2007 IIB 4M15 Dr S Scott

sas37@eng.cam.ac.uk

1) a i) H_2 is not found on the earth and thus must be manufactured. The manufacture of H_2 requires energy, some of which is stored within the H_2 in the chemical bond (H - H)

[5%]
1 mark

ii) There are three ways in which H_2 can be produced from fossil fuels:

1) Steam reforming of methane, where steam is reacted with methane at a high temperature in the presence of a catalyst.

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

The water gas shift reaction also takes place

$$CO + H_2O \rightleftharpoons H_2 + CO_2$$

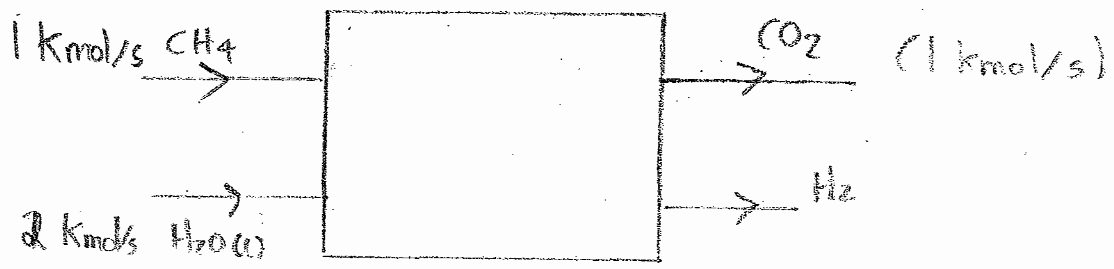
giving a syngas mixture (H_2, CO, CO_2, H_2O). This reaction is also used down stream to convert H_2O and CO to H_2 and CO_2. The CO_2 can be removed by amine scrubbing giving H_2.

2) Gasification of a solid fuel such as coal. The coal can be reacted with air, steam or CO_2 to produce syngas. The syngas can be processed as described above

3) Electrolysis of water. Electricity produced in a conventional fossil fuel plant can be used to split water electrochemically.

[35%]
7 marks

b)



Need to work out H_2 flow, H atom balance:

$$\underbrace{4 \times 1 + 2 \times 2}_{\text{INFLOW}} = \underbrace{2\dot{n}_{H_2}}_{\text{OUTFLOW}}$$

$$\dot{n}_{H_2} = 4 \text{ kmol/s}$$

To work out the energy input required we do an enthalpy balance

$$0 = \overset{\text{ENERGY INPUT}}{\boxed{Q+W}} + \underset{\text{STREAMS IN}}{\sum H_i} - \underset{\text{streams out}}{\sum H_i}$$

Enthalpies are provided with respect to a consistent standard state across species.

$$\text{Energy input} = 1\,\underline{h}_{CO_2} + 4\,\underline{h}_{H_2} - 1 \times \underline{h}_{CH_4} - 2\,\underline{h}_{H_2O}$$

$$= -393510 + 4 \times (0) - (-74600) - 2(-285830)$$

$$= 252750 \text{ kJ/s}$$

$$= \underline{252.75} \text{ MJ/s}$$

[20%]

4 marks

ii) The availability of a stream is $H - T_0 S$.
Since the streams are pure this is $\dot{n}(\underline{h} - T_0 \underline{s})$.

Stream	$\underline{h}$	$\underline{s}$	$\underline{h} - T_0 \underline{s}$
CH_4	-74600	186	-130055.9
H_2O	-285830	70	-306700.5
CO_2	-393510	214	-457314.1
H_2	0	131	-39057.7

So change in availability is

$$\Delta B = \Sigma B_{out} - \Sigma B_{in}$$

$$= -39057.7 \times 4 - 457314.1 \times 1 + 130055.9 + 2 \times 306700.5$$

$$= 129912 \text{ kJ/s}$$

$$\equiv 129.912 \text{ MJ / kmol methane}$$ [15%]

3 marks

iii) The work you could get out by diluting CO_2 down to the atmospheric concentration is given by the absolute exergy of the CO_2

$$\text{Exergy} = B_{CO_2} - B_{CO_2\,env}$$

$$= \left[\cancel{\underline{h}_{CO_2}} - T_0(\cancel{\underline{s}} + \bar{R}\ln(1))\right] - \left[\cancel{\underline{h}_{CO_2}} - T_0\left(\cancel{\underline{s}} + \bar{R}\ln\left(\frac{0.04}{100}\right)\right)\right]$$

$$= -T_0 \bar{R} \ln\left(\frac{0.04}{100}\right)$$

$$= +19394 \text{ kJ / kmol}$$

$$= +19.4 \text{ MJ / kmol}$$

[10%]

2

iv) Given the exergy flow of methane, we already know the exergy of the water (Zero because of the definition of the environment)

∴ Exergy H_2

molar exergy = $\underline{e}_i$

$$= \Delta B + \underline{e}_{CH_4} + 2\underline{e}_{H_2O} - \underline{e}_{CO_2}$$

From (ii)

$$= 129.912 + 829.8 + 0 - 19.4$$

$$= \mathbf{940.3} \text{ MJ/s}$$ (N.B. stream flow rate 4 kmol/s)

$$\therefore \frac{\text{Exergy } H_2}{\text{exergy } CH_4} = \frac{940.3}{829.8} = \underline{1.13}$$

There is more exergy in the H_2 than has been added in the methane. However we have not taken into account energy must also be supplied to this process (ie part (i)). For a steam reforming plant this energy will be mainly heat, supplied to the reformer. This high temperature heat adds exergy to the system so that the methane feed is not the only exergy input. Thus, providing the exergy input from the heat supplied to this plant is greater than the increase in availability for the process streams, the second law is satisfied and the process is feasible.

[5%]

2 a) Lifecycle analysis considers the enviromental impact of a good or service from raw material extraction, through to use and final disposal (ie cradle to grave). The product system consists of all the stages which contribute to the product. The product system should be defined so that the system boundary (effectively a large control volume) around the product system only interacts with the environment via elementary streams. Elementary streams consist of raw materials which have yet to be transformed by human means (inputs) or streams which are discarded to the environment without further processing.

[20%]

b) Embodied energy = Energy from non-renewable sources used to manufacture a substance or good

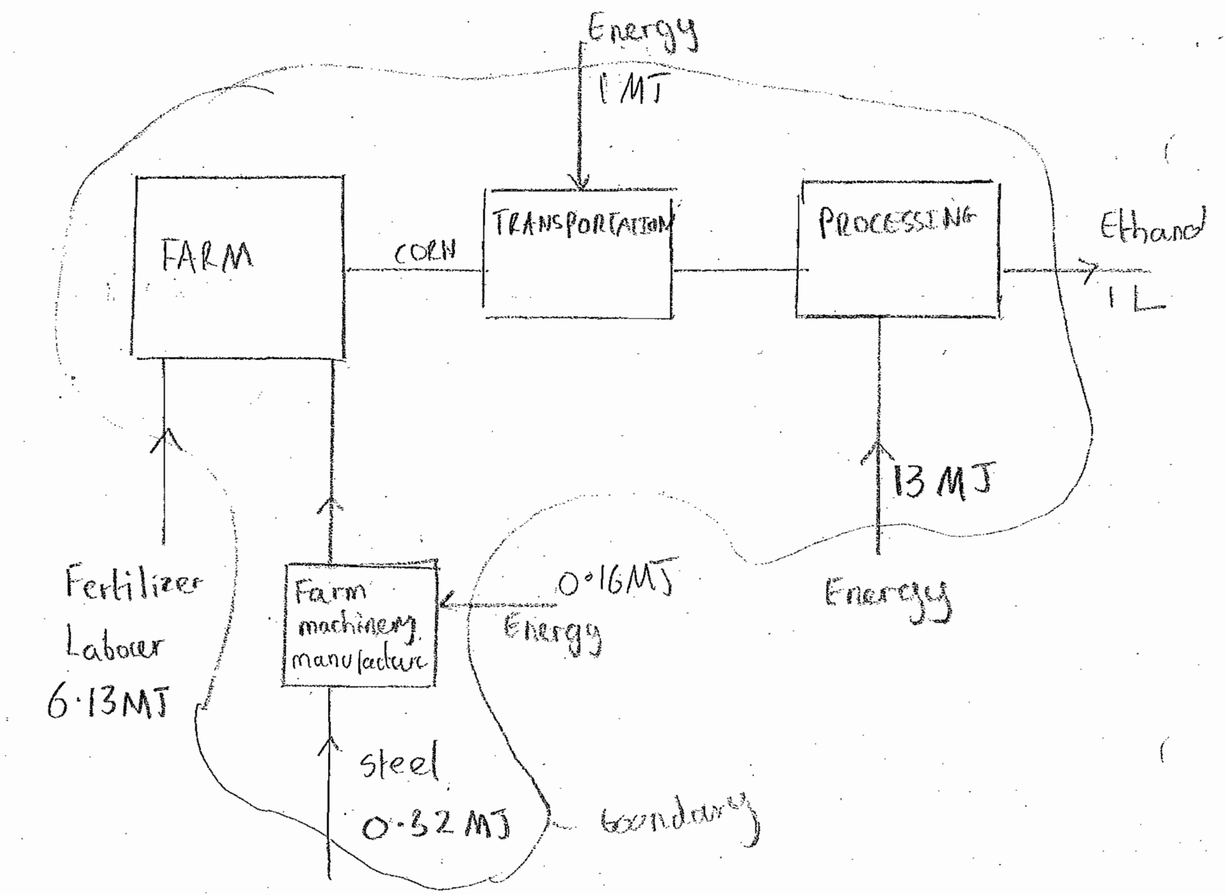
\+

intrinsic energy of any <u>non-renewable</u> feed stocks. (some of the intrinsic energy can be recovered by combustion)

CO_2 footprint = Total CO_2 emmitted in order to produce a defined quantity of substance or good.

[15%]

ii)



The embodied and actual energy flows are shown above.

1L of ethanol requires $3.\dot{3}$ kg of corn, which is grown on 3.3×10^{-4} hectares of land.

The embodied energy of fertilizer and labour is

$$\frac{18.4}{10{,}000} \frac{\text{GJ}}{\text{hectare}} = 1.84 \times 10^{-3} \text{ GJ / kg of corn}$$

$$= 1.84 \text{ MJ / kg}$$

So we need 1.84×3.3 MJ for 1 L of ethanol

Using farm machinery with life time of 15 years, means that on average we are using $\frac{600}{15}$ kg of new machinery each year.

Each kg of corn produced requires an input of

$$\frac{600}{15} \times \frac{1}{10000} \text{ kg of steel}$$

The embodied energy of steel is 24 MJ / kg

So the energy input is

$$24 \times \frac{600}{15} \times \frac{1}{10{,}000} = 0.096 \text{ MJ/kg of corn}$$

So per L of ethanol the embodied energy of farm equipment is 0.32 MJ/L. To manufacture the equipment, we need 50% of this, i.e 0.16MJ

Transportation requires 0.3 MJ/kg of corn $\equiv$ 1 MJ/L of ethan
Processing requires 3.9 MJ/kg of corn $=$ 13 MJ/L of ethan

So the total energy input is 20.6 MJ per L of ethanol produced

[35%]

ii) The net energy benefit for the ethanol is

$$\frac{21.3}{20.6} = \underline{\underline{1.03}}$$

Very poor. You might question whether it is worth producing bio ethanol this way [5%]

iii) We cannot calculate the CO_2 foot print because we dont know the form of the energy used as the energy inputs. e.g. 1 MJ of deisel has a different CO_2 foot-print to 1 MJ of electricity produced from a coal fired power station. [5%]

d) i) Amount of petrol used running on 100% petrol is

$$\frac{10{,}000}{15} = 666 \text{ L of petrol} \equiv 21.07 \text{ GJ}$$

Running on 15% bio ethanol

we would need the same energy input. Calculate
Fuel used :

$$21067 = 31.6 \; 0.85F + 21.3 \times 0.15F$$

$$= \underline{700.9\ L}.$$

ie 105 L of ethanol
595 L of petrol

The amount of fossil fuel energy used is
$595 \times 31.6 + 105 \times 20.6 = 20965$ GJ

so we have saved <u>102</u> MJ per year.
A saving of <u>0.48</u> %

The company would be better off sticking with petrol and using more efficient cars or car-sharing.

[20%]

3. (A model answer)

We live on one planet which contains finite resources. These resources are provided by natural processes in the environment. The environment is also a service provider; the earth is a closed system and the products of our activities are discarded into the environment, which has the capacity to recycle or render harmless our wastes. To be sustainable we must use resources in such a way that the ability of the environment to regenerate the resources is not compromised. For pollutants this means releasing waste only at the rate at which the environment can render it harmless.

Any definition of sustainability will also recognise that a sustainable world will have to be a fair and equitable world. From the point of view of "sustainable energy", given that most of the world uses only a fraction of energy of the developed world, there is a potential conflict between reducing energy consumption, and allowing the rest of the world to enjoy the standard of living we often take for granted. If anything, this will tend to drive energy consumption in future years.

Prior to the industrial revolution, the population and consumption were stable and at a relatively low level (by today's standards). Technology has improved our standard of living, but has removed some of the natural feedbacks which have kept consumption under control. Population and consumption have the capacity to grow exponentially, provided enough resources exist. However, the resource base is finite and does not grow. Thus, growth has meant that we (as a species) are now in a position where the natural cycles which we have relied on to provide environmental goods and services can be overwhelmed.

In this context, sustainable energy would imply that we can only consume energy at a rate which can be supplied in perpetuity by the environment. Fossil fuels are clearly not being used sustainably, since the resource base cannot regenerate at the rate which they are used. Despite this, our entire economy is based on fossil fuels. Fossil fuels will eventually run out, but it is Global warming caused by the CO_2 released from when fossil fuels are burned that is more likely to limit their use. The atmosphere is a complex system, and one important subsystem which mankind has perturbed is the carbon cycle. Prior to the industrial revolution, the carbon cycle maintained a relatively constant concentration of CO_2 in the atmosphere, where respiration was balanced by the CO_2 taken in by photosynthesis. Fossil fuels have released a large amount of carbon into the atmosphere. Natural feedback mechanisms, such as absorption of CO_2 into the oceans, have limited this to some extent, but the quantity of fossil fuel use has meant CO_2 concentrations have risen. Thus, sustainable energy means that in addition to only using energy at rate which the environment can supply it sustainably, we must also ensure that other environmental services are not degraded. One natural limit, perhaps, might be that we should not use energy at a rate greater than the rate at which biomass can photosynthesize and store carbon. Biomass, after all, provided mankind with its first sustainable fuel. Estimates of our energy use show that we our energy use is about ¼ the energy which is stored by biomass on land each year. In this sense, it is the scale of our activities which are to blame.

To behave unsustainably defies reason, and yet as a species we continue to act in a way which depletes the stock of natural capital on earth. Presently, the world economy is largely based on the free market, and there are those who look to the free market to provide a solution to our continued use of energy. It could be argued that the free market will naturally correct for any unsustainable behaviour. For example, as fuels become scarce, the price rises. The market then acts on this price signal, and invests in alternatives, either other non-renewable or renewable sources. It is here that problems are encountered. The price of a natural resource often does not reflect the size of the resource base left. A good example here is the price of oil, which bears no relation (at the moment) to how much oil is left in the world. Rather the price is determined by how quickly the oil can be brought to market. It is true that when oil begins to run out, the price will rise, but by then there may be little time left for the market to act. In many ways, the market treats the price of the environment as zero.

Aside from the problems of free market and political will, which is usually lacking when sustainability has to compete with short term economic interests, there is a problem of understanding. It has taken nearly 200 years for our society to recognise the problem posed by global warming. Mostly this has been due to lack of knowledge about how the environment works and our inability to measure changes in the environment. The temperature changes which have been caused by global warming to date are small (but still significant in terms of environmental response). The environment is complex and there are always problems in linking actions to environmental consequences. Until recently, there was valid scientific debate about whether global warming could in fact be linked to fossil fuels, or was just part of normal cyclic changes in the environment. Without a direct link between an action (burning fossil fuels) and a direct (and obvious) impact on our lives, the market has no way detect and respond to environmental problems.

New technology is often seen as the solution to all problems and, in the past, limits to our growth have been overcome by some new trick. New technology is usually developed in response to the market, and often is not aimed at solving the problem, simply delaying it or exploiting previously marginal resources (e.g. the interest in unconventional oil shale now oil is expensive). Some technologies do offer the real prospect of sustainable energy as they rely on a renewable resource base. However even these have limits, due mainly to our large demand for energy. Our economy has grown to such an extent that there would not be enough land in the UK to grow enough biomass to feed our power stations. Using biomass on such a scale would have a massive impact on other natural cycles, and compete with food production. One of the most significant resource bases is solar, but here the challenge is producing the solar panels cheaply. A large scale switch to renewable power would also mean changing from reliable and abundant sources of power, to more intermittent power sources. What technology cannot overcome is the fact that the resource base is finite. Continued growth in energy consumption means that no matter how clever the technology, a limit will be reached. Other technologies, such as fusion, offer the possibility of an almost infinite resource base. However, this would be a step change in technology far greater than brought about by e.g. the industrial revolution. Relying on some, as yet, unspecified future technology is inadvisable.

In conclusion, , it does not appear as if the free market, left to itself would provide a solution to sustainable energy. Even an ideal market would struggle to respond sufficiently to prevent environmental degradation. The signals the market receives in the form of prices do not reflect the actual resource bases and there are delays in the feedback response. The free market can be made to provide for a future where we use energy sustainably only if the cost of energy reflects the true cost to society and the environment as a whole. This requires input from e.g. governments to change the current economic model, to one which recognises the value of the environment. Sustainable energy consumption can only be realised by reducing our appetite for energy, coupled to the development of new technologies which move us away from carbon based fuels.

Question 3. 20 Marks total.

A structured essay (1 mark), with balanced well argued points and a good conclusion (4 marks).

Bullet points which an answer should contain (15 Marks, 1 mark per point made Max 15):

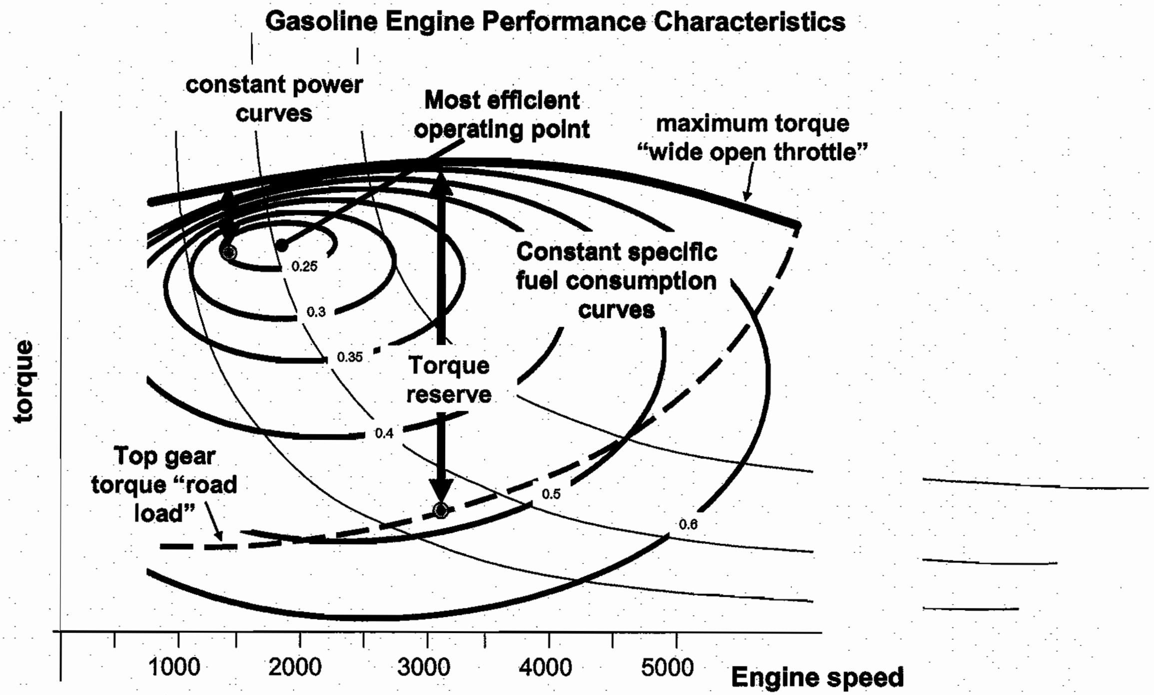
- We live on one planet which contains finite resources. These resources are provided by natural processes in the environment.
- The environment is also a service provider; the earth is a closed system and the products of our activities are discarded into the environment, which has the capacity to recycle or render harmless our wastes.
- Sustainability means that we must use resources in such a way that the ability of the environment to regenerate the resources is not compromised. For energy use to be sustainable we can only consume energy at a rate which can be supplied in perpetuity by the environment. Fossil fuels are clearly not being used sustainably
- For pollutants, sustainability means releasing waste only at the rate at which the environment can render it harmless. Global warming as an example of a natural cycle which is being dangerously perturbed (Carbon Cycle).
- Fossil fuels will eventually run out, but it is Global warming caused by the CO_2 released from when fossil fuels are burned that is more likely to limit their use.
- Sustainability should also consider fairness and economics
- Most of the world uses only a fraction of energy of the developed world, there is a potential conflict between reducing energy consumption, and allowing the rest of the world to enjoy the standard of living we enjoy.
- Mankind's growth has in the past been constrained by natural feed-backs or barriers (e.g. Prior to the industrial revolution, the population and consumption were stable and at a relatively low level (by today's standards)).
- Technology removes barriers to growth (e.g. industrial revolution and use of fossil fuel, and the subsequent growth)
- Population and consumption have the capacity to grow exponentially, provided enough resources exist. However, the resource base is finite and does not grow. Thus, growth has meant that we (as a species) are now in a position where the natural cycles which we have relied on to provide environmental goods and services can be overwhelmed.
- Some comment on the scale of the problem. E.g. Biomass provided mankind with its first sustainable fuel. Estimates of our energy use show that we our energy use is about ¼ the energy which is stored by biomass on land each year. In this sense, it is the scale of our activities which are to blame.
- To behave unsustainably defies reason, and yet as a species we continue to act in a way which depletes the stock of natural capital on earth. (or some comment about the rationality of being sustainable).
- The idea that the free market should correct for unsustainable behaviour.
- A description of the idealised free market e.g. For example, as fuels become scarce, the price rises. The market then acts on this price signal, and invests in alternatives, either other non-renewable or renewable sources.
- Why the free market might not work and the idea of the price of environmental goods and services.

- The idea that the environment is free.
- The price of a natural resource often does not reflect the size of the resource base left (usually just how easily it is exploited)
- The exponential growth in consumption means that by the time a shortage occurs and prices rise, it may be too late to correct.
- The free market can be made to provide for a future where we use energy sustainably only if the cost of energy reflects the true cost to society and the environment as a whole. This requires input from e.g. governments
- Other delays in the free market system make some sort of overshoot more likely. E.g. Political will, competition with short term economic interests, the time it takes for society to recognise the problem.
- The environment is complex and there are always problems in linking actions to environmental consequences. Until recently, there was valid scientific debate about whether global warming could in fact be linked to fossil fuels, or was just part of normal cyclic changes in the environment. Without a direct link between an action (burning fossil fuels) and a direct (and obvious) impact on our lives, the market has no way detect and respond to environmental problems.
- New technology is usually developed in response to the market, and often is not aimed at solving the problem, simply delaying it or exploiting previously marginal resources (e.g. the interest in unconventional oil shale now oil is expensive).
- Some technologies do offer the real prospect of sustainable energy as they rely on a renewable resource base. However even these have limits, due mainly to our large demand for energy.
- What technology cannot overcome is the fact that the resource base is finite. Continued growth in energy consumption means that no matter how clever the technology, a limit will be reached.
- Inertia in the free market and the difficulty in a large scale switch to renewable power.
- Technologies which might have such a large resource base technology could offer a solution E.g. fusion. (but relying on some as yet unproven technology is not a good idea).

Marks were deducted from the 15 available above for each of the following points not addressed in some way.

- Failure to mention global warming (-1 mark)
- Failure to note that sustainability means not using resources faster than they can regenerate (- 1 mark)
- Failure to note that the environment is also a sink of pollutants and sustainability means that pollutants must not be released faster than environment can work (-1 mark)
- Failure to describe how a market works (-1 mark)
- Failure to note that market sees price of environment as zero and why this is so (-1 mark)
- Failure to note that even technology has its limits, i.e. the finite resource base (-1 mark)
- Failure to note that the scale of our activities are causing problems, which in many cases new technology does not address (-1 mark)

Question 4 (20 marks)



[4 marks for figure]

(a) The maximum torque is at the condition when the maximum quantity of air (and thus oxygen) is trapped in the cylinder. Clearly this is the case, as there is no restriction on how much fuel can be added. Note that the maximum torque characteristic is synonymous with wide open throttle.

The maximum amount of air is determined by a) the density of the air in the cylinder, and b) how much of the residual (i.e. oxygen depleted) gas from the previous cycle remains.

Two opposing trends affect these two quantities.

1) At low engine speed, pressure losses through the intake system, especially the valves, are smallest, so the pressure and hence density of the inlet gases will be high. (Density also of course involves the temperature of the inlet gases, but this is not strongly affected by the engine speed.) Also pressure down the exhaust system will be low, and hence the "back pressure" will be low, and thus the residual gases in the cylinder will be of low density. Unfortunately, the residual gas left in the cylinder clearance volume (typically 10% of the swept volume), limits the air quantity that will be induced.

But

2) At high engine speed, the exhaust gases have high momentum, and as the inlet and exhaust valves are both open at around non-firing TDC, the exhaust gas motion causes a suction, despite the piston being effectively stationary, and the residual gases are partly sucked out. Unfortunately, due to the very high engine speeds, and hence flow velocities and hence pressure drops, especially across the valves, are increased, and so the density of the incoming air is reduced, but the density of the residual gases are increased.

The effect of these effects is that the maximum torque occurs in practical engines at intermediate engine speeds.

[4 marks]

(b) The top gear road load is the engine torque required to propel the vehicle at constant speed across the engine rpm range. At low engine speeds this is dominated by the rolling resistance (tyres etc), but as speed increase, the air drag soon dominates, and the since the drag force is given by $C_d = Drag / \left(\frac{1}{2} \rho . velocity^2 A_F \right)$, (where the drag coefficient, density and frontal area are assumed constant), then $Drag \propto velocity^2$. Now in a particular gear, $velocity \propto rpm$, and since the engine power requirement is given by $Power \approx Drag.velocity \propto Torque.rpm$ (where the drag is assumed to be entirely wind drag), then we see that the $Torque \propto rpm^2$. This is the trend that is "added" to the rolling resistance.

The maximum power requirement will be at the vehicle's maximum speed, and hence the torque requirement at maximum rpm is close to the maximum torque curve at that rpm. If the vehicle's gearing is such that the maximum rpm is reached at a torque below the maximum, then maximum speed is unobtainable due to a "rev limit"; If vice versa, then maximum speed is unobtainable due to a torque limit. Either way, the maximum power output of the engine is unusable, except as a means of obtaining maximum acceleration in lower gears.

[4 marks]

(c)Specific fuel consumption (sfc), that is the fuel usage per unit work output, is affected in two main ways:-

1) The engine power being used to overcome friction increase with engine speed, as the friction torque does not decrease with rpm (in fact it increases). Thus the sfc to increase with engine rpm (more strictly we should say with increasing rpm along constant power curves – see below).

2) When the engine load is varied at constant rpm, this has to be achieved by throttling the air intake. In this way the mass of charge (fuel + air) is reduced, while maintaining a constant (near stoichiometric) air/fuel ratio, necessary to ensure reliable combustion. Throttling represents a lost opportunity to do work, so necessarily increases sfc.

Other effects are a) the tendency to richen up the mixture to obtain maximum torque, which has the effect of increasing sfc near the maximum torque line, and b) the effect of large quantities of residual gas at throttled +low rpm conditions (where back flow from the exhaust into the inlet manifold occurs) on combustion duration, which leads to increased sfc at the lowest rpm's

The considerations above lead to the contours show. The actual values vary form engine to engine – the figures shown are typical.

[

(d) As we saw in (b) $Power \propto Torque.rpm$, so constant power curves are rectangular hyperbolae. Clearly driving at (say) 60mph, which for typical vehicles will correspond to roughly half of maximum rpm, and the figure suggests that the sfc will be much less than the minimum obtainable, which would be a significantly lower rpm, but much higher proportion of maximum torque. On he other hand at this condition, there would be very limited “torque reserve” for acceleration/hill climbing etc.

Two simple ways of obtaining better sfc might be:-

1) Fit vehicles with variable gear ratio transmissions (sometimes called continuously variable transmissions, CVT’s), where the gear ratio causes the engine to run minimally throttled – i.e. a much higher gear ratio than normally obtainable – but which allows the gear ratio to change (“down”) when extra power is required.
2) Fit vehicles with energy storage devices, so that when acceleration is required, it is delivered from the energy storage device (e.g. battery, hydraulic accumulator, flywheel). The energy storage device is then recharged during braking, or normal running. The implication is that the engine is “downsized”, as the power required for high acceleration is not coming from the engine directly. In other words, the engine is operated nearer to the maximum torque, reduced throttling condition than the larger engine. Smaller engines have inherently better fuel economy, due to less frictional losses. Nevertheless, the maximum engine power is necessarily reduced, as is maximum continuous speed. I side benefit of some of the practical embodiments of these concepts, so called hybrid vehicles, is that the engine may be stopped altogether when the vehicle is stationary or moving slowly, which has a further beneficial effect on fuel economy.

[4 marks]