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The 95th Thomas Hawksley Lecture

ENERGY FOR TRANSPORT

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Energy for Transport

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Transport is an essential element of our society. It determines where we live, where we work and how we enjoy our leisure time. It enables the exchange of goods which are essential to our economy. It has resulted in a global economy.

Growth in demand is linked to growth in the economy. As we get richer, we travel further and faster. And travelling further and faster uses more energy and produces more emissions.

Transport is now one of the largest components of our energy use and this proportion is growing. Because of the dominance of the car, transport fuel use is dominated by burning hydrocarbons with resultant carbon dioxide production. It is largely because of growing transport demand that we will certainly fail to meet our emissions targets. Indeed this problem is becoming ever more intractable because of the present lack of coherent Government energy, transport and environment policy.

This lecture will outline the engineering challenge generated by this problem and discuss some possible solutions. All modes of land, sea and air transport will be examined, together with alternative fuels, mitigation prospects and the role of technology in reducing transport demand.

Professor Roderick A Smith is currently the Royal Academy of Engineering Research Professor in Advanced Railway Engineering and Chairman of the Future Rail Research Centre at Imperial College London. He has previously been Head of Mechanical Engineering at the University of Sheffield and Imperial College. He is a Trustee of the Institution of Mechanical Engineers and of the National Museum of Science and Industry.

"And what is a man without energy? Nothing – nothing at all." **Mark Twain**

"Energy is an eternal delight, and he who desires, but acts not, breeds pestilence." **William Blake**

"Power when wielded by abnormal energy is the most serious of facts." **Henry B Adams**

1. I am delighted to begin in the tradition of speakers at eponymous lectures by acknowledging my debt to the founder of this lecture, Charles Hawksley, and to his father, Thomas Hawksley, whose career it celebrates; and to whom we all have a great debt of thanks for the water supplies that he engineered for most of the large cities of this country, most of which are still vital cornerstones to our present arrangements. He is an outstanding example of the contribution of engineering to the health and well being of society. Some key details are given in Appendix 1.

2. This Institution recently adopted four key themes: Energy, Transport, Environment, and Education. This lecture and paper serves to integrate all of them. The first two form the title, the third, the Environment, is adversely affected by the use of Energy in Transport and I hope to promote, in a modest way, the fourth, Education, by drawing to the attention of the audience and readers some of the vital and far-reaching issues arising from our use of Energy in Transport. This aim is assisted by a collection of further reading outlined in Appendix 2.

3. It is also a custom of lecturers to acknowledge that they have built on the foundations laid by their predecessors. I am more than happy to do this. Last year's lecture [1] delivered by Sir John Houghton was an authoritative overview of the evidence which leads us to believe that climate change due to human activities is now a scientifically established fact, that the consequences are extremely serious for mankind, and that "greenhouse gases" of which carbon dioxide (CO_2) is a major component have accumulated in the atmosphere and, by absorbing infra-red radiation from the earth's surface, are making the earth warmer than it otherwise would be. I will not cover the ground so expertly described by Sir John, but must mention two more recent key reports. The first is the 4th IPCC report [2], produced by around 600 authors from 40 countries and reviewed by 620 experts and governments, that stated *"warming of the climate system is unequivocal"* and *"most of the observed increase in globally averaged temperatures since the mid-20th century is very likely (means assessed likelihood >90%) due to the observed increase in anthropogenic greenhouse gas concentration."* It went on to examine the effects of different rises in mean earth temperature over the coming century whilst stating that the most likely rate of rise will be 0.2 $^{\circ}$C per year over the coming decades.

4. Lord Rees, the President of the Royal Society, responded, *"This report makes it clear, more convincingly than ever before, that human actions are writ large on the changes we are seeing, and will see, to our climate. The IPCC strongly emphasises that substantial climate change is inevitable, and we will have to adapt to this. This should compel all of us – world leaders, businesses and individuals – towards action rather than the paralysis of fear. We need both to reduce our emissions of greenhouse gases and to prepare for the impacts of climate change. Those who would claim otherwise can no longer use science as a basis for their arguments."* [3]

5. The second report is the Stern Report [4], which extensively examined the economic consequences of climate change. The key message included: *"The effects of our actions now on future changes in the climate have long lead times. What we do now can have only a limited effect on the climate over the next 40 or 50 years. On the other hand what we do in the next 10 or 20 years can have a profound effect on the climate in the second half of this century and in the next.*

6. *No-one can predict the consequences of climate change with complete certainty; but we now know enough to understand the risks. Mitigation – taking strong action to reduce emissions – must be viewed as an investment, a cost incurred now and in the coming few decades to avoid the risks of very severe consequences in the future."*

7. It was produced, not by a scientist, but by the Head of the UK Government Economic Service, and a former Chief Economist of the World Bank. Reaction was generally favourable and recognised the need for action: *"The overwhelming message of... [the] Stern Review on the economics of climate change is that it is now time to move on from arguing about statistics to taking drastic action at an international level… Even if Stern is only half right then… the consequence of doing nothing is still so dreadful that it ought not to be contemplated."* (The Guardian); *"The Stern Review shows us, with utmost clarity, while allowing fully for all the uncertainties, what global warming is going to mean; and what can and should be done to reduce it. It provides numbers for the economic impact, and for the necessary economic policies. It deserves the widest circulation. I wish it the greatest possible impact. Governments have a clear and immediate duty to accept the challenge it represents."* James Mirrlees, recipient of the Nobel Prize for Economics in 1996.

8. Before turning to transport specifically, it is worth reminding ourselves of the key science of climate change. Our planet earth is surrounded by a thin atmosphere. If the earth was the size of a football, then the atmosphere would be a wrapping as thin as a sheet of brown paper. The two major constituent gases are nitrogen (78%) and oxygen (21%). The others, including carbon dioxide (CO_2), nitrous oxide and methane, make up only a fraction, but a vital fraction, of the remaining 1%.

9. As long ago as the beginning of the nineteenth century [5], Fourier posed the question: what determines the temperature of a planet like the earth? Why does the energy we receive from the sun not continue to warm the earth? He supposed, correctly, that heat is carried away by infrared radiation, but when he calculated the resulting temperature, it was well below freezing (about -18 $^{\circ}$C). Fourier reasoned that somehow the atmosphere acts like a blanket to prevent the loss of some of this radiation. Later, in 1859, John Tyndall discovered that although the main constituents of the atmosphere, nitrogen and oxygen, were transparent to infrared, carbon dioxide was opaque, what we now term a *"greenhouse gas"*, like nitrous oxide and methane; so emerged the great importance of CO_2 although it only forms a few parts in ten thousand of the atmosphere. It was left to Arrhenius in 1896 to laboriously calculate the likely effect of CO_2 concentration changes: his estimate was that doubling the CO_2 in the atmosphere would raise the earth's temperature by about 5 or 6 $^{\circ}$C and that this would take about two thousand years. It is interesting to note the combined efforts distributed over a century of a Frenchman, an Englishman and a Swede laid the scientific foundations of climate change science well before joint European projects were dreamed of.

10. Before the industrial revolution, the earth's atmosphere contained about 280 parts per million (ppm) of CO_2. When it was measured in the late 1950s its concentration had risen to 315 and now it is at 380 ppm. We are clearly increasing at a rate much faster than that anticipated by Arrhenius. Why? Since the industrial revolution the population of the world has increased dramatically: from just over 1 billion in 1860, to 2 in 1940, doubling to 4 by 1975, and now reaching 6.6 billion and is expected to reach 9 billion by 2050. And we are living longer. The statement that there are probably more people on earth today than have died throughout the course of history can be understood by "*exponential growth*", explained in Appendix 3. In the process of our economic development we have burned lots of fossil fuel, initially coal and, latterly, oil. Combining oxygen with carbon (for good quality coal is essentially carbon), produces heat (of course) and CO_2. Simple theory of atomic weights leads to 12 mass units of carbon producing 44 (12+2x16) units of CO_2. That is each kg of coal burned produces 3.7 kg of CO_2. Now hydrocarbon fuel, of which petroleum is pre-eminent, is essentially linked chains of carbon atoms with hydrogen atoms occupying two bonds per carbon atom. Since hydrogen is the lightest element, relative atomic mass 1, the above calculation needs little modification. In round figures burning 1 kg of petrol or kerosene produces 3.14 kg CO_2.

What is transport?

11. Transport is the movement of people and goods from one place to another. It is the engine of our economic activity. The volume of transport, measured in passenger km (pass km) or tonne km has increased hugely and continues to increase linked to economic growth. If we think of the range of movement of our great grandparents, limited to within about 15 km of their homes and our world roving activities now, the point is well made. Think of the limited range of food and manufactured goods in the shops 50 years ago compared with the wide and international choice available now, and the explosion of transport is evident. The travel from and back to home available in a day is an important concept (the word journey is linked to the French for a day, *un jour*). Figure 1 makes the link between distance and wealth.

12. Figure 2 examines our daily travel budget. The conclusions are simple: as we get wealthier we travel further and because we tend to limit our travel time budget to 1.5 hours per day we travel by faster modes. But faster modes consume more energy.

13. In 1881 Sir William Thomson (later Lord Kelvin) [7] attributed about all the sources of motive power or work on earth to the heat of the sun, directly or indirectly. At about the same time he was introducing the formal concepts of thermodynamics which govern the interchange of energy and work. The relationship between speed of travel and energy use has been extensively studied. More than 50 years ago, Gabrielli and von Kármán [8] examined trends and produced a famous plot which we have recently updated [9], see Figure 3.

14. For any vehicle type, motion is achieved through the action of a tractive force, which is the ratio of installed power (P) divided by maximum velocity (V). If this ratio is further divided by the weight (W) then the non-dimensional specific tractive force (ε) is obtained ($\varepsilon = P/WV$).

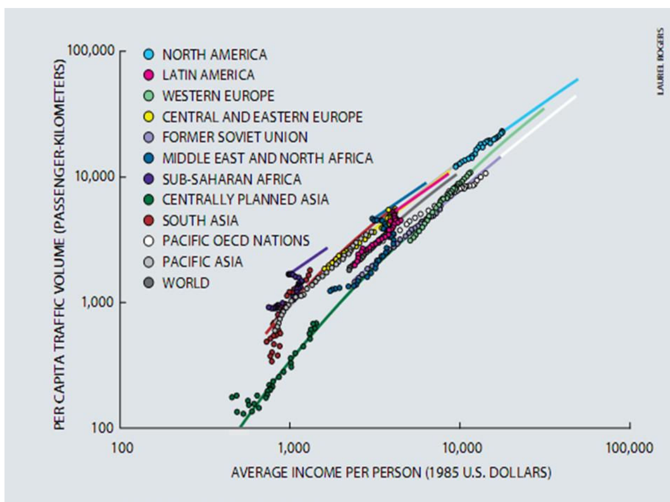

Figure 1: The link between income and propensity to travel [6]

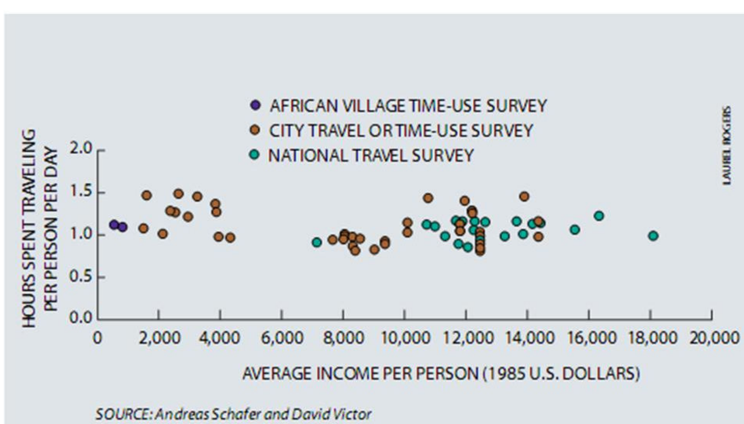

Figure 2: Travel time per day and income [6]

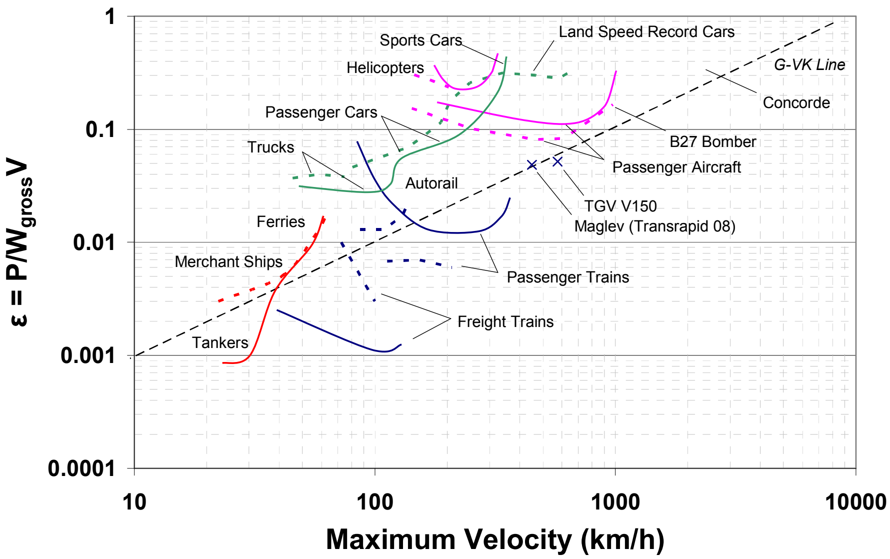

Figure 3: Specific tractive force (resistance) against speed, the Gabrielli / von Kármán plot

World transport by major modes			
Passengers (bn pass km)		Freight (bn tonne km)	
Car	16,000	Sea	40,000
Bus/coach	7,000	Road	7,000
Air	2,800	Rail	6,500
Rail	1,900	Oil pipeline	2,000
Urban rail	250	Inland navigation	1,500

Source: various

Table 1: Major modes of world transport

15. This can also be interpreted as the specific resistance, akin to a coefficient of friction: the lower the value, the more 'efficient' the transport mode. Gabrielli and von Kármán assembled a collection of data for installed power, maximum velocity and gross weight for a wide variety of transport modes. This is the data shown in Figure 3, in which ε is plotted as a function of speed. Broadly speaking, sea, land and air transport are divided into bands of ε from 0.001 to 0.01, between 0.01 and 0.1, and greater than 0.1 respectively. The shorter lines shown are the lower bounds for a collection of data from transport of a particular similar type. The bulk of the data lies above a line of gradient 1, identified as the Gabrielli – von Kármán (G-VK) line, which represents an empirical relationship between the minimum specific power and the vehicle's maximum speed, $P_{min} = AV^2$ where A is a factor of proportionality with dimensions of reciprocal speed. The gradient line was drawn by the original authors with the suggestion it was the best that could be achieved, with the exception of trains which benefit from the convoy system to which length can be added without proportionate increase in resistance. This remained true when we re-examined the situation 50 years later, but with the addition of very large ships beating the trend. Indeed the original line has proved to be very resistant to change through technological advance. It is a reminder that the laws of physics cannot be violated.

16. The major modes we use to transport people and goods are shown in Table 1.

17. The dominance of the car for passenger transport is clear, as is the major role of shipping to transport

goods around the world. Shipping, largely out of sight and out of our consciousness, really is the facilitator of the world economy. We should remember there are vast regional differences. Buses and coaches are less used in developed regions of the world, urban rail share is small but many major cities of the world, including London and Tokyo, simply could not operate without major rail and subway networks. Worldwide, rail is relatively small in passenger transport, Japan being an exception where its share is approaching 30%; conversely rail freight is small in Japan, but very significant world wide. Growth rates vary too. Rail is essentially globally static in a globally expanding market; cars, aircraft and ships continue to grow strongly, whilst there is a general switch from public to private transport as economies strengthen. The dominant transport modes are largely dependent on petrol, kerosene and diesel fuels. A major part of this paper is therefore taken up by a discussion on how this situation might be changed. Basically the options are few. We might travel less, but this is very unlikely; we might switch to more efficient, generally public forms of transport, but experience shows that this too is unlikely; we can improve the energy efficiency of transport and switch to non-carbon fuels; we could travel more slowly, again hardly popular, or a "magic" technical fix may come along to solve the problem. In the developing countries the demand for more transport is very strong and new infrastructure to satisfy this demand is being built on an extensive scale. In the developed economies congestion, particularly on roads, is a major preoccupation. Increasing demand has been driven by a general reduction of travel costs, of which the rise of the budget airlines is a prime example. A truly global economy has increased the demand for freight transport. In general people want to travel more and not less.

Reducing fuel consumption

18. In all forms of transport great efforts have been made to reduce fuel consumption. The engine can be made to burn fuel more efficiently; the exterior vehicle surfaces might be streamlined to reduce resistance; the vehicle might be made lighter. These activities have an effect of nibbling away the corresponding emissions from the vehicle. Cars were a prime target for drag reduction during the oil crisis of the early 1970s, but more recently many of these gains have been reversed by a trend towards larger vehicles of the 4x4 type. Huge efforts have been made and continue to be made to improve fuel combustion. However, features on both small and large cars, once optional but now standard, are offsetting the fuel savings of more economical engines e.g. air conditioning, power steering. Aircraft engines have improved considerably; see Figure 4. In planes too some of this improvement is being eroded by the desire of passengers to travel in greater comfort. An increase in larger premium priced seats leads to a smaller number of passengers and an increase in fuel use and emissions per head.

19. Modern trains have improved somewhat: the biggest efficiency gains have been in ultra long freight trains, but high-speed passenger trains have become more aerodynamic and lighter. It is worth noting that the main motivation for lighter trains is to reduce track damage as speeds increase because the dynamic forces generated at the wheel rail interface increase with (approximately) the square of the speed and are governed by both axle loads and unsprung mass (that is the mass of wheels, axles and bogies below the main suspension). In terms of CO_2 emissions, it makes sense to electrify the railway and to increase the proportion of electrified route. Thus Switzerland has essentially carbon free traction through the use of hydropower; France is in a similar position because of its extensive nuclear power generation (French President Chirac has announced that SNCF & RATP "*should not consume a drop of oil in 20 years time*", The Times, 6 January 2006. It also allows Eurostar to claim carbon neutral journeys between London and Paris). Britain, unfortunately, has the lowest electrified route ratio of all major western European countries.

20. The question is often asked of a particular vehicle, what is its fuel consumption? The answer is not simple and cannot be represented by a single figure. As any car driver knows, the answer depends, *inter alia*, on the condition of the vehicle, the pressure in its tyres, the load it is carrying, the manner in which it is driven, the weather and the route over which it is driven together with the density of traffic in which it is used. It is clear that stop-start conditions increase fuel consumption, whilst the best figures are obtained at constant speed on smooth level roads. The engine has, of course, a speed at which fuel consumption is a minimum; higher speeds are usually accompanied by a sharply increasing fuel consumption, further exacerbated by increasing aerodynamic drag. The low speeds caused by congestion therefore lead to increasing fuel consumption as well as frustration and time wasting. The data in Figure 5 illustrate this point.

21. This study from Helms [10] was directed at the fuel saving possibilities due to weight saving in heavy trucks: note that, all other factors being equal, the fuel consumption in a given set of conditions is linearly related to the mass. The same approach was used to compare the likely energy saving for a wide range of vehicles [11], taking into account their relative use over their different usage in km travelled over their lives. Figure 6 illustrates the outcome, whilst Figure 7 extends this analysis to include the resultant energy saving recognising the different mode share of these vehicles in different parts of the world. The results of this kind of study are particularly valuable for highlighting where the greatest research effort should be concentrated. Although any fuel efficiency savings in any mode of transport are to be welcomed, on the global scale the greatest efforts will come from improvements to cars, then aircraft. The caveat remains that small improvements will be quickly swamped by increasing demand. Timescale is

important too. Virtually the whole of the world's car fleet is replaced in a ten year period.

The technological replacement windows for trains can be more like 40 years and a similar period for aircraft.

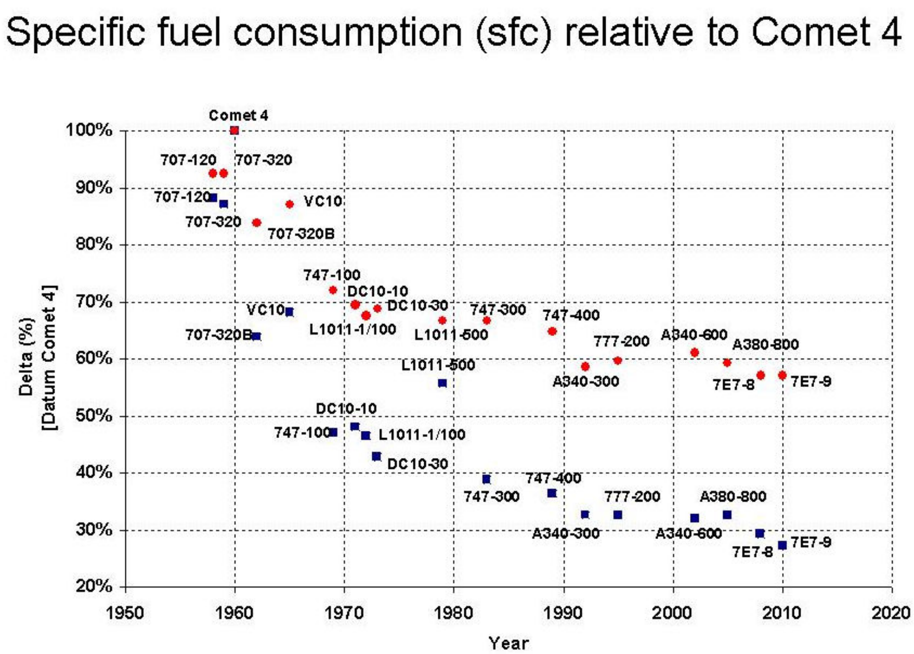

Figure 4: Improvements of specific fuel consumption in jet aircraft (sfc is kg fuel burn per hour/kg thrust)

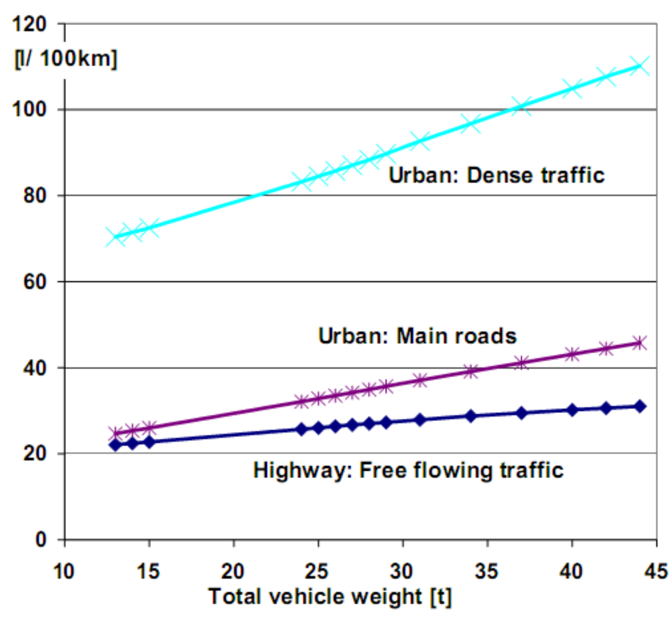

Figure 5: The effect of route and vehicle mass on fuel consumption of heavy trucks [10]

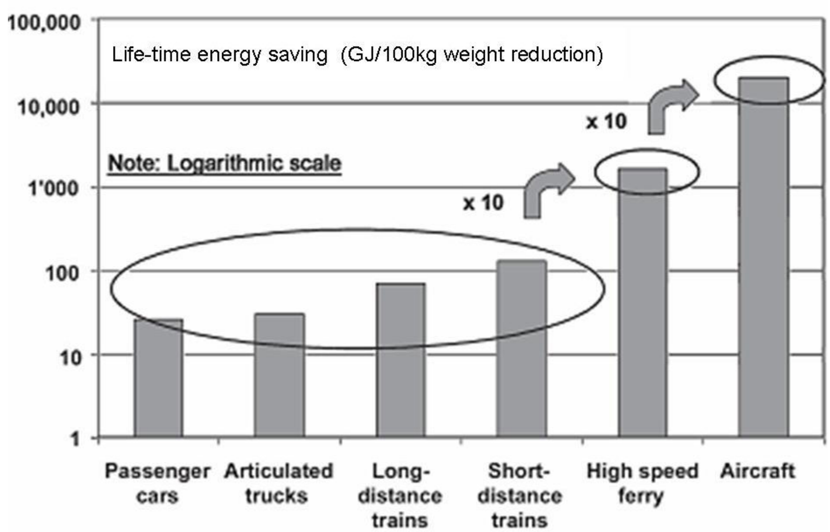

Figure 6: Vehicle life-time energy savings (PJ) resulting from a 100 kg weight reduction [11]

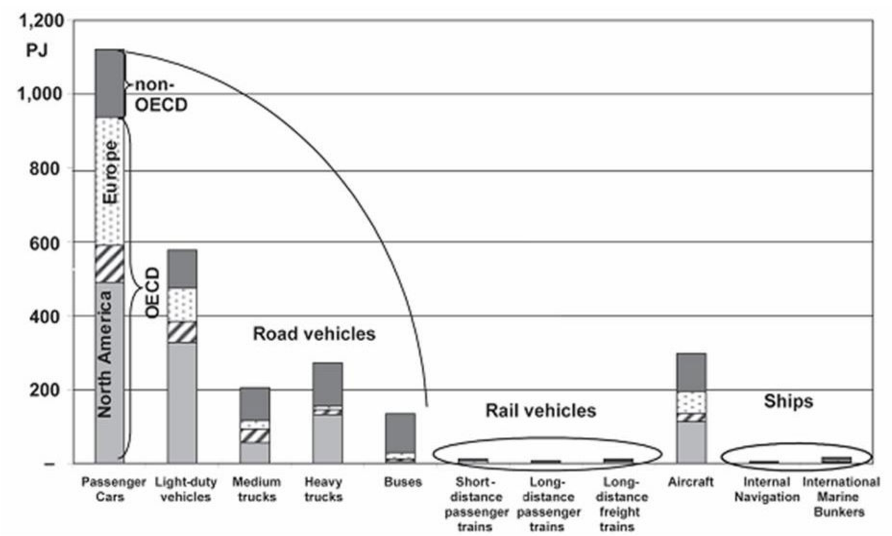

Figure 7: Total energy saving (PJ/year) resulting from 100 kg vehicle light weighting [11]

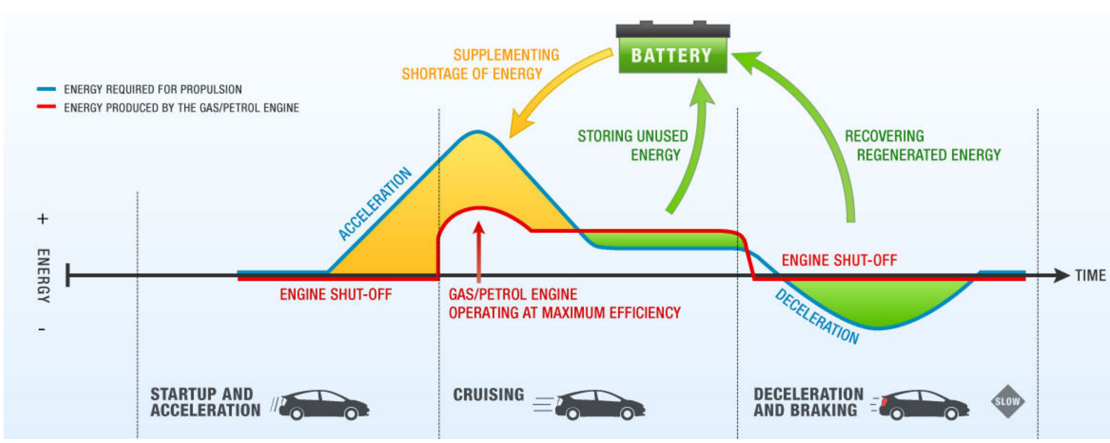

Figure 8: Illustration of the hybrid principle (Toyota Motor Corporation)

Prospects for hybrid engines

22. There is currently much interest in hybrid vehicles which use two or more distinct sources of power. For a car this usually means a battery as an on-board energy storage system, with an electric motor coupled to a conventional internal combustion engine.

23. Cars such as the Toyota Prius have proved to be practical and potentially realise fuel saving in the order of 35 to 45%. Currently they are more expensive to buy and are heavier than corresponding conventional cars. There are also some questions about life-time energy costs. When production of batteries and electric motors, together with disposal costs are considered, the advantages may not be so clear.

24. Trains too can significantly reduce fuel consumption by hybrid design. Hitachi has worked with JR East in Japan on a hybrid single coach train which has been running since 2003 and has recently modified a HST power car in the UK. This "*Hayabusa*" (Falcon) train uses a lithium ion battery pack of 48 kWh capacity. At a station, the engine can be stopped and the train can depart using battery power only. The energy management system ensures an efficient blend of diesel power during ordinary running, whilst under braking regenerated energy is fed into the battery to await the next cycle. For a system with a low electrification ratio like the UK this represents a practical alternative. Our independent calculations [12] suggest that significant energy saving of the order of 10 to 25% can be made depending on mission and route. Acceleration can be improved by battery assist and noise and emissions in stations can be reduced to nearly zero.

Prospects for replacement fuel

25. Of the several possible alternative fuels which may displace petroleum, many in practice offer only small CO_2 reductions on a life-cycle or well-to-wheel basis. Only four options can provide greater than 50% reduction in CO2 equivalent emissions per km of driving. These are: -

- Alcohol derived from cellulose biomass, using biomass as the process fuel
- Bio-diesel from oil crops
- Hydrogen produced from a low greenhouse gas (GHG) source (e.g. renewable electricity), used to power fuel cell vehicles
- Low GHG electricity itself when used with electric cars, but batteries need further improvement of their energy density storage capabilities so that the extra weight of batteries does not cancel out the benefits

26. These options are all relatively expensive and the latter two would need large investments in new types of vehicles and refuelling infrastructure. Crops for fuel require considerable water for irrigation: this may prove an important limitation. Changes in agricultural land use to grow fuel crops have already pushed up the price of food. The problems of land availability can be exposed by a simple order of magnitude calculation. UK arable land area is in the order of 64,000 km^2. Given the yield of rapeseed is about 1000 kg/hectare, then if the whole of our arable land was turned to rapeseed production, then the yield would be 6.4 million tonnes which could produce about 6.2 million tonnes of bio-diesel. Given that UK transport consumes 54 Mt of petroleum per year, this would be sufficient for only about 12% of current demand.

27. However, the tantalising prospect of a hydrogen economy is worthy of further comment.

The hydrogen economy

'"Without coal there would be no machinery, and without machinery there would be no railways, no steamers, no manufactories, nothing of that which is indispensable to modern civilisation!" "But what will they find?" asked Pencroft. "Can you guess, captain?" "Nearly my friend." "And what will they burn instead of coal?" "Water" replied Harding. "Water!" cried Pencroft, "water as fuel for steamers and engines! Water to heat water!" "Yes, but water decomposed into its primitive elements by electricity. Water will be the coal of the future." replied Harding. "I should like to see that", observed the sailor.'

(The Mysterious Island, Jules Verne, 1874)

28. The potential of hydrogen as a fuel has long been recognised. The current prospect is to use hydrogen combined with oxygen from the air in a fuel cell to produce electricity to supply electric motors for traction power. The fuel cell is not new: a prototype was constructed in 1839 by William Grove, the principle being reversed electrolysis. Since energy is converted without combustion, thus avoiding Carnot efficiency limitations, and the only by-product of the fuel cell is water, it would seem to offer a solution to many of the energy problems for cars. However, practical realisation is still some time away because of some major problems. The hydrogen must be produced without adding to our CO_2 problems and it must be stored in a practical way in order for sufficient to be carried to allow practical ranges of, say, 300 miles to be achieved; the cost of a fuel cell stack needs to be reduced to say $1/100^{th}$ of its current level; its lifetime needs to be increased by 5 times; its energy output needs to be enhanced, and a hydrogen distribution and fuelling infrastructure needs to be created. Clearly, these issues will not be resolved overnight: realistically, we should anticipate that a hydrogen economy is, at the very least, 25 years away.

29. Hydrogen can, and is, produced from fossil fuels, but at the usual cost of energy and CO_2 emissions. Long term prospects include using coal as the hydrogen source and capturing and storing (sequestrating) the resulting emissions. Possible viable carbon free

routes include using solar, hydro or nuclear power with electrolysis. If this problem is not solved and energy and emission benefits on a well-to-wheel basis cannot be demonstrated, then the rug is pulled from the prospects of hydrogen. Currently, only Iceland, using its considerable geo-thermal energy, has started to use hydrogen powered cars on a limited scale.

30. At the heart of a fuel cell, a proton-exchange membrane (PEM) acts both as an electrolyte and to separate the hydrogen and oxygen. Electrons are stripped from the hydrogen atoms by catalytic action on the membrane surface. The charged, hydrogen ions, or protons, migrate through the membrane and combine with the oxygen to form water. The membrane represents some 35% of the costs, while the platinum based catalyst represents 40%. Considerable research is on going in both these areas, in particular to increase the life of the rare metal catalyst and to enhance its activity level.

31. Unfortunately hydrogen exists as a gas with an energy density 1/3000th that of liquid petrol. It will take about 6 kg to propel a car for a range of around 350 miles. In its gaseous form at ambient pressures, this would be a hugely impractical volume. A 20-gallon tank of hydrogen gas at room temperature and pressure would propel a car just under 200 m. Even pressures as high as 2500 psi (17.2 MPa) are not sufficient to store enough, although work is progressing to achieve double this pressure. An alternative is to liquefy the hydrogen, but this needs temperatures as low as -253 °C, and energy is needed to maintain this temperature, whilst more hydrogen is lost through boil off. Metal hydrides have been investigated as "hydrogen sponges" but they too suffer from a weight problem. The storage problem is summarised in Figure 9 from a recent review [13]. The system volume and weight includes the equipment needed to store the hydrogen and ancillary components needed to run the system. A system that stored 6% by weight as hydrogen and 45 gm of hydrogen per 1 by 2010 would meet the needs of first-generation fuel-cell vehicles, but nothing available now is capable of this. Even better performance would be needed to reach the 2015 target for a wider range of vehicles.

32. The technical problems associated with establishing a hydrogen distribution and fuelling system are not insuperable: such systems currently exist to distribute hydrogen for industrial purposes, and research is on-going on the effect of hydrogen on pipelines, valves and seals, the hardware of a practical system. The real problem will be that of substituting the current highly developed petroleum system. A "chicken-and-egg" situation will exist. Consumers will be reluctant to buy a hydrogen car until the infrastructure exists, yet investment in such an infrastructure will depend upon a growing demand.

33. A recent report, The King Review [14], of low-carbon cars took as its starting point: "*Traffic is currently growing in the UK at a rate of 1% per year. If this were to continue at a similar rate up to 2050, the number of kilometres driven each year would almost double. In order to reduce emissions from cars to 20% of 2000 levels we would actually need to achieve a 90% reduction in per-kilometre emissions by 2050 to offset the effect of traffic growth*".

34. It concluded that, although this is a large and challenging target, it is achievable: in the short term by using low emission cars (30% less CO_2 per kilometre) and in the long term by a combination of battery-electric hybrids, bio-fuels and hydrogen. I would like to share this optimism but am doubtful. In the UK it is probable that traffic will rise by more than 1% per year, if only because recent population estimates suggest we may exceed 75 million by 2050 [15], a rise of 15 million by the middle of the century and 6 million higher than existing projections. The Office of National Statistics is suggesting a population of 75 million by 2031 and as much as 109 million by 2081. Averaged over the last 40 years, a 1% growth in traffic per year has been much exceeded, and will continue to be if strong population growth continues. Further, the technology assumptions are optimistic. Globally, the growth in developing countries will inevitably use cheaper, higher CO_2 emitting technologies and the low-carbon vehicles will be slow to develop and diffuse into these markets.

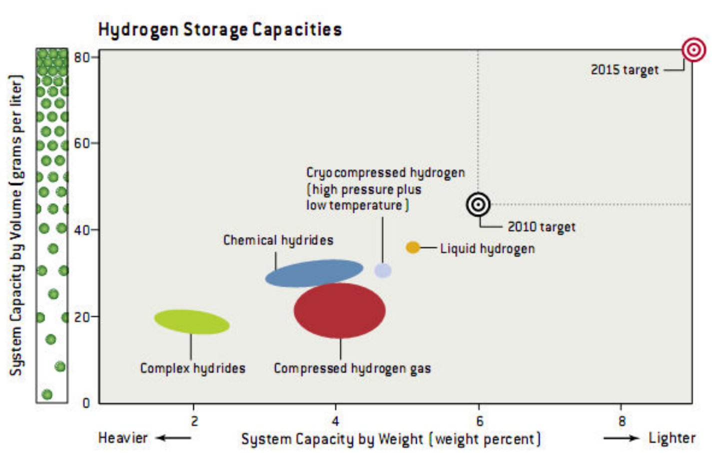

Figure 9: The hydrogen storage challenge [13]

The problem with planes

35. The invention of the jet engine transformed post war air travel. Package holidays gave opportunities for travel to the sun; the Jumbo democratised air travel. Concord was fast but economically and environmentally suspect; low cost airlines have opened up corners of Europe long considered off the beaten track. The net result has been a spectacular and continuing growth of air travel. Despite the improvements in efficiency of jet engines, coupled with better aerodynamics and light-weighting, air transport emissions still cause concern. Behind this concern lies the fact that no practical methods are on the horizon to replace the burning of kerosene, that emissions at high altitudes are though to be more damaging, and that once given the freedom of the world, it is going to be very difficult to change peoples habits. However, high-speed rail offers a real alternative to journeys of up to three hours duration, and dissatisfaction with delays at airports, partly caused by enhanced security measures, this may extend to longer times, giving trains a time advantage over air for trips of up to 1000 km.

36. The advantage of trains in terms of emissions is well illustrated by data collected by the author on his own travels, shown in Figure 10.

37. Each point represents a particular flight. The distance is the great circle distance between airports. The total fuel used has been divided by the actual number of passengers on board and converted to CO_2 produced per passenger km (1 kg kerosene equals 3.14 kg CO_2). There are three distinct regions. Short flights (<1200 km), medium length flights and long haul flights, about at the limit of range of current aircraft. The short flights show great scatter because of many factors. The passenger load factor varies from as low as 20% to nearly 100%, actual distances flown can be considerably longer than the great circle distance (because of routings and air traffic delays), taxiing to take off can be significant (the longest being over 45 minutes from push back). Generally the long-haul flights had load factors greater than 75%, but here we enter a rising curve because of the weight of fuel which must be carried to cover such long distances. Note too as an example, a return flight from London to Toyko, a distance of 2 x 9620 km, burns in the order of 225 tonnes of fuel and produces 700 tonnes of CO_2. On a per head basis, one such flight will produce as much CO_2 as an individual's normal annual footprint.

38. Now the Tokaido shinkansen [13] between Tokyo and Osaka returns figures as low as 9.3 g of CO_2 per seat (0.01 kg on the scale below). This represents a huge environmental advantage for high-speed trains. It is a requirement of the EU that all cars must produce a less than 130 gm CO_2 per km by 2012. It is unlikely that this target will be met and, on the basis of the previous discussion, emissions on actual journeys are likely to be considerably higher. Thus high-speed rail will continue to have an advantage (at least in energy terms) over cars.

39. The effect of CO_2 emissions at high-altitude is increased over the ground level effect. Debate on the magnitude of this effect so-called "radiative forcing" is on-going, but a commonly accepted multiplier is 2.7, but others claim a figure as high as 4. Other greenhouse gases, particularly nitrous oxide thought to be responsible for the depletion of the ozone layer, are partly caused by aircraft contrails and their sometimes cirrus-forming aftermath. This means that the effect of contrails could be about 2.5 times higher than that from CO_2 alone [16].

40. Whilst air transport currently is responsible for only 2 to 3% of the world's total CO2 emissions, the growth rate in demand is alarming at about 5.2% for passengers and 6.2% for cargo. Furthermore, there are no technical fixes available now or in the foreseeable future, other than a small nibbling around the edges [17]. It is clear that for travel over long distances, say greater than 1000 km, air will remain the preferred mode of travel, and over huge distances, say more than 2000 km, there is no practical alternative.

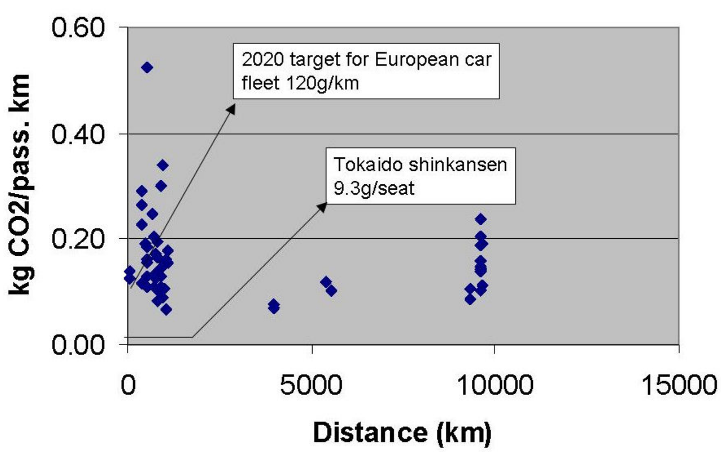

Figure 10: Personal data: aircraft CO_2 emissions against flight length

Ships and emissions

41. There are currently some 90,000 large vessels plying the sea routes of the world, carrying something like 90% of the world's trade. It is envisaged that this trade could increase by 75% in the next 25 years. Shipping is an essential component of our economic activity, but generally out-of-sight and therefore largely out-of-mind. Currently ships are one of the least regulated sources of anthropogenic emissions. The fleet is diesel powered, generally operating on very low grade "bunker fuel". CO_2 emissions are estimated to be in the region of 600 to 700 m tonnes annually, about 5% of the world's total. Because of the low grade fuel used, ships produce large quantities of other harmful emissions, including nitrous oxides and sulphur dioxide [18], [19]: concerns about these have led to the partial switching to cleaner fuels for near shore operations.

42. However, it must be acknowledged that large ships are extremely efficient, as demonstrated by our previous Gabrielli - von Kármán analysis. Furthermore, the now ubiquitous container has reduced costs hugely, and contributed to global prosperity. As with other transport modes, technical fixes, of which there are some possibilities, are incremental and likely to be swamped by rising volumes of traffic. Optimisation of hull shape and propeller design will deliver some energy savings, low sulphur fuel is available and alternative fuels may be a longer term prospect. Cost will be an obstacle: the shipping industry is known for its parsimony, a trait from which we are currently happy to benefit.

Transport demand management (TDM)

43. There is understandable scepticism that transport demand can be reduced by changing people's attitudes and behaviour. The car was originally seen as the great liberator and if its appeal is being tarnished in developed societies it is because of its very ubiquity, whilst in developing economies car ownership is a badge of success and progress. Nevertheless, attitudes can be changed; there are successful examples: drinking and driving, the use of seat belts and the diminution of smoking.

44. Before turning to TDM measures, it is worth mentioning the possibilities of information technology for reducing the need for travel. The indications so far are less than persuasive that any real reductions have taken place. Indeed, the contrary could be argued. It is now so easy to plan and book travel without leaving one's desk that demand may well have increased. There may be a role to play for increased flexible working, both in hours and from home, and this may serve to ameliorate the commuting peaks which cause problems with transport into cities.

45. Many TDM strategies have been suggested, summarised in Table 2 [20]. The role of technology here is both direct and indirect. Many of these schemes require organisation, monitoring and control which are relatively straightforward electronic tasks, requiring mere development of existing technologies and opportunistic use of newly developed techniques.

Examples of TDM strategies. TDM includes more than three dozen strategies that improve travel options, encourage use of efficient modes, and create more accessible land use patterns.

Improve transportation options	Incentives to reduce driving	Parking and land use management	Policy reforms and program
Alternative work schedules Bicycle improvements Bike/transit integration Car sharing Flextime Guaranteed ride home Individual actions for efficient transport Park and ride Pedestrian improvements Ride sharing Shuttle services Small-wheeled transport Taxi service improvements Telework Traffic calming Transit improvements Universal design	Walking and cycling encouragement Commuter financial incentives Congestion pricing Distance-based pricing Fuel taxes HOV (high-occupancy vehicle) priority Parking pricing Pay-as-you-drive vehicle insurance Road pricing Speed reductions Street reclaiming Vehicle use restrictions	Bicycle parking Car-free districts and pedestrianized streets Clustered land use Location-efficient development New urbanism Parking management Parking solutions Parking evaluation Shared parking Smart growth Smart growth planning and policy reforms Transit-oriented development (TOD)	Access management Campus transport management Car-free planning Commute trip reduction programs Comprehensive market reforms Context sensitive design Freight transport management Institutional reforms Least-cost planning Regulatory reform School transport management Special event management TDM marketing Tourist transport management Transportation management associations

Source: Victoria Transport Policy Institute (2002).

Table 2: Transport Demand Management Strategies [20]

The original intentions may be far from transport, but parasitic opportunities will arise. The use of technology for example, to enforce speed limits and hence increase capacity, to monitor and collect payments for road charging schemes, to provide better real time information for public transport, is already working and is relatively cheap. Improved technologies will undoubtedly emerge, so that technology will not be a barrier to the implementation of TDM schemes.

46. Towards a Sustainable Transport Policy [21], a recent report, was typical of many Government reports, verbose and short on detail. The following is typical: "*We will therefore identify robust emissions reductions for transport starting domestically. We will come forward with proposals in due course.*" Whilst acknowledging the need to put a price on carbon, one of the few concrete suggestions was the extension of "Active Traffic Management (ATM), basically allowing cars to use the hard shoulders of motorways and thus increase capacity at low cost.

47. (The long awaited Eddington Transport Study [22] was another example of the above. Weighing in at 4 volumes of 366 pages plus voluminous appendices, it made the not unexpected claim that transport was essential to the economy, the surprising claim that the system in the UK was basically sound, and went on to propose only tinkering to solve the problems.)

Discussion

48. On reading a previous Hawksley lecture delivered just as I was starting my research career, I am struck with the rapidity with which the environment has now become the overriding consideration. In 1978 [23], the energy crisis was discussed largely as a question of supply of potentially scarce resources. Global warming was not mentioned. Just before then, Sir William Hawthorn, the Head of the Engineering Department at Cambridge, in which I then worked, gave an extremely authoritative review of the energy situation [24]. Again, carbon dioxide was not on the agenda.

49. Transport poses a particular and increasingly difficult problem to our attempts to curb CO_2 emissions. It is likely to remain heavily dependent on petroleum products for the foreseeable future. There are some promising short term developments which will help to ameliorate the problem, but these are likely to be overtaken by rising demand. In the longer term, the hydrogen economy promises much, but some practical issues remain to be overcome. "Fixes" for ships and planes are of the incremental variety, and no real alternatives exist for these modes for freight and long haul travel respectively. It is clear that there are some huge engineering problems which await solution in the future. We are fortunate that the younger generation seem to be well aware of the challenges ahead, and we must encourage them to fully apply their talents or the benefit of mankind.

50. Transport opportunities are firmly linked to personal freedom. Attempts by coercion to limit these opportunities will be highly unpopular. In general public transport use can contribute to reduced energy consumption. It is essential that public transport in and around big cities in particular is enhanced. The link of transport demand to economic growth and rising prosperity is particularly difficult to overcome.

51. Indeed, because continuous growth is by definition unsustainable, and is in any case going to be hampered by resource depletion, one is tempted to say that, in the longer term, this problem is so severe it threatens the heart of our global economic system. We should recognise that the fundamental of our economy is the capture and processing and eventual disposal of the world's resources [25]. The use of energy and transport are essential components of this activity. The real economy is governed by fundamental laws of thermodynamics and mass conservation. Money is merely our convenient rate of exchange. The real (external) costs of our activities need to be acknowledged by pricing if the market is to act in a way which will husband our resources. It is just possible that if we act immediately, internationally, unselfishly and over a wide range of activities, we can tackle the problem of carbon emissions bit by bit with existing and emerging technologies, the so-called Sokolow wedge approach [26], [27]. We need to assist the developing countries to grow without causing irreversible damage to the environment. Perhaps, too, we need to question our current economic model which is predicated on unsustainable continuous growth. Time is short and real leadership is required. A recent UN report on human development singled out the UK government for failing to show enough ambition in its plans to combat greenhouse gases, citing the upward trend in emissions from the energy and transport sectors and the lack of progress in the development of renewable sources of energy (The Guardian, 28 November 2007). So far our Government, indeed Governments generally, have been long on rhetoric but woefully short on action.

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APPENDIX 1

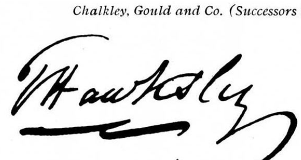
Background of the Hawksley lecture

The Thomas Hawksley Fund was founded by the late Charles Hawksley, Member of Council of the Institution of Mechanical Engineers 1913-1917, President of the Civil Engineers 1901, to commemorate the centenary of the birth of his father, Thomas Hawksley FRS, President of the Institution 1876-77. The fund provides for the maintenance of the Thomas Hawksley Memorial Lecture, an annual lecture on any subject connected with mechanical engineering.

Thomas Hawksley (1807-1893) FRS

Thomas Hawksley, the son of John Hawksley and Mary Whittle, was born at Arnold, near Nottingham, on 12 July 1807. He was educated at the local grammar school, then articled to an architect and surveyor, Mr Staveley, in Nottingham. He became a partner in the business before leaving to work in London in 1852.

Taken August 1882. Chalkley, Gould and Co. (Successors to Adams and Stillard)



Hawksley was a gas and water engineer: probably the leading water engineer of the nineteenth century [28]. He pioneered the continuous supply of water to Nottingham as early as 1830, before going on to engineer the gravitational supplies from impounding reservoirs of, *inter alia*, Liverpool, Huddersfield, Weardale, Leicester, Rochdale, Barnsley, Merthyr and Bury, together with pumped supply works at Darlington, Stockton, Middleburgh, Norwich, Derby, Yarmouth, Sunderland, Cambridge, Coventry, Oxford, Worcester, Cheltenham, Boston, and Lowestoft. Amongst the total of some 150 works he was associated with the supplies of Bombay, Vienna and Stockholm.

He was one of the oldest members of the Institution of Civil Engineers, having joined in 1840. He was elected President in 1871-2, one of the very few engineers to head both Institutions. Strangely, he did not produce any formal papers. His Presidential Address [29], delivered in Bristol in the summer of 1877 to the Mechanicals, has been described as "*one of the most cheerless of them all*" [30]. He noted Britain's dependence on trade and the import of food, and urged engineers to change the government policy of building large battleships in favour of light, fast ships which "*would succeed in driving every enemy's ship from the face of the seas*". Noting that the growing trade deficit was caused by the imported food bill, and was increasing because foreign countries would not buy our manufactured goods, which were either too expensive or not well made. He was in no doubt where the faults lay: "*We have passed through a period of unnatural and factitious prosperity. The capitalist has, unfortunately for himself and his country, in too rapid a manner, duplicated and reduplicated his wealth; whilst the working man observing this, and being misinstructed by his popular advisers – themselves utterly ignorant of the first principles of international political economy – has conceived and become thoroughly imbued with three transparently false notions. First. That he is entitled to share in his employer's success in business. Second. That he has a right, in combination with others, to exact conditions from and prescribe terms to his employer. Third. That he has a right, in combination with others, to force his employer to yield to his exactions and prescriptions – exactions and prescriptions which concern not merely himself, but which are so exercised as to control the employer in regard to the manner in which he shall conduct his business, and even in respect of his relations to the general public at home and abroad.*" This prompted Mr Frederick Bramwell (Immediate Past President, knighted 1889) to state, in moving a vote of thanks to the President, that "*like all documents emanating from him, it was of a highly suggestive and argumentative character*".

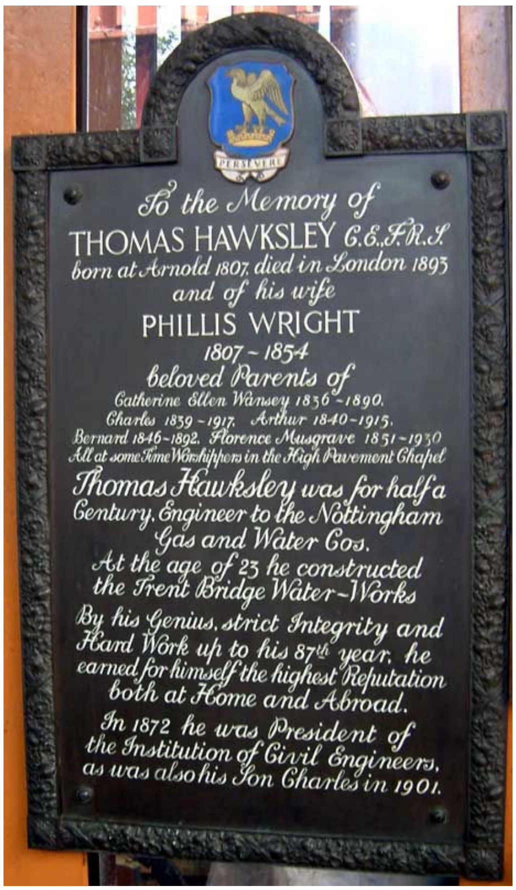
In an incident much earlier in Hawksley's career, in 1839, during the Chartist Riots, the gas works in Nottingham was attacked [31]. He proved more than equal to the radicals, "*he marshalled his small staff, coupled up pipes, connected them with the gas supply, and through a nozzle played a great tongue of fire on the attacking party. This surprised the mob* (!), *and they precipitously left the works. Following up his advantage, he threw barrels of gas tar upon the adjacent streets, and thus obviated any recovery and further attack by the affronted Chartists*".

However, it would be quite wrong to judge Hawksley only on the basis of these incidents in his life. In 1832 he erected the first cholera hospital in the country and personally attended to the patients. He understood the importance of sanitation, and was associated with Bidder and Bazalgette on the development of the great London sewage scheme. He took a great interest in students, encouraging them to continue their study of mathematics, applied sciences and languages.

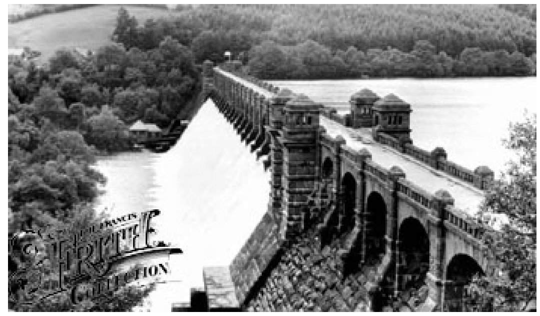
Hawksley's legacy

It is remarkable how little we appreciate the importance of our water supply on our quality of life and our debt to the Victorian water engineers, on whose work we still hugely depend. Many of the great cities of this country owe a large debt to Hawksley. He did much to improve the health of the nation.

He is commemorated by a plaque in the Museum at Woolaton Hall, Nottingham.



Of the great impounding dams he engineered (with G F Deacon), perhaps Vyrnwy, supplying Liverpool, some 68 miles away, is the most spectacular. In contrast to the previous earth embankment dams, Vyrnwy was the first masonry dam in the country. The pumping station at Ryhope, north east Durham, closed in 1967, but reopened as a museum, in which the two great double acting compound rotative steam beam engines manufactured by R & W Hawthorn of Newcastle in 1868 are still operated for the delight of visitors. On my daily commute through Hyde Park from Paddington, I am reminded of Hawksley's architectural origins by his ornate pumping station still standing at the head of the Serpentine.



Vyrnwy dam, mid Wales

Ryhope pumping station, Durham

Serpentine pumping station, Hyde Park, London

APPENDIX 2

The literature of energy issues, transport and climate change is enormous and growing exponentially (see Appendix 3). The following list has no claim other than that the author found the cited references to be particularly useful in the preparation of this paper.

Most of the basics of energy are covered in a book of the same name by Janet Ramage [32]. She is also associated with a team from the Open University which has written a particularly clear and comprehensive guide to energy systems and sustainability [33]. The way in which energy use effects the environment is treated at an introductory level in a textbook by Rubin [34]. Coal has played, and continues to play, such an important role in our lives, that it is not surprising that books are written on the way in which it affects matters ranging from individual health to global politics [35].

The Rough Guide series of travel guidebooks have probably contributed to our problems by providing clear, accurate and up-to-date information on many parts of the world. It is therefore appropriate that a book of climate change with the same admirable characteristics should come from the same stable [36]. Many articles on climate change have appeared in periodicals at the serious end of the market. Some recent expositions include Climate Change: A Guide for the Perplexed, in the New Scientist [37], and The Undeniable Case for Global Warming in Scientific American [38].

Although the scientific consensus is nearly complete, the few doubts are seized upon and given far more publicity than they proportionally deserve. Perhaps many members of the public subconsciously need to reinforce denial to comfort themselves and hide from the worst of the effects predictions, which will not really kick-in during their own lives. The most famous Sceptical Environmentalist is Lomborg [39], [40]. Basically he acknowledges that global warming is happening, but argues that resources spent combating it would be better directed elsewhere, for example in the eradication of curable diseases. He is joined by a strange group of companions, all with a particular axe to grind, and all looking increasingly like Flat Earthers. The right wing of politics, led by President Bush, gets support ranging from ex-Chancellor Lawson [41], David Bellemy and Melanie Phillips. The latter's contribution can be summarised by "*blaming global warming on mankind's activities in producing carbon dioxide is utter garbage*", Daily Mail 25 February 2002. Which is, of course, unintentionally, very true since CO_2 is a waste product.

A useful account of the development of transport in Britain is given in a book by Bagwell and Lyth [42]: an account which emphasises the unplanned and haphazard way in which our transport infrastructure has developed and the problems that this has generated. Christian Wolmer has produced a splendidly entertaining account of the history of our railways [43], and makes very much the same point. Some of the essential features of flight such as scaling and power requirements are described in a fundamental way by Tennekes [44]. The future of transport has been explored in a special issue of Scientific American [6]. The Handbook of Transport and the Environment [30] is an invaluable source of detailed scientific and technical information on a huge range of topics which come under this heading.

The future of energy was the topic of a special issue of Scientific American [45] and at a higher level was the basis of a discussion meeting at the Royal Society [46], and of a book on global perspectives [47]. A useful overview of the potential of bio-fuels appeared in National Geographic [48].

The question of what we could do is addressed at various levels, from the viewpoint of a concerned activist [49], to the outputs of major scientific workshops [50].

APPENDIX 3

Understanding the characteristics of exponential growth

Because the consequences of exponential growth over an extended period are so severe and these characteristics seem to be little discussed and appreciated, the basic theory is reproduced here.

Many activities and processes grow at a rate which is proportional to their current size,

i.e. $\frac{dQ}{dt} = RQ$ where R is the constant of proportionality.

Integrating

$$Q = Q_0 e^{Rt}$$

in which Q is the current activity level at time t after the initial level Q_0.

We define the doubling time, t_D, as the time taken to double the activity level, thus

$$2Q_0 = Q_0 e^{Rt_D}$$

$$2 = e^{Rt_D}$$

On taking (natural) logs

$$t_D = \frac{\ln 2}{R}$$

Hence we can construct the following table:

R	t_D (years)
0.01	69.3
0.03	23.1
0.05	13.9
0.10	6.9
0.15	4.6

Thus at an apparently low growth rate of 3%/year, about the rate at which the mature economies of the world wish to grow, the activity doubles in 23.1 years. For a rapidly developing economy, such as China's, the growth rate is approximately 10% /year, implying a doubling in only 6.9 years! A good approximation is
t_D(years) = 70/ (% growth rate/year).

The total cumulative activity (a measure proportional to the total resource consumed in the particular example of economic growth), can be found by integrating the exponential growth curve between the time intervals under consideration. Thus between times t_1 and t_2 we obtain:

$$\int_{t_1}^{t_2} Q_0 e^{Rt} dt = \frac{Q_0}{R}\left[e^{Rt_2} - e^{Rt_1}\right]$$

For the particular case of the sum of all the consumption between t_1=0 and t_2=T, the above reduces to:

$$\frac{Q_0}{R}\left[e^{RT} - 1\right] = \frac{Q_0}{R} e^{RT}$$

after many doubling periods and when T becomes large.

Now consider what happens in the next doubling period, t_D:

We integrate from t_1= T to t_2= T + t_D to get the result

$$\frac{Q_0}{R}\left[e^{R(T+t_D)} - e^{RT}\right] = \frac{Q_0}{R} e^{RT}\left[e^{Rt_D} - 1\right]$$

But $e^{Rt_D} = 2$ from the earlier definition of doubling time, hence the consumption in the next doubling period is

$$\frac{Q_0}{R} e^{RT}$$

that is, the really remarkable result, that the total consumed in the next doubling period is equal to the total consumed in all the previous doubling periods combined.

In this very important result lies the unsustainability of exponential growth. Put simply and alarmingly, it means that if an economy grows for example, at the modest rate of 3% /year, then in 23 years **the activity (the size of the economy) will have doubled and in that doubling period we will need to use resources equal to all the resources consumed in the history of the economy.** Note that these resources include the scarce resources of materials and energy. It is therefore apparent that the term sustainable growth is an oxymoron.

We might care to apply this to many examples: the world population, depletion of natural resources and, in the context of the subject of this paper, the fact that continuing growth in transport will quickly lead to the depletion of hydrocarbon fuels and that percentage improvements in performance efficiency will be swamped by the inexorable growth in demand. These facts alone are a cogent reminder of the huge importance of the challenges facing society if we continue on our present path.

Thomas Malthus as long ago as 1798 in his *Essay on the Principle of Population* [51] is credited with being first to point out the fact that populations grow geometrically whilst food production increases arithmetically. His predictions of problems arising from this were avoided in the 19th century were avoided by mass emigration from Europe to America and huge increases in the efficiency of food production and distribution. Essentially he anticipated the pressing arguments now current on population, growth and resource depletion.

APPENDIX 4

On 22 November, Ruth Kelly, Transport Secretary, announced a plan to build a third runway and a sixth terminal at Heathrow airport. On 23 November I received the following circular e-mail sent to all members of BA's Executive Club by the Chief Executive of British Airways. My reply of 25 November is appended without further comment.

Dear Prof Smith,

You may have heard about the public consultation the Government has just launched on its plans to expand Heathrow airport.

As a regular flyer from Heathrow, you will know how prone it is to delays. Whilst Terminal 5 will deliver a seamless and relaxed customer experience, we are still restricted by the limited take-off and landing slots available at Heathrow.

The proposals are to change the method of runway operation to create more take-off and landing slots, and to build a short third runway as a permanent solution to Heathrow's congestion.

The benefits of these proposals are:

- Reduced delays for departures and arrivals;
- The opportunity to add up to 75 new destinations, giving you more choice when flying from Heathrow;
- Less queuing for take-off and landing, reducing aircraft carbon dioxide emissions 330,000 tonnes a year.

I support the Government's proposals very strongly.

I believe these plans – which must pass strict environmental tests – represent our best hope for making your experience as our customer easier, calmer and more reliable.

I would be very grateful if you felt able to support our position. Doing so will take less than a minute of your time.

To register your support please click on the "find out more" button above, sign in to your Executive Club account and click on the "Register your support" button.

It is very important to us that the Government hear from our most frequent customers, as you are the people who know Heathrow best.

With best wishes,
Willie Walsh, Chief Executive, British Airways

Dear Mr Walsh,

You suggest that a new runway at Heathrow will save some 1/3 million tonne per year of CO_2 because of reduced queuing of aircraft.

You also say it will enable you to add 75 new destinations from the airport and, presumably, add extra flights to existing destinations. Other airlines will also be able to expand operations.

Can you estimate how much extra CO_2 this will produce?

Thank you for your attention to this matter.

Yours sincerely
Roderick Smith