Engineering Tripos Part IIB

Module 4A13

Examples Paper - Internal Combustion Engines **Lent 2020**

1. Provide explanations for the following statements. Add equations or scaling as necessary.
   (a) throttle is required to vary the load of gasoline engines
   (b) gasoline engines work at stoichiometric conditions
   (c) compression-ignition engines operate lean
   (d) the crank angle over which combustion takes place is roughly independent of engine speed for gasoline engines
   (e) the bore and stroke of most automotive gasoline engines for land use are equal
   (f) compression ignition engines of a similar power output typically have a better sfc than gasoline engines
   (g) large cylinder volume diesel engines have a better sfc than small cylinder volume engines
   (h) why turbochargers are used - advantages and disadvantages.

2. Understanding the speed-load diagram.
   (a) Sketch a typical bmep vs. speed diagram for a naturally aspirated gasoline engine, showing the maximum (wide open throttle) bmep, lines of constant power, contours of constant sfc, and a top gear road load characteristic.
   (b) Justify with brief notes the characteristics you have sketched.
   (c) In the context of the diagram, discuss possible options for improving the specific fuel consumption of gasoline engines.

3. The per unit piston area P/A_p, also called engine specific power, is a measure of the designer's success in using the available piston area regardless of size. The power per unit engine weight is a good measure of the efficacy of the device in delivering power.
   (a) Derive an expression for P/A_p involving bmep and mean piston speed
   (b) Assuming that bmep, P/A_p, and the maximum mean piston speed are independent of cylinder size, and that the mass of an engine scales linearly with total displacement volume, determine how the specific mass of an engine (engine mass/engine power) varies with the number of cylinders for a fixed total displacement. Assume that the engine bore and stroke are equal.
   (c) Based on your result in (b), determine whether it makes sense to have multiple cylinder engines for increased power.

4. Consider an idealised four-stroke engine cycle, running under throttled conditions.

(a) Assuming the working fluid is a perfect gas, with ratio of specific heats γ, find expressions for the gross and net imep, as a function of cycle parameters and inlet conditions. Assume isentropic compression and expansion strokes.

(b) If the compression ratio is 9, the inlet temperature T_1 = 288 K, γ = 1.4, the temperature rise on combustion is 1400 K, and the exhaust and inlet manifold pressures are 1 bar and 0.5 bar respectively, determine the peak pressure p_3, and the gross imep.

(c) Determine the pumping work, the pmep and the net imep.

(d) Sketch the $p - V$ diagram, and add to this a sketch an unthrottled cycle operating between the same minimum and maximum volumes, which would produce the same net work as the throttled cycle, based on late inlet valve closing. You may assume that the unthrottled inlet pressure is equal to the exhaust pressure p_e . No calculations are required, but justify with a few comments the sketch you have made.

5. A compression-ignition engine is fitted with a turbocharger. The AFR is 18:1, inlet to the compressor (of isentropic efficiency 70%) is at 0.95 bar abs, 15 °C, and outlet of the compressor is at 2 bar abs. The exhaust gases enter the turbine (of isentropic efficiency 80%) at 1.8 bar abs, 600 °C, and leaves at 1.05 bar. Assume that the properties of air are $c_{p,a}$ = 1.01 kJ/kg K, and $\gamma_a = 1.4$, and that for the exhaust gases, $c_{p,e}$ = 1.15 kJ/kg K, and γ_e = 1.33.

   (a) Draw the turbocharger process on a $T - s$ diagram.

   (b) Determine the gas temperature at exit from the compressor and turbine.

   (c) Calculate the mechanical efficiency of the turbocharger.

   (d) If an intercooler were fitted at the exit of the compressor, of effectiveness 0.5, and the AFR, the compressor delivery pressure and temperature are unchanged, estimate the increase in engine power. (Assume the temperature available for heat exchange is 15 °C.)

6. Estimate the extent to which exhaust gas recirculation (EGR) can reduce the rate of NO formation in a SI engine operating at stoichiometric conditions. For a baseline case of combustion with $x_r = 0.05$ residual mass fraction of burned gases, and an estimated temperature at ignition of 722 K, the peak temperature is 2500 K. Assume that total burned mixture is given by the sum of residual mass, x_r (which remains unchanged) and the EGR fraction added to the manifold, x_{EGR}. Assume that the specific heat capacity at constant volume of the burned gases is $c_{v,b}$ = 2.0 kJ/kg, and that of the unburned mixture is $c_{v,a}$= 1.2 kJ/kg K, and that the ignition temperature is unchanged. Assume that the molecular oxygen molar fraction present, $[O_2]$, is diluted proportionally to the amount of total burned gas, i.e. $[O_2] = [O_2]_0[1-(x_r+x_{EGR})]$, and atomic oxygen can be considered to be in equilibrium in the burned gases. Use a Zeldovich mechanism, and assumption of equilibrium for $[O]$ concentrations, with $k_1 = 1.8 \times 10^{14} \exp(-38730/T)$, and an equilibrium constant, $K_p = \frac{{p_O}^2}{p_{O2}}$. Values for $\log_{10} K_p$ can be found in the Jannaf tables for the O atom: `https://janaf.nist.gov/tables/O-001.html`. Comment on how addition of recirculated EGR may affect intake mixture properties and alter the calculation.

7. Explain how three way catalytic converters work to reduce emissions from SI engines, and limitations to their efficiency and performance. Explain what constraints they put on operation of SI engines, and why this is a problem.

8. Explain what are the key pollutants from CI engines, how they are formed, how they can be controlled, and any tradeoffs in their operation. Include any diagrams, as necessary.

9. Explain the advantages and disadvantages of hybridisation for engines. Explain the differences between parallel and series operation, and their respective advantages and disadvantages.

ANSWERS

1. -

2. -

3. (a) $\frac{P}{A_p} = \frac{\text{bmep}}{2n_R}\overline{S}_p$

   (b) $\frac{m_e}{P} \propto n_c^{-1/3}$

   (c) -

4. (a) $$\frac{\text{imep}_\text{n}}{p_1} = \left(1 - r_c^{-(\gamma-1)}\right)\frac{r_c}{r_c-1}\frac{1}{\gamma-1}q^* - \left(\frac{p_a}{p_1} - 1\right)$$

   (b) 32.7 bar, 4.0 bar

   (c) 0.5 bar, 3.5 bar

   (d) -

5. -

   (a) -

   (b) 385.5 K, 785.6 K

   (c) 93%

   (d) 14.5%

6. $x_r = [0, 0.1, 0.2, 0.3] \rightarrow w/w_0 = [1.000, 0.220, 0.051, 0.012]$

7. -

8. -

9. -

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Solutions

1. Provide explanations for the following statements. Add equations or scaling as necessary.

   (a) *throttle is required to vary the load of gasoline engines*
   A throttle acts to control the load provided by the engine during operation, by the following means:

   (i) reducing the total pressure in the cylinder, which reduces the total mass of air in the engine. For a fixed air/fuel ratio, the total heat release rate per unit cycle (and thus the total load) is proportional to the total mass of air in the cylinder.

   (ii) reducing the net imep, by consuming part of the gross work as pumping work to bring the air in through the resistance of the throttle.

   (b) *gasoline engines work at stoichiometric conditions*
   For purposes of efficiency, one would rather operate lean, as that offers higher γ, but the requirement of stoichiometry comes from the need both to *oxidize* CO and HC to CO_2 as well as reduce NO to N_2 over the catalytic converter. The converter stores NO, CO and HC briefly whilst the mixture switches between slightly rich and slightly lean within a percent of stoichiometry.

   (c) *compression-ignition engines operate lean*
   CI engines operate fuel-lean, typically at between ϕ 0.3 – 0.7. Further increases lead to incomplete combustion and smoke, as not all the fuel is able to effectively mix and oxidise during the cycle.

   (d) *the crank angle over which combustion takes place is roughly independent of engine speed for gasoline engines*
   The rate of combustion is proportional to the turbulent flame speed, which is approximately proportional to the laminar flame speed times approximately one half power of the turbulent kinetic energy. The latter is proportional to the square of the engine speed, so that the overall crankangle range required for combustion is approximately constant with speed, of the order of 30-40 degrees in a cycle:
   $\Delta\theta \propto \dfrac{BN}{S_T} = \dfrac{BN}{S_L k^{1/2}} \propto \dfrac{BN}{S_L N} \propto \dfrac{B}{S_L}$.

   (e) *the bore and stroke of most automotive gasoline engines for land use are equal*
   An approximately equal bore and stroke allows the flame to propagate approximately spherically away from the walls as the piston expands, minimising heat losses and maximising the rate of combustion.

   (f) *compression ignition engines of a similar power output typically have a better specific fuel consumption (sfc) than gasoline engines*
   In general, because they can be operated at higher compression ratios, and the net efficiency η_f is higher than that of spark-ignited engines:

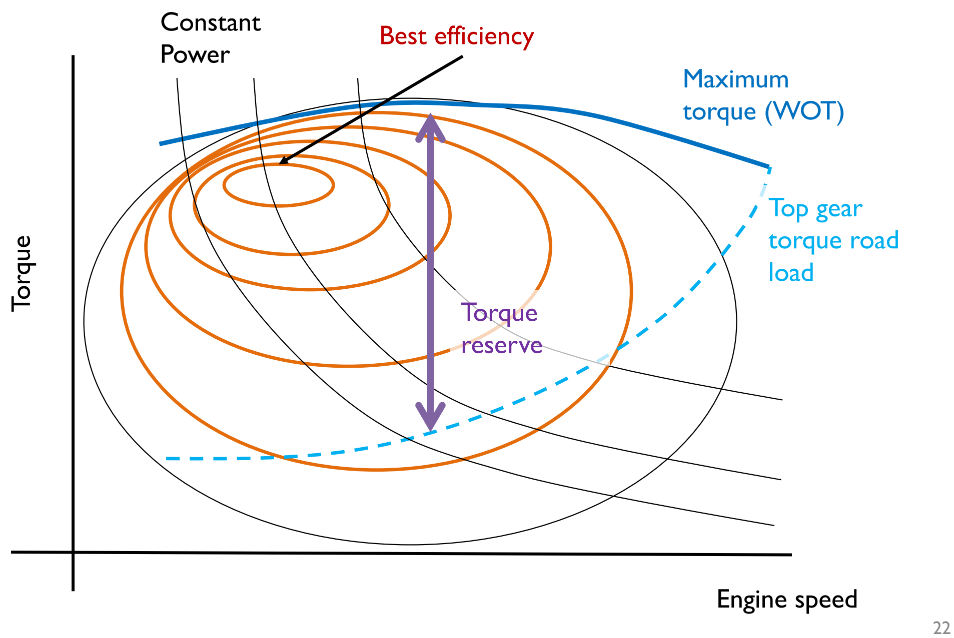
   $$\text{sfc (g fuel/kWh)} = \frac{1}{\eta_f q_f}$$

   (g) *large cylinder volume diesel engines have a better sfc than small cylinder volume engines*
   Typically they operate more slowly and have lower heat losses.

(h) *why turbochargers are used - advantages and disadvantages.*
Turbochargers increase the density of the intake air, and therefore the total power delivered for a given condition. The energy of the turbocharger is extracted from the exhaust. Compression ignition engines use turbochargers to vary the total air charge delivered at a fixed speed, as the fuel/air ratio is limited by the onset of soot emissions. Spark-ignition engines can also benefit by turbocharging, by downsizing the engine to a smaller maximum torque. The disadvantages are the need for an extra piece of equipment, as well as consequences to emission control, *e.g.* the turboset needs to spool up during accelerations, and the failure to deliver sufficient air quickly enough can create high particulate matter emissions; the lower temperatures downstream of the the engine exhaust can make it difficult to keep catalytic converter efficiencies high.

2. Understanding the speed-load diagram.

(a) Sketch a typical bmep vs. speed diagram for a naturally aspirated gasoline engine, showing the maximum (wide open throttle) bmep, lines of constant power, contours of constant sfc, and a top gear road load characteristic.



(b) Justify with brief notes the characteristics you have sketched.

- Power lines: $P \propto \text{bmep}\ N$, so that on a bmep-speed graph the isopower lines are asymptotic to the axes;
- The top gear road load line goes up with speed (typically because drag increases with the square of the speed); low load, low speed lines for shifting gears appear similarly, with discontinuities between gears.
- The maximum torque or bmep is limited by volumetric efficiency at the low end for SI engines, and compressor/turboset air delivery characteristics for CI engines. For high speeds, component durability under high power conditions (high temperatures) limits the bmep/torque.

- The best cycle efficiency (lowest specific consumption) for most engines appears at mid-speed, mid-load range: friction losses and volumetric efficiency decrease at high speeds, and volumetric efficiency is lower at low speeds; heat losses limit efficiency at high speeds. The maximum efficiency usually appears at a torque slightly lower than maximum, limited by the gas exchange efficiency (lower volumetric efficiency).
- The difference between the torque demanded at mid-speed, top gear and the maximum provided by the engine provides a torque reserve that allows one to 'downshift' gears, move to a higher engine speed and higher torque when overtaking.

(c) In the context of the diagram, discuss possible options for improving the specific fuel consumption of gasoline engines.
Engine characteristics are optimised for power, noise, consumer experience, not necessarily bsfc. Better bsfc can be obtained engine downsizing, which can operate closer to the optimum specific consumption, and use other storage techniques (e.g. superchargers, batteries) to provide additional torque only when needed. Other techniques to improve efficiency may be continuous variable transmission (to optimise the engine speed to an optimum, at variable loads), variable valve timing (to minimise throttling losses in SI engines).

3. Ideal constant volume cycle @ throttled conditions.

   (a) Using the assumptions of isentropic compression and expansion, and isochoric heat addition, we have:

$$p_2 = p_1 \qquad T_2 = T_1 r_c^{\gamma-1}$$
$$p_3 = p_2 T_3/T_2 \qquad T_4 = T_3 r_c^{-(\gamma-1)}$$

$$\begin{aligned}
w_{1234} &= c_v[(T_3 - T_4) - (T_2 - T_1)] \\
q_{23} &= c_v(T_3 - T_2) \\
\eta &= \frac{w_{1234}}{q_{23}} = \frac{(T_3 - T_4) - (T_2 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2} \\
&= 1 - \frac{T_3 r_c^{-(\gamma-1)} - T_1}{T_3 - T_1 r_c^{\gamma-1}} = 1 - r_c^{-(\gamma-1)}
\end{aligned}$$

$$\begin{aligned}
\mathrm{imep_g} &= w_{1234}\frac{m}{V_d} = \eta q_{23}\frac{p_1 r_v V_c}{(r_c-1)V_c} = \eta\left(\frac{p_1}{RT_1}\right)\frac{r_c}{r_c-1}c_v(T_3 - T_2) \\
\frac{\mathrm{imep_g}}{p_1} &= \eta\frac{r_c}{r_c-1}\frac{1}{\gamma-1}\underbrace{\frac{T_3 - T_2}{T_1}}_{q^*} = \left(1 - r_c^{-(\gamma-1)}\right)\frac{r_c}{r_c-1}\frac{1}{\gamma-1}q^* \\
\frac{\mathrm{imep_n}}{p_1} &= \left(1 - r_c^{-(\gamma-1)}\right)\frac{r_c}{r_c-1}\frac{1}{\gamma-1}q^* - \left(\frac{p_a}{p_1} - 1\right)
\end{aligned}$$

   where

$$q^* = \frac{T_3 - T_2}{T_1} = \frac{m_f q_f}{m} = \frac{m_f}{m_a}\frac{m_a}{m}q_f = \frac{1}{AFR}\left(1 - \frac{m_f}{m} - \frac{m_r}{m}\right)q_f$$

   For zero or small residual gases, $m_a \approx m$ and $q^* = \dfrac{q_f}{AFR}$ is approximately constant.

   In that case, $\dfrac{\mathrm{imep_n}}{p_1}$ is only a function of the compression ratio, and $\dfrac{p_a}{p_1}$.

   (b)

$$p_3 = p_2\frac{T_3}{T_2} = p_1 r_c^{\gamma}\frac{T_2 + \Delta T}{T_2} = p_1 r_c^{\gamma}(1 - \frac{\Delta T}{T_1 r_c^{(\gamma-1)}})$$

$$= (0.5 \text{ bar})9^{1.4}(1 - \frac{1400 \text{ K}}{288 \text{ K}}9^{-(1.4-1)}) = 32.7 \text{ bar}$$

$$\begin{aligned}
\frac{\mathrm{imep_g}}{p_1} &= \left(1 - r_c^{-(\gamma-1)}\right)\frac{r_c}{r_c-1}\frac{1}{\gamma-1}q^* \\
&= \left(1 - 9^{-(1.4-1)}\right)\frac{9}{9-1}\frac{1}{1.4-1}\frac{1400}{288} = 8.0
\end{aligned}$$

$$\mathrm{imep_g} = 8.0(0.5 \text{ bar}) = 4.0 \text{ bar}$$

(c)

$$w_p = p_a - p_1 = (1.0 - 0.5)\ \text{bar} = 0.5\ \text{bar}$$
$$\text{imep}_\text{n} = \text{imep}_\text{g} - w_p = 4.0 - 0.5 = 3.5\ \text{bar}$$

(d) See Figure: the net work represented by I+II should be equal to the cycle on the RHS. I+III is the gross work, and II+ III the pumping work. The cycle can then work unthrottled, but producing the same amount of work as required. However, this requires that the valve closure be at a different point in the compression cycle, which demands a variable valve timing (typically with a hydraulic valve set).

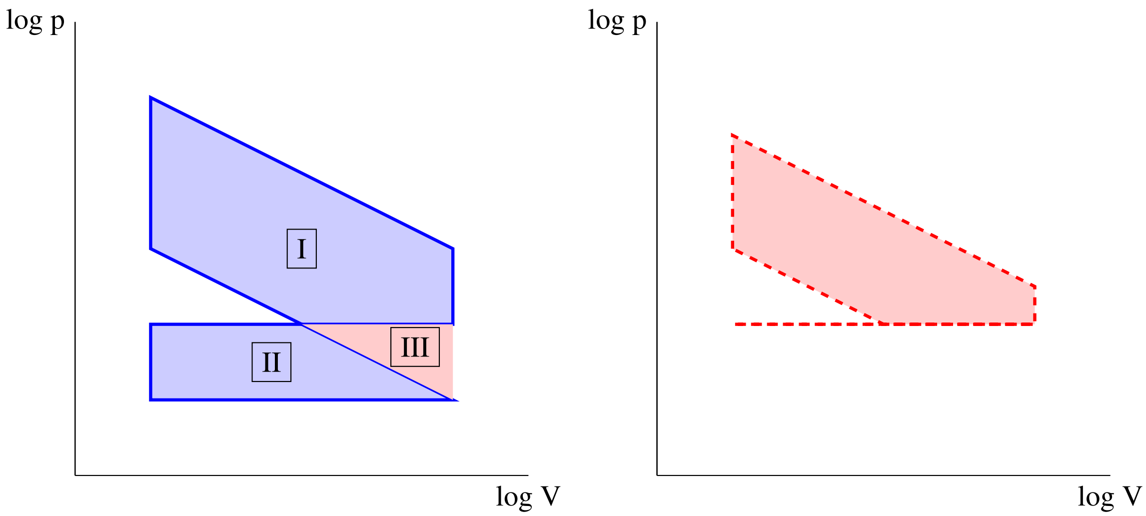
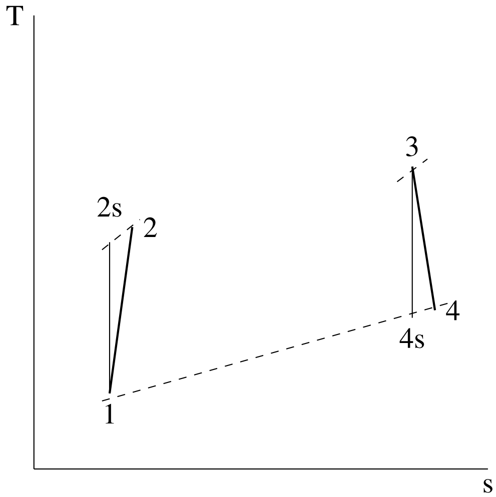


Figure 1: (left) original cycle, (right) modified cycle.

4. See T-s diagram. The dashed lines represent iso-pressure curves.



(a)

$$\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma} = \left(\frac{2}{0.95}\right)^{(0.4)/1.4} = 1.239$$

$$T_{2s} = 356 \text{ K}$$

$$\frac{w_{12}}{w_{12,s}} = \frac{1}{\eta_c} = \frac{1}{0.70} = \frac{T_2 - T_1}{T_{2s} - T_1}$$

$$T_2 = 288 + (356 - 288)/0.70 = 385.5 \text{ K}$$

$$\frac{T_{4s}}{T_2} = \left(\frac{p_3}{p_4}\right)^{(\gamma-1)/\gamma} = \left(\frac{1.05}{1.8}\right)^{(0.33)/1.33} = 0.875$$

$$T_{2s} = 763 \text{ K}$$

$$\frac{w_{34}}{w_{34,s}} = \frac{1}{\eta_t} = 0.80 = \frac{T_3 - T_4}{T_3 - T_{4s}}$$

$$T_2 = 873 - 0.80(873 - 763) = 785.6 \text{ K}$$

(b) The work provided by the turbine must equal that of the compressor:

$$w_t = w_{34} = \frac{w_{12}}{\eta_m}$$

$$\eta_m = \frac{w_{12}}{w_{34}} = \frac{\dot{m}_a c_{p,a}(T_2 - T_1)}{\dot{m}_e c_{p,e}(T_3 - T_4)} = \frac{1.01(385.5 - 288)}{1.15(873 - 785.6)} \frac{1}{1 + 1/18}$$

$$\eta_m = 0.93$$

5. We start by estimating the final gas temperature as a function of EGR:

$$mc_v(T_f - T_i) = m_f q_f$$
$$[x_r c_{v,b} + (1 - x_r)c_{v,b}](T_f - T_i) = Q^*$$
$$[(x_r + x_{EGR})c_{v,b} + (1 - (x_r + x_{EGR})c_{v,a}] = Q^*$$
$$(T_f - T_i) = \frac{Q^*}{[(x_r + x_{EGR})c_{v,b} + (1 - (x_r + x_{EGR})c_{v,a}]}$$

We can calculate the value of Q^* for the case with a known temperature T_f, x_r, $x_{EGR} = 0$, and use it to calculate the subsequent temperatures for different x_{EGR} values.

The rate of formation of NO is given by (See ICE-5 lecture, and previous lectures on NO formation) $w_{[NO]} = 2k_1(K_p[O_2]/c)^{1/2}$, for each estimated temperature. The molecular oxygen concentration is assumed to be diluted according to the amount of residual plus EGR. We observe that the total density does not change for constant volume combustion, if we neglect the change in molecular weight of the total gases , so that

$$\frac{w_{[NO]}}{w_{[NO]}{}_0} = \frac{k_1(T)}{k_1(T_0)} \left(\frac{K_p(T)}{K_p(T_0)} \frac{[O_2]}{[O_2]_0} \right)^{1/2}$$

x_{EGR}	T_f	$\log_{10} K_p$	K_p	$k_1/k_{1,0}$	$[O2]/[O2]_0$	$K_p/K_{p,0}$	w/w_0
0	2500	-1.8390	0.014487	1	1	1	1
0.1	2392	-2.0807	0.008304	0.497	0.895	0.573	0.220
0.2	2297	-2.3123	0.004871	0.254	0.789	0.336	0.051
0.3	2212	-2.5370	0.002904	0.133	0.684	0.2007	0.012

The rates of formation are therefore significantly reduced by a relatively small change in dilution gas. Key to the process is the high c_v of the burned gases.

In the present case, we assumed that there are no changes to the total mass trapped in the system, or the initial pressure and temperature. However, those will of course be affected by the presence of additional burned gases, by changing the mixture properties , such as temperature and specific heats.

6. Explain how three way catalytic converters work to reduce emissions from SI engines, and the limitations to their efficiency and performance.

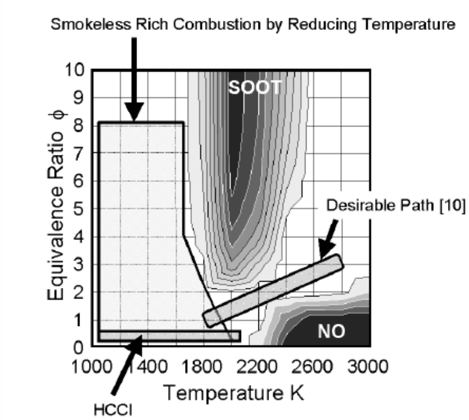
   Three way catalytic converters are called three-way converters, because they convert hydrocarbons, CO and NO simultaneously. Catalytic converters are made of blocks of temperature resistant ceramics, coated with Pt/Pd/Rh. Reactions happen at temperatures above 200 $\circ$ C, after the converter has been warmed up by exhaust gases. A large (90%) amount of the CO and HC emitted by engines during a standard cycle takes place during the first few seconds of operation, as the converter is not yet warmed up. NO is reduced by remaining hydrocarbons trapped during the slightly rich operation over the catalyst. CO and HC are oxidized over the catalyst, helped by O_2 stored in the CeO_2 or ZrO_2material. Catalytic converters remove most of the hydrocarbons and NO when fully warmed up. They can be easily poisoned by additives in lubricants. Current practice is to have on-board diagnostics to detect failures, as they have to be certified to 100,000 km.

   The catalytic converter switches the equivalence ratio of operation between lean and rich over a time scale of about 1 Hz, providing for periodic storage of O_2 and HC. Lean operation would be more desirable from the point of view of efficiency, as leaner mixtures have higher γ. However, NO levels are too high at the point where the engine can still be run ($\lambda = 1.3$), and beyond this value, engine operation becomes unstable.

7. Explain what are the key pollutants from CI engines, and how they can be controlled, and any tradeoffs in their operation.

   The key pollutants of concern for CI engines are NOx and particulate matter. Non-premixed combustion produces high temperatures in the near stoichiometric regions produced in the mixing layer. The high temperatures lead to high NO formation on the stoichiometric to oxidiser side, and high temperature pyrolysis of fuel, leading to and soot formation on the fuel side.

   Design of the operation attempts to march along combustion that takes place away from the high soot and high NO area, by using early injection (low temperature combustion) but this can lower the maximum possible load, and depends on engineering the rate of turbulent mixing of fuel and air during injection.

   Abatement of the formation of soot and NO include using EGR (which is effective up to 30% of the charge, but leads to lower power density), as well as selective catalytic reforming (SCR) using ammonia as a reactant to reduce NO and NO2 back to N2. Diesel particle filters (DPF) can be used to remove particles. These trap the particles in small passages of the filter, until periodic oxidation is done, using some of the fuel to heat up the DPF under overall lean conditions. These techniques typically have a fuel efficiency penalty of up to a few percent.

8. Explain the advantages and disadvantages of hybridisation for engines. Explain the differences between parallel and series operation, and their respective advantages and disadvantages.

   Hybrid electric vehicles can improve the overall efficiency of vehicles propelled by internal combustion engines (ICE) through the following mechanisms:

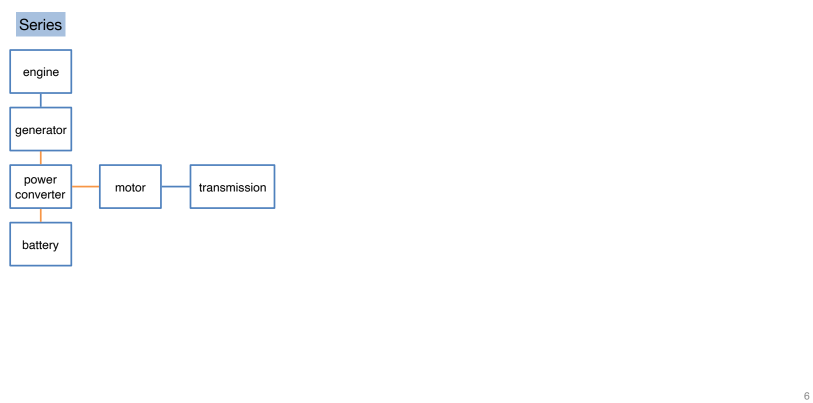
   (a) Allowing IC engines to operate closer to their optimum design conditions at the highest efficiencies. These points are typically designed to be at typically at mid-load, low-speed conditions. By using electrical motors to go from starting conditions, the hybridisation can avoid the unfavourable fuel consumption conditions of the engine map at idle low torque.
   (b) Allowing for energy storage by using regenerative braking
   (c) Allowing a different optimisation point for the engine map to be designed

   The overall effect can double the mean efficiency of vehicles.

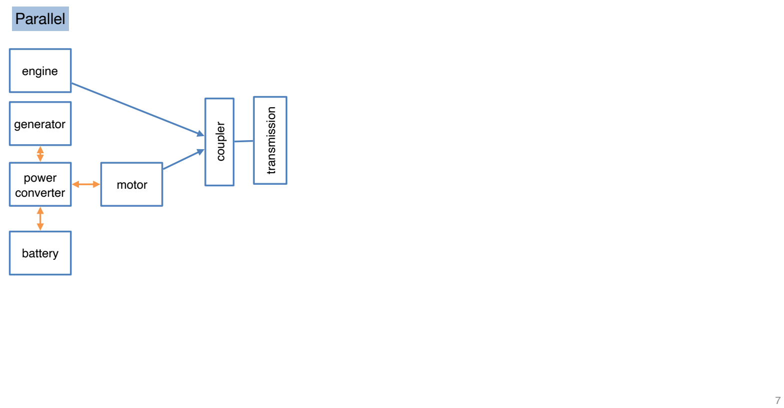
   Disadvantages are associated with the extra weight and cost of an additional motor and batteries. There are also potential issues associated with repeated cold starts, leading to pollutant emissions over cold catalysts, which must be managed. Minimum hybridisation can be used, where the starter motor is used as an alternator/generator, thus capturing some of the benefits without incurring the additional weight and costs.

9. Series/parallel topologies

(a) A series hybrid vehicle is primarily an electric vehicle with an on-board battery charger. An ICE is generally run at an optimal efficiency point to drive the generator and charge the propulsion batteries on-board the vehicle. When the state of charge (SOC) of the battery is at a predetermined minimum (around 60-70%), the ICE is turned on to charge the battery. The ICE turns off again when the battery has reached a desirable maximum SOC. There is no mechanical connection between the ICE and the wheels. The advantage with the series HEV configuration is that *the ICE is running mostly at its optimal combination of speed and torque*, thereby, having a low fuel consumption and high efficiency. However, there are two energy conversion stages during the transformation of the energy between the ICE and the wheel (ICE/generator and generator/motor). *Some energy is lost because of the two-stage power conversion process*. A series hybrid vehicle is more applicable to the start/stop city driving.



(b) A hybrid vehicle with the parallel configuration has both the ICE and the traction motor mechanically connected to the transmission. The vehicle can be driven with the ICE, or the electric motor, or both at the same time and, therefore, it is possible to choose the combination freely to feed the required amount of torque. In parallel HEVs, there are many ways to configure the use of the ICE and the traction motor. The most widely used strategy is to use the electric motor alone at low speeds, since it is more efficient than the ICE, and then let the ICE work jointly with the electric motor at higher speeds. When only the ICE is in use, the traction motor can function as a generator and charge the battery. Energy can also be also saved due to regenerative braking. The advantage with the parallel HEV configuration is that there are *fewer energy conversion stages compared to the series* HEV and, therefore, a smaller part of the energy is lost.



(c) A series-parallel system attempts to take the best of the series and parallel system. However, this comes at the cost of higher complexity, and some duplication in subsystems.