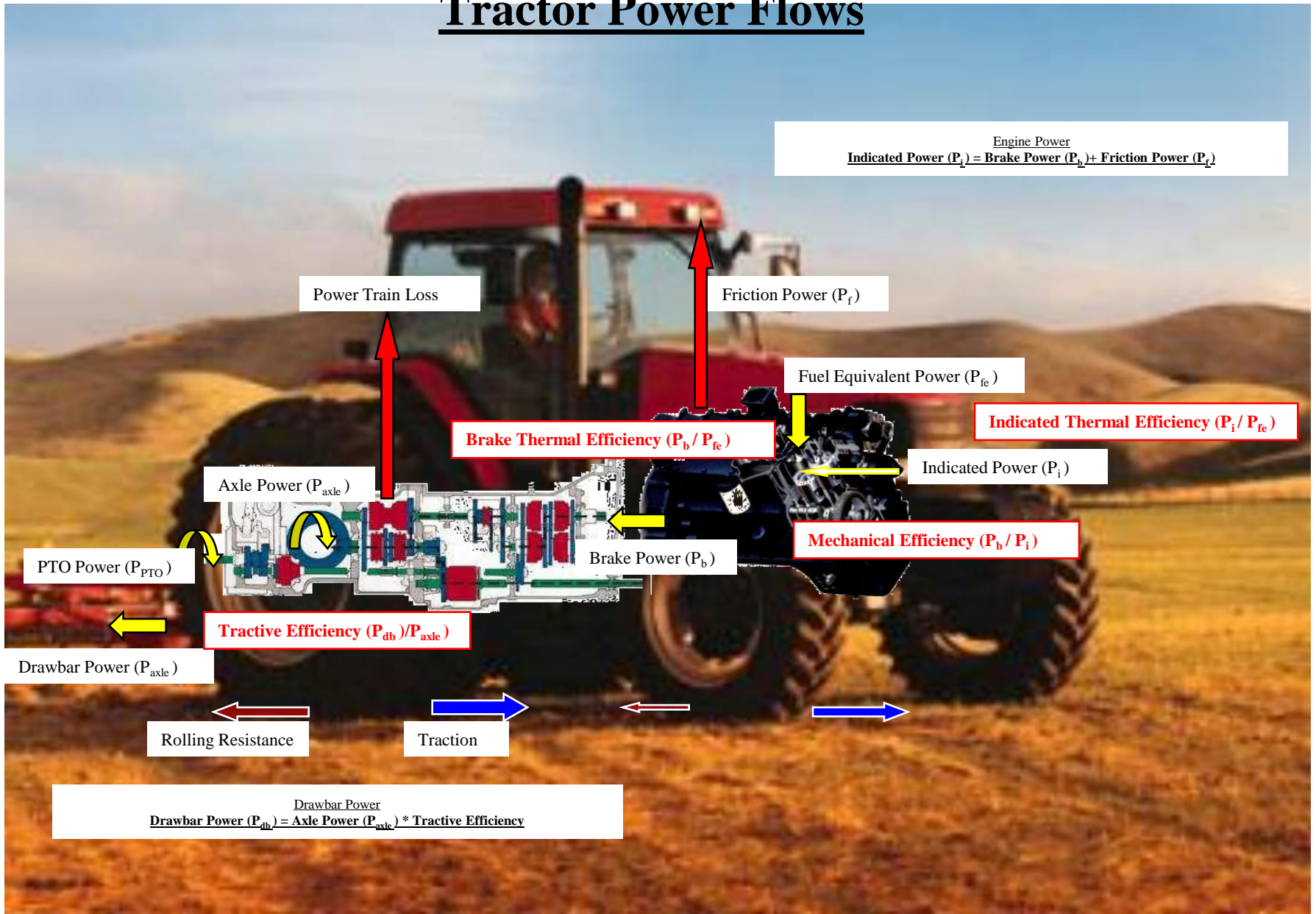


# Tractor Power Flows



# Force, Torque, Work and Power

## Fundamental Units

|               | <u>Metric (SI) Units</u> | <u>English Units</u>    |
|---------------|--------------------------|-------------------------|
| • Time        | seconds (s)              | seconds (s)             |
| • Length      | meter (m)                | foot (ft)               |
| • Temperature | Celsius (°C)             | Fahrenheit (°F)         |
| (Absolute)    | Kelvin (°K)              | Rankin (°R)             |
| • Mass        | kilogram (kg)            | Slug (hardly ever used) |

## Derived Units

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

# Force, Torque, Work and Power

**Force:**                    **Force = Mass \* acceleration**

Metric (SI) Units, (N)

$$\text{Force (N)} = 1 \text{ (kg)} * 1 \text{ m/s}^2$$

$$1 \text{ N} = 1 \text{ kg.m/s}^2$$

English Units, (lb<sub>f</sub>)

$$\text{Force (lb}_f\text{)} = 1 \text{ (slug)} * 1 \text{ ft/s}^2$$

$$1 \text{ lb}_f = 1 \text{ slug.ft/s}^2$$

**Work / Energy:**                    **Work = Force \* Distance**

Metric (SI) Units, (J)

$$\text{Work (J)} = 1 \text{ (N)} * 1 \text{ m}$$

$$1 \text{ J} = 1 \text{ N.m}$$

English Units (ft-lb)

$$\text{Work (ft-lb)} = 1 \text{ (lb)} * 1 \text{ ft}$$

$$1 \text{ (ft-lb)} = 1 \text{ ft-lb}$$

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)

$$\text{Power (w)} = 1 \text{ (J)} \text{ per second}$$

$$1 \text{ w} = 1 \text{ J/s}$$

English Units, (Hp)

$$\text{Power (ft-lb}_f\text{/s)} = 1 \text{ (ft-lb)} \text{ per second}$$

$$1 \text{ ft-lb}_f\text{/s} = 1 \text{ ft-lb/s}^2$$

$$1 \text{ Hp} = 550 \text{ ft-lb/s}^2$$

# Power

Power is the rate of doing work

## Metric (SI) Units, (watts, W)

$$P = \text{Work/time} \quad (\text{N}\cdot\text{m/s} = \text{J/s} = \text{W})$$

$$P = \text{Force} * \text{distance/time} = \text{Force} * \text{velocity} \quad (\text{N}\cdot\text{m/s} = \text{N}\cdot\text{m/s} = \text{J/s} = \text{W} )$$

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

## English Units, (Horsepower, Hp)

$$P = \text{Work/time} \quad (\text{ft}\cdot\text{lb/s} = ?? \text{Hp})$$

$$P = \text{Force} * \text{distance/time} = \text{Force} * \text{velocity} \quad (\text{lb}\cdot\text{ft/s} = \text{ft}\cdot\text{lb/s} = ?? \text{Hp} )$$

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

$$\text{Power (Hp)} = [\text{Force}\cdot\text{distance/time (lb}\cdot\text{ft/s)}] / [550 (\text{lb}\cdot\text{ft/s per Hp})]$$

# Torque and Power (Metric)

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

|        | <u>Metric (SI) Units</u> | <u>English Units</u> |
|--------|--------------------------|----------------------|
| 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)

|        | <u>Metric (SI) Units</u> | <u>English Units</u> |
|--------|--------------------------|----------------------|
| Torque | N.m                      | ft.lb                |

## Torque and Power

$$\begin{aligned}\text{Torque} &= \text{Force} * \text{Lever Arm} \\ &= F * L\end{aligned}$$

$$\begin{aligned}\text{Work per revolution} &= \text{Force} * \text{Distance} \\ &= F * (2\pi * L)\end{aligned}$$

$$\text{Work per revolution} = \text{Torque} * 2\pi = 2\pi * T \quad (\text{N.m/rev or ft.lb/rev})$$

## English Units, (Horsepower, Hp)

$$\begin{aligned}\text{Work per Revolution} &= 2\pi * T \quad (\text{ft.lb/rev}) \\ \text{Power} &= \text{Work} / \text{Time} \\ &= \text{Work per Revolution (ft.lb/rev)} * \text{Revolutions per minute (rev/min)} \\ &= [2\pi TN \quad (\text{ft.lb/rev} * \text{rev/min})] / [60 \quad (\text{sec/min})] \\ &= 2\pi TN / 60 \quad (\text{ft.lb/s}) \\ &= 2\pi TN / 60 \quad (\text{ft.lb/s})\end{aligned}$$

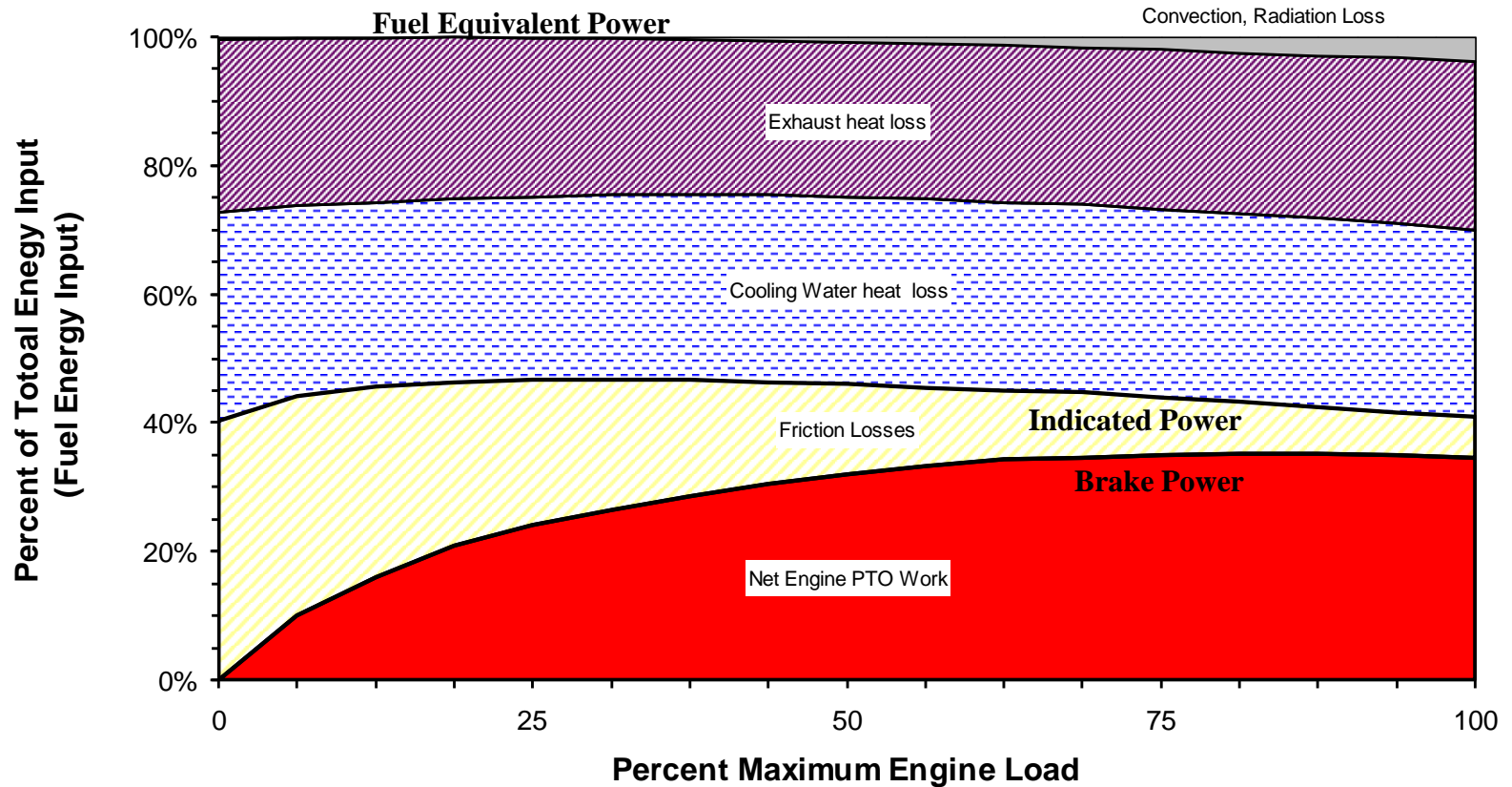
Power is normally given in horsepower (Hp) Note: 1 Hp = 550 ft.lb/sec

$$\begin{aligned}\text{Power} &= [2\pi TN / 60 \quad (\text{ft.lb/s})] / [550 \quad (\text{ft.lb/sec per Hp})] \\ &= 2\pi TN / (60 * 550) \text{ Hp} \\ &= 2\pi TN / 33,000 \text{ Hp}\end{aligned}$$

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

# Power (Energy) Flows in an Engine

## Energy Balance for Typical Diesel 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)\***

$$\text{Indicated}_{(Power/Torque/MEP)} = \text{Brake}_{(Power/Torque/MEP)} + \text{Friction}_{(Power/Torque/MEP)}$$

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

# 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)

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

$$= HV * M_f / 3600 \text{ (kW)}$$

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

$M_f$  = Fuel Consumption (kg/hr)

### English (Hp)

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

$$= HV * M_f / [60 * 33000] \text{ (Hp)}$$

$$= HV * M_f / 2545 \text{ (Hp)}$$

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 stroke

#### Metric (kW)

$$\begin{aligned} P_i &= \text{Force} * \text{Distance} / \text{Time} && (\text{Force} = \text{Pressure} * \text{area}) \\ &= [\text{IMEP (kN/m}^2) * A_p(\text{cm}^2) * L(\text{cm}) * 10^{-6} (\text{m}^3/\text{cm}^3)] / [\text{Time}] \\ &= [\text{IMEP} * A_p * L (\text{kJ})] / [\text{Time}] && (\text{Time} = \text{rev. cycle} / \text{rpm}) \\ &= [\text{IMEP} * A_p * L (\text{kJ})] * N (\text{rev/min}) / [\text{rc (cycle/rev)} * 60 (\text{sec/min})] \end{aligned}$$

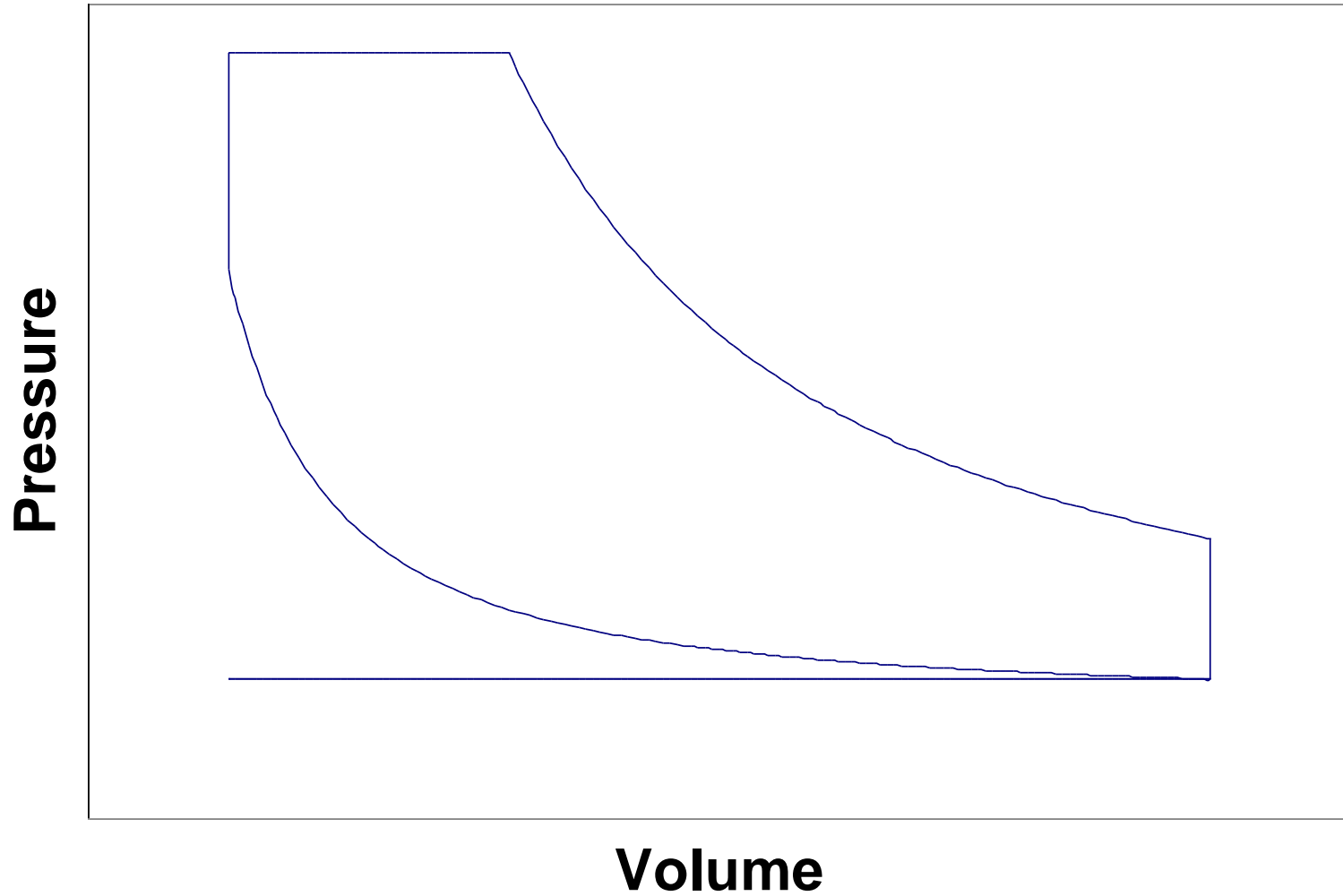
$$P_i (\text{kW}) = [\text{IMEP} * L * A_p * N * n] / [\text{rc} * 60 * 10^6]$$

IMEP = Indicted Mean Effective Pressure (kPa), L = Stroke Length (cm),  $A_p$  = Piston Area ( $\text{cm}^2$ )  
N = Engine Speed (rpm), n = number cylinders, rc = revolutions per cycle

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

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

#### English (Hp)

$$\begin{aligned} P_i &= \text{Force} * \text{Distance} / \text{Time} && (\text{Force} = \text{Pressure} * \text{area}) \\ &= [\text{IMEP (psi)} * A_p(\text{in}^2) * L(\text{in}) * 1/12 (\text{ft/in})] / [\text{Time}] \\ &= [\text{IMEP} * A_p * L/12 (\text{ft-lb})] / [\text{Time}] && (\text{Time} = \text{rev. cycle} / \text{rpm}) \\ &= [\text{IMEP} * A_p * L/12 (\text{ft-lb/cycle})] * N / [\text{rc}] (\text{cycles/min}) \\ &= [\text{IMEP} * A_p * L/12 * N / [\text{rc}]] (\text{ft-lb/min}) \\ &= [\text{IMEP} * A_p * L/12 * N / [\text{rc} * 33,000]] (\text{Hp}) \end{aligned}$$

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

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

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

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

# Increase Indicated Engine Power

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

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)

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

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

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

- English Units, (Hp)

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

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

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

# Increasing Engine Brake Torque

- Metric Units, (watts, W)

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

Therefore :

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

$$\text{Torque} = \quad = [BMEP*D] / [rc*2\pi]$$

- English Units, (Hp)

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

Therefore :

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

$$\text{Torque} = \quad = [BMEP*D] / [rc*2\pi *12]$$

- 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)

# Friction Power

$$\text{FMEP} = \text{IMEP} - \text{BMEP}$$

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