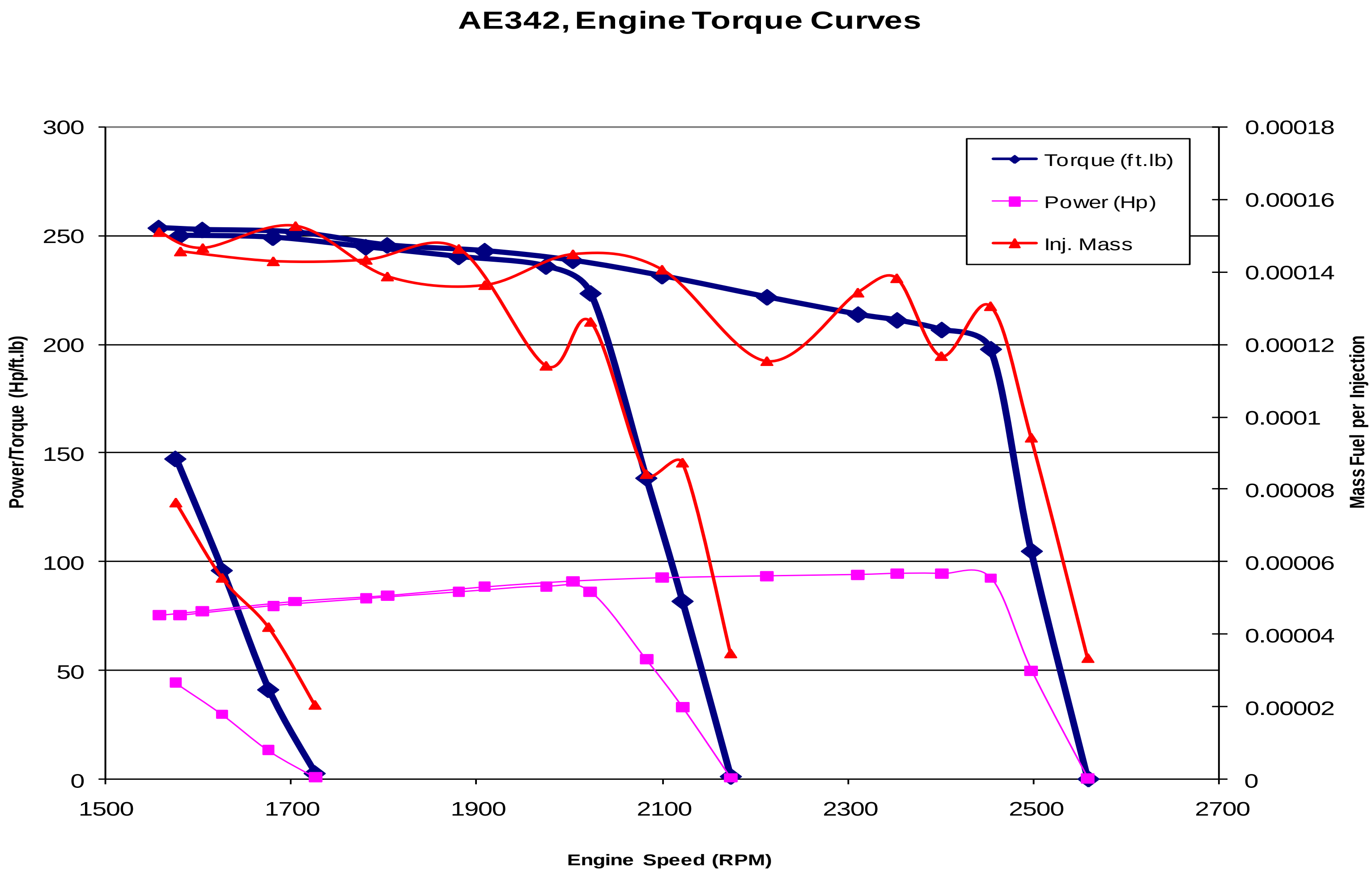
$T_f = [FMEP*D] / [rc*2\pi]$ $\quad$ $\mathbf{FMEP = a_o + a_1 *(N/1000) + a_2*(N/1000)^2}$

$$\mathbf{T_f = [FMEP*D] / [rc*2\pi]}$$

$$T_b \mathbf{= [(e_{it}\, H_g)/(0.06\pi)] * [\, m_f /2N\,] - [FMEP*D] / [rc*2\pi]}$$

"Constant" **Mass Fuel/Inj. Cycle** **Friction Torque**

Torque Curves



Friction Power

FMEP = IMEP - BMEP

Friction Power = Mechanical Friction + Pumping Loss + Auxiliaries

- Auxiliaries:
  - Oil Pump, alternator, water pump etc
- Pumping Loss:
  - Work required for intake & exhaust stroke
    - Air cleaner & Intake pressure drops
    - Valve Pressure Drops
- Mechanical
  - Bearings etc
  - Piston & Rings (approx 75% Total Mechanical Friction)
    - Proportional to speed

Engine Efficiency

- **Specific Fuel Consumption**

$$SFC = m_f / P_x \quad (\text{ kg/kW.h or lb/Hp.h })$$

- **Loading and Efficiency**

$$e_{bt} = e_{it} * e_m$$

$$e_{bt} = e_{it} * (P_b / P_i)$$

$$e_{bt} = e_{it} * (P_b / [P_b + P_f])$$

$$e_{bt} = e_{it} * (1/[1 + P_f /P_b])$$

Engine Performance Maps

- **Brake Specific Fuel Consumption**

$BSFC = 3600 / (H_g * e_{bt})$

$e_{bt} = e_{it} * e_m$
$e_{bt} = e_{it} * (BMEP / IMEP)$
$e_{bt} = e_{it} * (BMEP / [BMEP + IMEP])$
$e_{bt} = e_{it} /(1 + FMEP / BMEP)$

$BSFC = 3600 / (H_g * e_{it}) * [1 + FMEP / BMEP]$

$FMEP = a_o + a_1 *(N/1000) + a_2*(N/1000)^2$

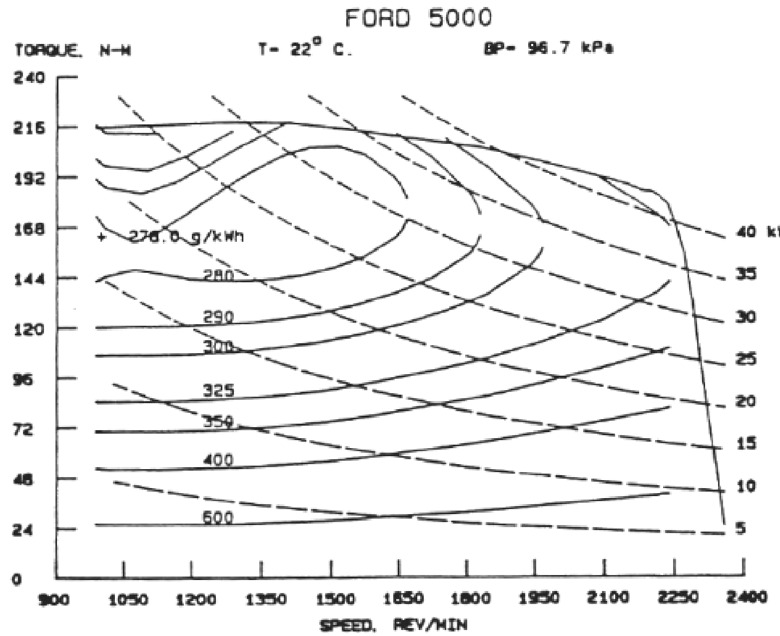


Figure 2.4. A performance map of an over-fueled engine.

$e_{it} = e_{ito} / [1 + T_b^{n} * f(N_e)]$
$f(N_e) = B_o + B_1(N_e/1000)^{-1} + B_2(N_e/1000)^{-2} + B_3(N_e/1000)^{-3} + B_4(N_e/1000)^{-4}$

e_{ito} = Indicated Thermal efficiency at low torque
n = constants for particular engine
B_i = constants for particular engine