The IMPACT of the Internal Combustion Engine

1. Setting the Scene

There is some dispute about who actually ***invented*** the internal combustion engine. In 1884 a French engineer, Edouard Delamare-Deboutteville, built and drove a vehicle with a single-cylinder, four-stroke engine that ran on petrol and although the design was registered, the vehicle never went into production.

In 1885, Gottlieb Daimler produced a prototype of the modern petrol engine. It was used to power a two-wheeled vehicle, the "Reitwagen" (Riding Carriage) and, a year later, the world's first four-wheeled motor vehicle.

For the first petrol-fuelled car to go into production, and which became available for sale to the public, we must thank Karl Benz who received the first patent (DRP No. 37435) on 29 January 1886.

For the last 130 years, the internal combustion engine has been used to power land, sea and air transport as well as portable plant and machinery. The IMPACT of the Internal Combustion Engine could be summarised as:

a disruptive technology which, over the past 130 years, has brought a multitude of benefits to humanity …
…. plus, several associated problems

Cars powered by the internal combustion engine had an immense influence on the history of the 20th century and, along with other inventions, from the printing press, electric light and textile mills to personal computing and the internet, can fully justify the description of a 'disruptive technology'. ***Just what are these 'benefits' and associated 'problems'?***

Pros:

- Improved social mobility
- Educational advancement
- Industrial advancement
- Enhanced national and international prosperity
- Enhanced employment opportunities
- Enhanced leisure opportunities
- Improved health and well-being[1]
- Environmental benefits[2]

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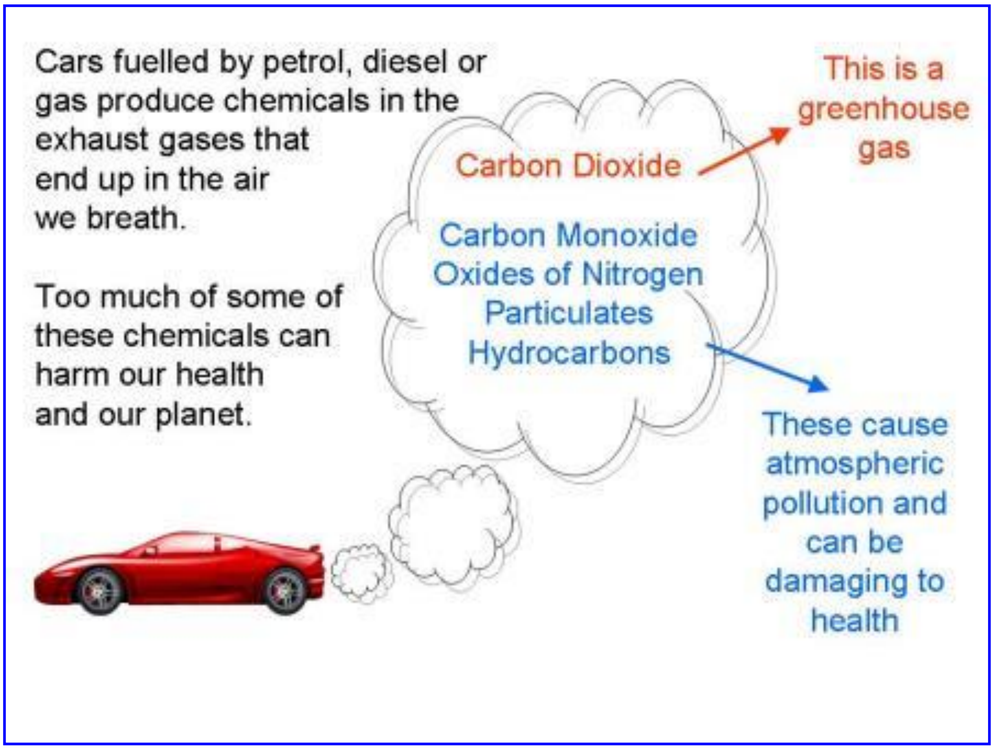
[1] Fresh produce to shops across the country within hours of being gathered or off-loaded at the ports provides choice and health benefits unavailable at the dawn of the motoring age, the car providing the final link to home in the chain.

[2] In 1894, the Times of London estimated that every street in the city would be buried under 9ft of horse manure by 1950 and in 1900, in London alone, 50,000 horses provided the motive power for public transport. They produced 1000 tonnes of dung per day. Then along came the car!

Cons:

- Environmental concerns, including (but not limited to):
    - Air pollution, particularly in urban areas, and consequent detriment to human health
    - Contribution to global warming and acidification of the oceans

The “Cons” list may be shorter but the IMPACT may be greater and be with us for centuries.



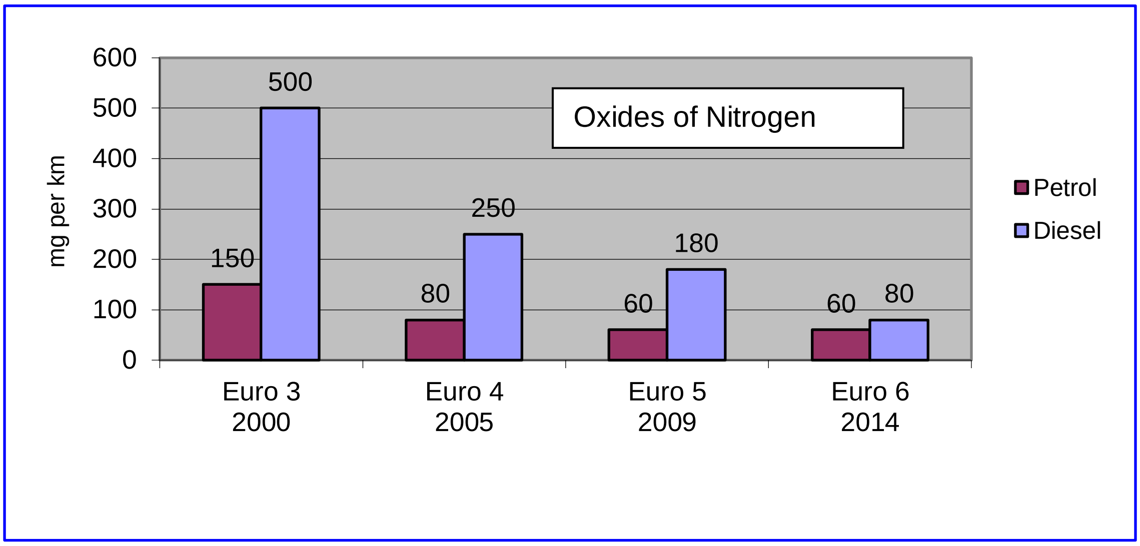
2. Air Pollution and Health

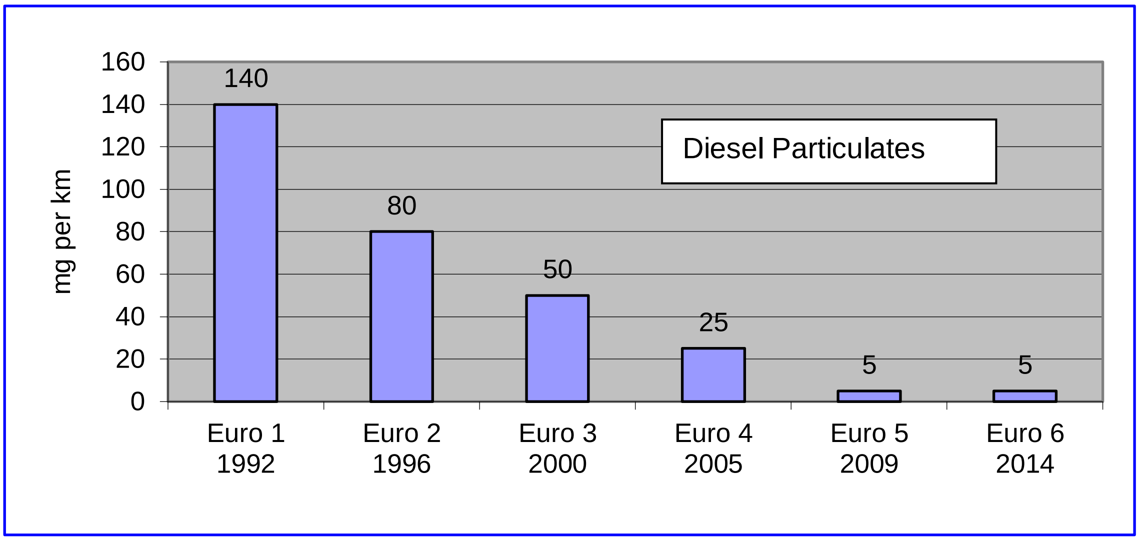
Air pollution has been linked to respiratory and cardiovascular disease, diabetes and cancer. It may also harm foetuses and cause cognitive problems in children and adults. In 2014, the World Health Organisation estimated that air pollution was a factor in ***7 million*** premature deaths worldwide each year. The corresponding figure for the UK is ***40,000*** each year of which nearly half are due to nitrogen dioxide[3]. A recent report from King’s College London claims that, in 2015, there were ***9,500*** premature deaths per year, in London, due to air pollution: specifically, particulate matter and nitrogen dioxide. For comparison, the number of fatalities through road traffic accidents in Great Britain during 2017 was 1793 (131 in London).

What steps are being taken to reduce harmful emissions from road transport?

[3] Death certificates do not bear the words “Air Pollution” as a cause of death. It is the mixture of particulate and gaseous vehicle emissions from which expert bodies, such as the UK Committee of the Medical Effects of Air Pollutants, assess the shortening effect on lifespan to be equivalent to tens of thousands of deaths per year.

Since 2000, European legislation, for both diesel and petrol cars offered for sale within the EU, has sought to legislate ever lower levels of harmful gases and fuel-derived particulates. (Particulates produced by wear from tyres and brakes are excluded from these figures). Two examples of the Euro 5 and 6 levels, along with earlier limits, expressed as milligrams (mg) per kilometre driven, are shown in the graphs below.





So surely, cars are getting cleaner, things are getting better?

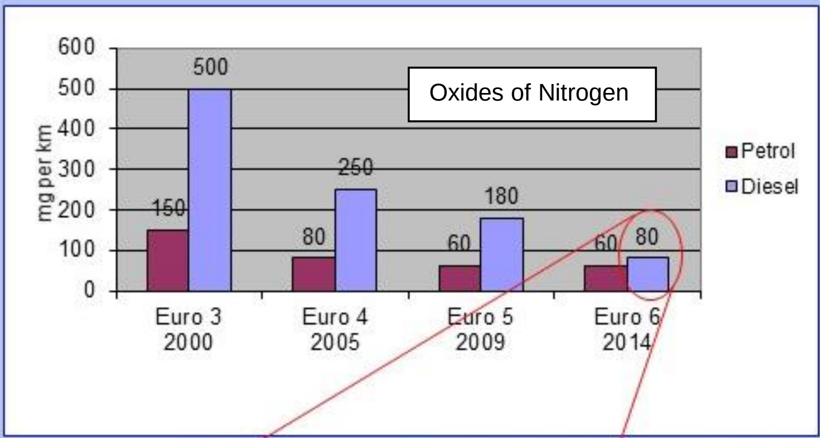
Well, there are a number of reasons why we should be wary of graphs such as those above.

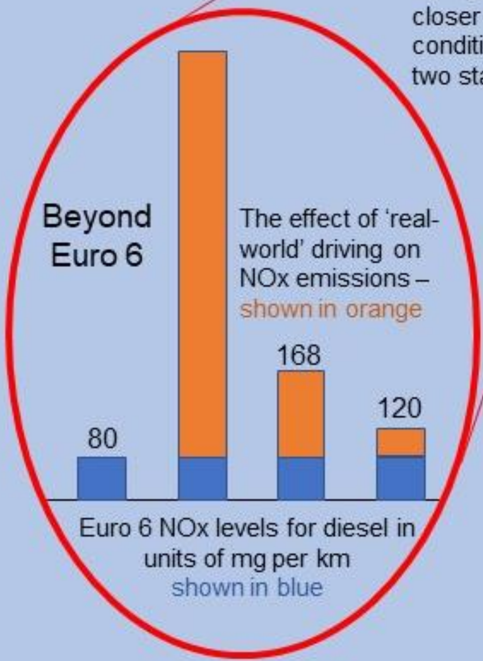
Firstly, a demonstration of compliance with the legally required standards shown in the graphs must be reproduceable from manufacturer to manufacturer and laboratory to laboratory across the globe. Consequently, the legislation defines a driving cycle against which emissions are measured and this driving cycle, known as the New European Drive Cycle (NEDC), ensures consistency across all laboratory testing.

It is however, widely recognised that this testing cycle is not representative of real-world driving. Consumer groups and others have shown that under real-world driving conditions, some new diesel-powered vehicles, compliant with Euro 6 under NEDC testing, can emit up to 20 to 25 times the Euro 6 limits of nitrogen dioxide.

Consequently, new diesel-powered cars are now required to comply with Real Driving Emissions (RDE) testing, which is being introduced in two phases: RDE1 and RDE2.The graphic below adds some figures and dates to this new testing regime.

The Evolution of Euro Standards for Diesel Vehicle NOx Emissions





European legislation beyond Euro 6 is aimed at moving closer to Euro 6 compliance under 'real-world' driving conditions. New emission levels are being introduced in two stages.

Column 1 (left): the Euro 6 definitions, and all preceding Euro levels, are specified under a repeatable, laboratory controlled testing regime. They are not representative of emission levels under 'real-world' driving conditions: 80mg/km is the Euro 6 NOx limit for a diesel vehicle.

Column 2: NOx emissions under 'real-world' driving conditions can vary, depending upon vehicle manufacturer and pattern of usage, up to 20 times more than those defined in Euro 6.

Column 3: Real Driving Emissions (RDE) testing is being introduced in two phases. RDE1 became mandatory for all new vehicle type approvals from 1 September 2017 and will apply to all new registrations from 1 September 2019. It will allow up to 2.1 times the Euro 6 limit of 80mg/km: ie 168mg/km.

Column 4: RDE2 becomes mandatory for all new vehicle type approvals from 1 January 2020 and all new registrations from 1 January 2021 and will allow emissions of up to 1.5 times the Euro 6 limit: ie 120mg/km. This standard will be known as Euro 6d ("d" for "diesel"?).

There are further reasons why the earlier graphs, which suggest we should be seeing a significant improvement in air quality, should be treated with caution. Since 1994, when compliance with the Euro 1 standard became mandatory:

- the number of vehicles on the UK roads has increased from around 25 million (of which 21 million were cars) to 38.2 million as at the end of June 2018. Of these 31.5 million were cars.

- The fastest growing category of vehicle is the van (Light Commercial Vehicle – LCV), growing in number by 29% over the decade 2002 to 2012, compared with just 11% for the number of cars. Delivering our internet shopping means that the average LCV typically covers 60% more miles per year than the average car. (As from September 2016, all new LCVs also must comply with Euro 6).

- the proportion of diesel cars, of all ages on UK roads, has increased from 7.4% in 1994 to 40.1% in 2017.

So, in summary:

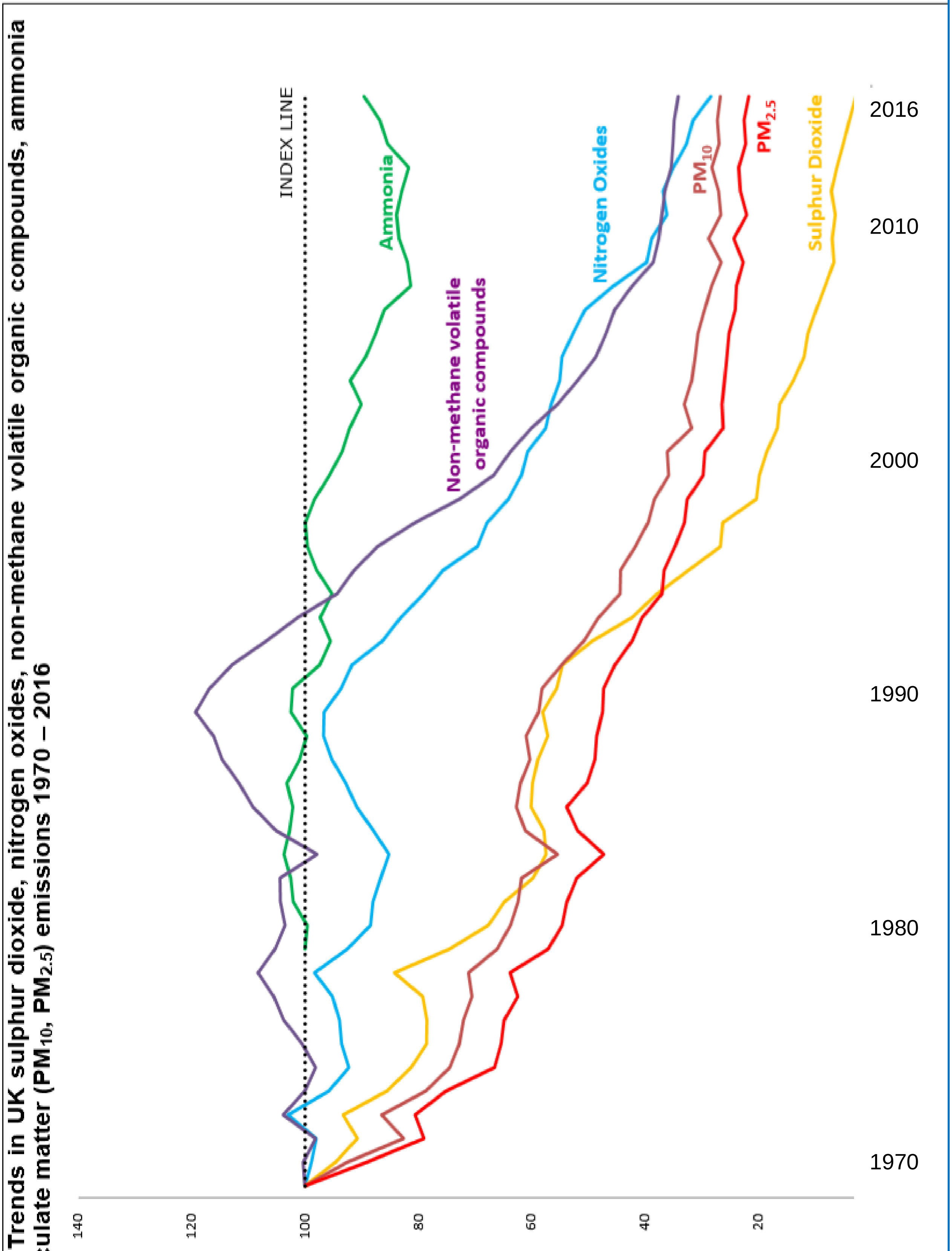
- particulate matter and nitrogen dioxide in car exhaust emissions adversely affect human health
- both are emitted in greater quantities from diesel engines than petrol
- the legislated emissions levels are far exceeded in real-world driving conditions
- the number of vehicles on the road has increased year on year since WW2
- the mix of vehicles has changed (more diesel, more LCV)

all hindering efforts to improve air quality in our urban areas.

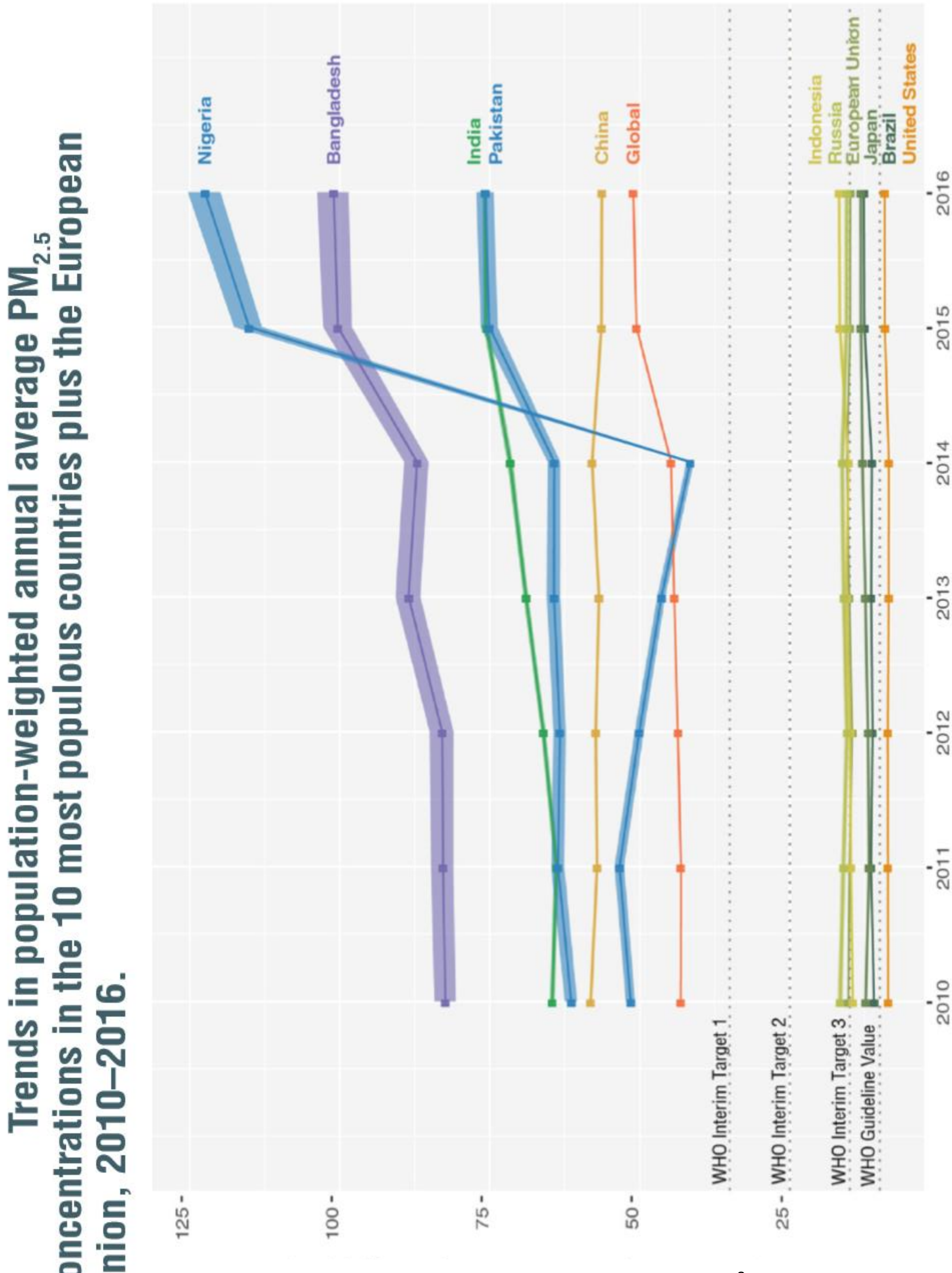
But, across the UK, EU, US, Australia and New Zealand, ***air pollution levels are falling***. For example, figures for particulate matter (soot) less than 2.5microns (ie 2½ thousandths of a millimetre), denoted as $PM_{2.5}$ in the figures below, have fallen steadily since 1970. DEFRA (Department for Environment, Food and Rural Affairs) figures for the UK are shown in the following chart.

They have not however, fallen fast enough to meet World Health Organisation guidelines and, globally, the figures are dwarfed by the increases from developing countries such as Nigeria, Bangladesh, India and China[4].

[4] See both New Scientist, 6 May 2017 and the sources of their data, "DEFRA STATISTICAL RELEASE: 15 FEBRUARY 2018 EMISSIONS OF AIR POLLUTANTS IN THE UK, 1970 TO 2016" and "The State of Global Air 2018" from which the following two graphs are reproduced.



Figures relative to 100 in 1970
(1980 for ammonia)
DEFRA National Statistics Release: Emissions of air pollutants in the UK 1970 to 2016

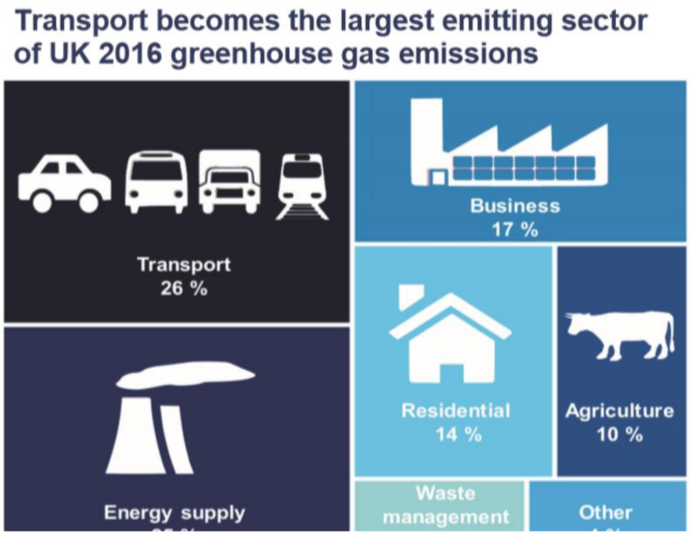


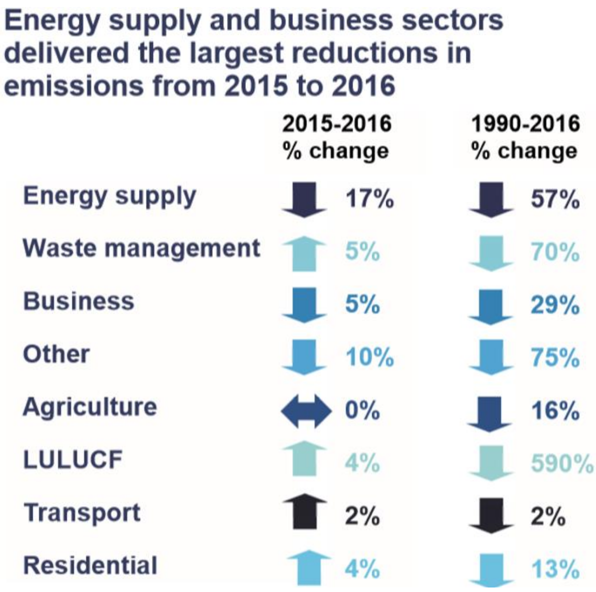
Population-weighted Annual Average $PM_{2.5}$ ($\mu g/m^3$)

3. Air Pollution and Global Warming

Carbon dioxide (CO_2), methane, nitrous oxide and other so-called greenhouse gases in the Earth's atmosphere have increased steadily since the time of the industrial revolution. Many graphs can be found that show pre-industrial levels of CO_2 averaging around 200 parts per million (ppm) while today, that level exceeds 400ppm: a level not seen for over 400,000 years[5]. Initially, the main contributors to the increase came from the new 19th century industrial economies of Europe, subsequently the US and are now dominated by China, India and newer, developing economies whilst the EU and US emissions are in decline.

Globally and closer to home across the 28 (27?) nations of the EU, power generation, with its heavy dependence on coal, has been the largest single source of CO_2 emissions: larger than the transport sector. However, in the UK in 2016, for the first time, greenhouse gas emissions from transport (26%) exceeded those from energy supply (25%). This trend is continuing in provisional figures for 2017 and is due to the reduction in the use of coal for power generation whilst the transport figures remain largely constant since 1990. The main contributors to the transport figures are petrol and diesel vehicles.





Reproduced from Dept for Business, Energy and Industrial Strategy

Historically, CO_2 emissions from road vehicles were not covered by EU legislation. With the increasing evidence that rising CO_2 levels are having a role in global warming, this changed in 2007. As a first step, EU legislation required the CO_2 emissions to be achieved by 65% of new cars registered in the EU from 2012, from each manufacturer, not to exceed 130 grams per kilometre (g/km). A sliding scale of limits applied from 2012 to 2015 at which time 100% had to meet the 130 g/km value.

In practice, by 2017, the average for all new cars was 118.5g/km.

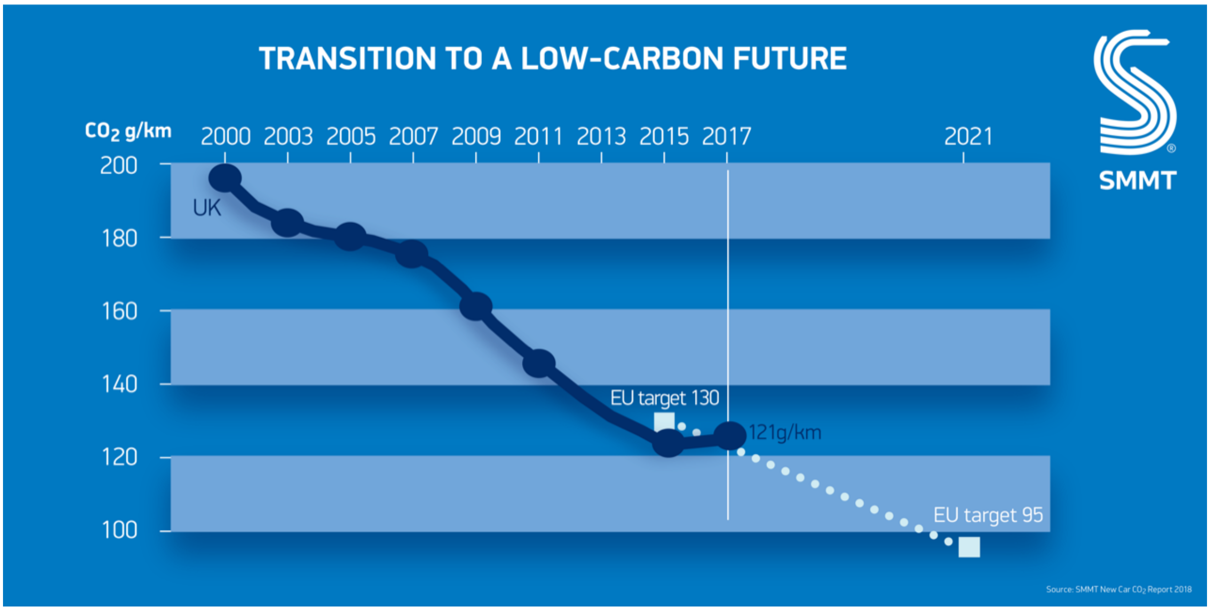
[5] Air bubbles trapped in ancient ice, in case you were wondering.

European legislation now requires a 95g/km limit for cars to be achieved by 2021 and 147g/km for LCVs. Beyond 2021, the targets are a 15% reduction on the 2021 figures for both cars and LCVs by 2025 and a 30% reduction by 2030.

From September 2017 the EU introduced a new test procedure, known as the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), it covers fuel consumption and CO_2 emissions and, although still a laboratory test, it reflects a 'real-world' driving profile and is the method by which compliance with the above limits will be determined.

The amount of CO_2 present in vehicle exhaust gases is very dependent on the fuel efficiency of the engine. It is for this reason that diesel fuel became the preferred choice for high-mileage drivers throughout Europe: like-for-like performance engines being generally more efficient when burning diesel than petrol. In the UK, this switch to diesel was encouraged by road and fuel tax incentives.

In the UK, the benefit of these incentives in reducing CO_2 can be seen in the SMMT (Society of Motor Manufacturers and Traders) graph below. This shows the year-on-year average CO_2 emissions for all ***new*** cars produced in that year. For comparision, the average of ***all*** cars on the roads of GB in 2017 was 144.3g/km.



The year-on-year downward trend in CO_2 emissions, which has been steady since 1980, when the average was typically around 250g/km, has recently reversed and this is due to the increased awareness amongst the vehicle-buying public of the adverse health implications of the emissions from the diesel engine. In 2017 petrol engine cars – with their higher CO_2 output - outsold diesel (53% to 42%) reversing the pattern from earlier years.

No matter how efficient the design, cars propelled just by petrol or diesel will struggle to achieve levels of CO_2 much below about 80-90 g/km. Moves to reduce CO_2 emissions from cars below this figure have seen the increasing use of electric power: either stand-alone electric or as a hybrid with internal combustion.

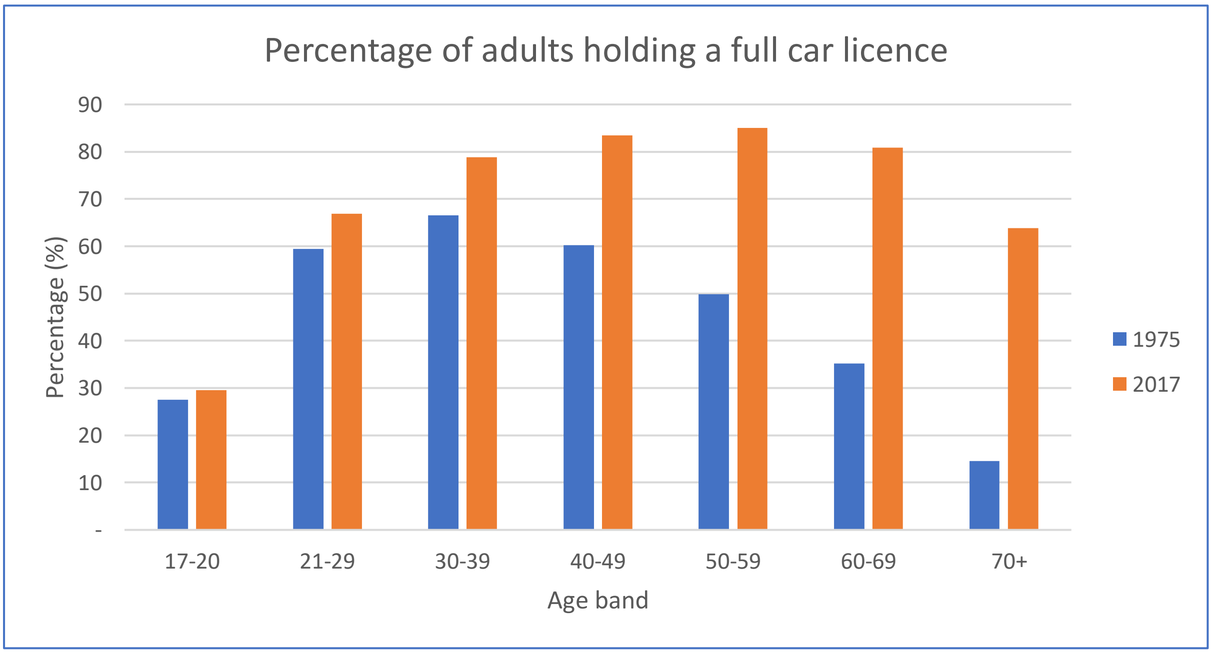
So, in summary:

- in the UK, transport is now the largest contributor to greenhouse gas emissions
- CO_2 emissions from vehicle exhausts dominates this mixture of greenhouse gases
- across Europe, 72% of vehicle emissions are generated by cars and LCVs
- EU legislation has driven down the average new car CO_2 emissions from around 250g/km in 1980 to a target of 95g/km in 2021
- in 2017, the average UK new car CO_2 emissions rose for the first time since the 1980s to 121g/km because of both the switch away from new diesel car registrations in favour of petrol and increased mileage[6].

4. The Future

Throughout the 20th century, as cars became 'easier' to own and drive, so the number on the roads of developed countries soared. As examples of why cars became 'easier' to own and drive, consider: the advent of the electric starter motor, avoiding the need for hand cranking an engine, pneumatic tyres, improving ride comfort, power assistance for steering and brakes, and the elimination of driver controls ranging from ignition timing to choke control to automated lights and wipers, not to mention lane keeping and collision avoidance. Couple this with the real terms decreasing cost of purchasing a car, and it is easy to see why the number of cars on UK roads has grown from 14 or 15 in 1895 to 9.97 million in 1970 to 31.5 million today.

In addition, people's life-expectancy is growing and car manufacturers are addressing the older driver through higher seating, easier access and moves towards autonomous cars: it doesn't look as if the number of cars on the road is about to decline for the next decade at least.



[6] Although the average annual mileage per car in the UK is decreasing, because there are more vehicles, the number of miles travelled per year is increasing. See Annex for Supporting Data.

The performance of the ICE has changed beyond recognition during the 130 years that it has come to dominate our lives. Driven by market competition and global legislation, environmental performance continues to improve and that seems likely to continue with incremental improvements in the efficiency of the ICE over the first few decades of the 21st century. Techniques such as automatic stop-start, turbocharging and cylinder deactivation are now in widespread use by many manufacturers. All help to improve fuel consumption, and hence reduce CO_2 emissions, with turbocharging allowing smaller, lighter engines of equivalent power output to their larger, heavier predecessors. Also, thanks to lower weight materials plus electric rather than hydraulic actuators and improved combustion, the fuel consumption and CO_2 emission figures of the average family saloon from even 10 years ago look very poor when compared with today's figures.

Even with these improvements to the ICE environmental performance however, legislation within many countries is aiming to move the ICE from the pedestal of prime motive power well before the middle of this century. It will be banned!

Globally, a report by the UN's Intergovernmental Panel on Climate Change has warned that:

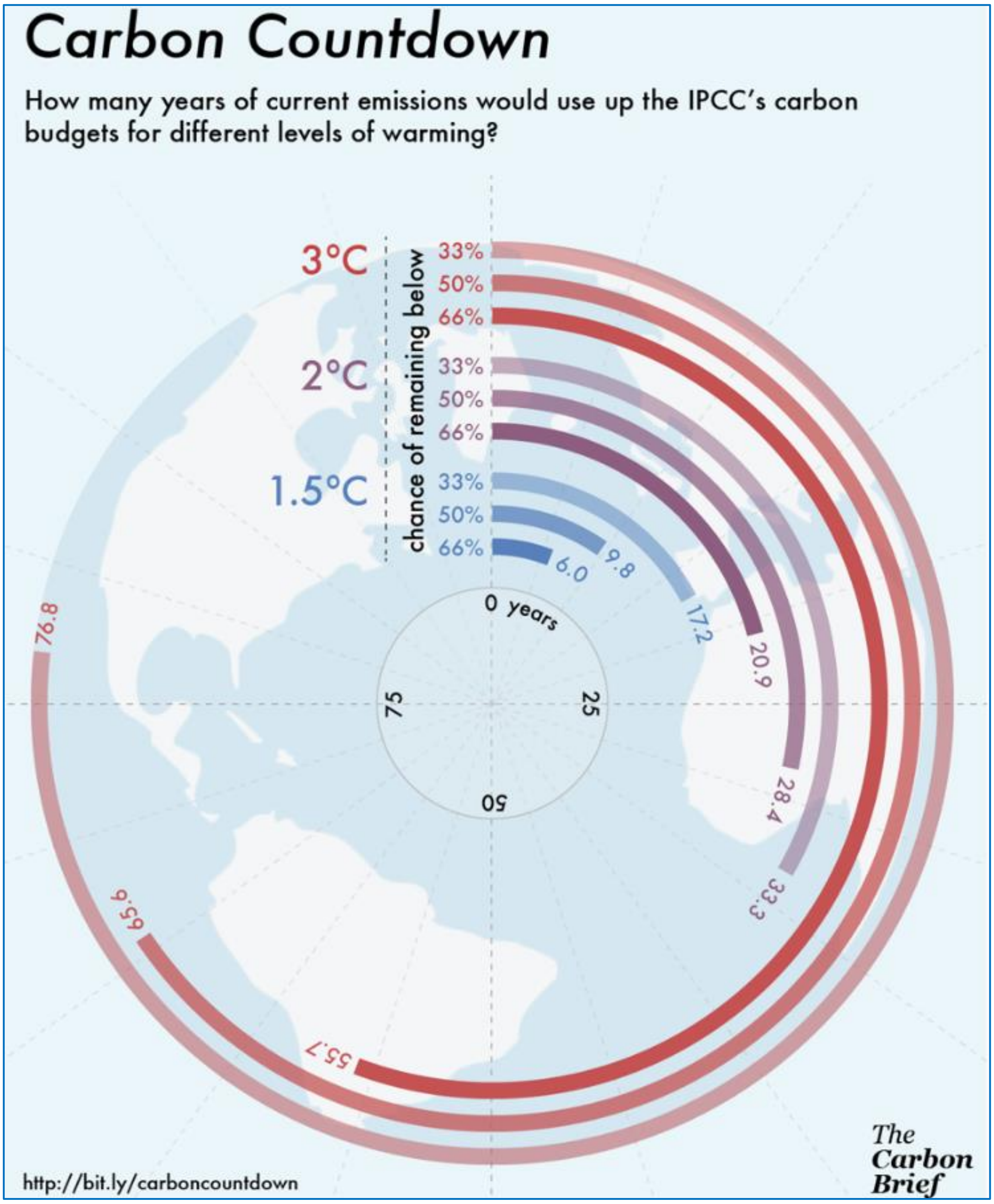
"… keeping to the preferred target [of global warming] of 1.5ºC above pre-industrial levels will mean rapid, far-reaching and unprecedented changes in all aspects of society are needed".

In the UK, the future ban on the sale of cars and vans, powered solely by petrol and diesel, is also partly a consequence of legal challenges to the government. The date currently set for the UK ban is 2040 although there is pressure to bring this forward to 2032. From China (2040) to Norway (2025) and many jurisdictions in between, similar dates have been passed into national law and some cities, which suffer particularly bad pollution, have earlier dates. In most countries, cars that use the ICE as part of a hybrid power train, will initially be exempt.

Are these dates consistent with best estimates of global warming by climate science?

Well, looking at the 2016 chart on the following page, the answer to that question seems to be "barely"! To keep global warming below 1.5ºC, with a 66% level of confidence, we can only continue to emit CO_2 at the current level until 2022. (ie 6 years beyond the date of the 2016 data). 2036 would be the equivalent date for a 2ºC increase. Given the global forecast for 2018 CO_2 emissions is likely to be an all-time high and the forecast of world oil production shows no decline until at least the end of 2020 – see Annex - there is not a lot of scope for optimism.

Battery powered electric vehicles and hybrids of ICE and battery electric are envisaged to be the immediate future, displacing the cars and vans powered solely by the ICE. Purely electric vehicles do not come without some well-known limitations such as range anxiety and limited charging infrastructure, not to mention concern over adequate capacity within the UK generation network. Furthermore, the CO_2 displacement only occurs if the recharging infrastructure is based on renewable energy: nuclear, wind, solar, tidal, wave, hydro or biomass, albeit displacing the location of the pollution from city centre to the site of generation.



It is difficult to see the hybrid vehicle – either plug-in or range-extended - as anything but a stop-gap measure. The weight penalty associated with carrying two power sources, electric motor(s) and ICE, on a single vehicle seems far from ideal.

What lies beyond the battery electric and hybrid era?

Hydrogen fuel cells have been under development for many years but, currently, the technology is still expensive in comparison with battery technology.

A fuel cell is an electrochemical, energy conversion device. It converts the chemicals hydrogen and oxygen into water, and in the process, it produces electricity. Electricity can be produced constantly if the flow of hydrogen and oxygen (from the air) continues.

Hydrogen production, for example through electrolysis of water, requires energy and unless this is derived from renewable sources, the overall CO_2 production associated with hydrogen propulsion may not be as little as first appears.

Technical challenges include:

- safe storage of hydrogen in the car. Compressed hydrogen gas – at a few hundred bar - rather than liquid hydrogen, is likely to be stored in carbon-fibre reinforced tanks
- production, distribution (99% of the transported load comprises the weight of the delivery vehicle) and storage infrastructure for hydrogen
- reliable use in cold weather
- reduction in cost through minimising the use of the expensive platinum catalyst.

Non-technical, societal changes may also provide part of the solution to the negative impact of the ICE. Driven by cost of ownership and increased congestion, even of electric and hybrid vehicles with partial or complete autonomy, the perception of a car as a status symbol may wither. Less personal ownership and more rent-on-demand services from fleets of battery or fuel cell electric vehicles, with the vehicle chosen to suit the journey and planned use, may become the norm, especially in busy cities.

So, in summary:

- the sale of new cars and LCVs powered solely by an ICE will be banned in most developed countries before 2040
- by that time, most new cars and LCVs will use battery electric or hybrid power sources
- the ICE will have been relegated to a diminishing support role in hybrid vehicles: its 150-year history will be coming to an end
- hydrogen fuel cells to power electric cars, LCVs and public transport are likely to be the first choice in urban areas
- reduced dependency on fossil fuels, specifically oil, will ensure that those reserves that are extracted are used for the medicinal, industrial and domestic uses for which there are few alternatives – rather than burn it.

The Internal Combustion Engine – The Future

Now

Diesel: better economy, than petrol, hence better for minimising CO_2 emissions. Concern over NO_x and particulates.

Petrol: improving economy, still higher CO_2 emissions, than diesel. Lower NO_x and particulates.

Quote from Dept for Transport, Vehicle Licensing Statistics, Q2 2018: "Average CO_2 emissions of new cars continue to increase. The average CO_2 emissions from cars registered for the first time in 2018 Q2 was 1.9% higher than in 2017 Q2, to an average figure of 124 g/km. Average CO_2 emissions from new cars have steadily fallen since records began in 2003, only starting to rise from mid-2016 onwards".

And this is why:

New car sales in UK in 2012: 50.5% diesel, 48.1% petrol
New car sales in UK in 2017: 42% diesel, 53.3% petrol

2020 - 2040

Legislation in UK will ban new cars powered solely by Diesel or Petrol from 2040. Other countries are earlier.

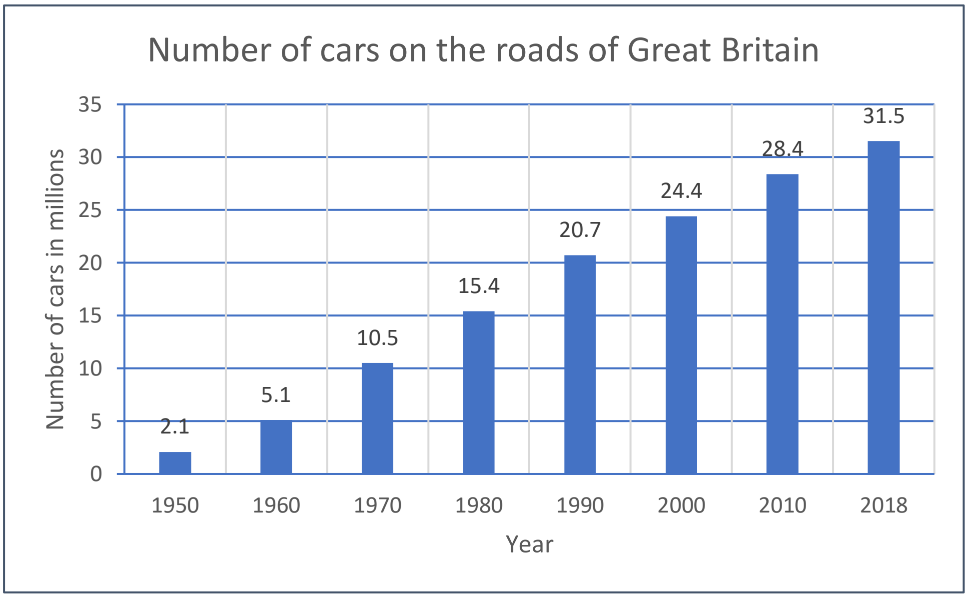
2030 and beyond

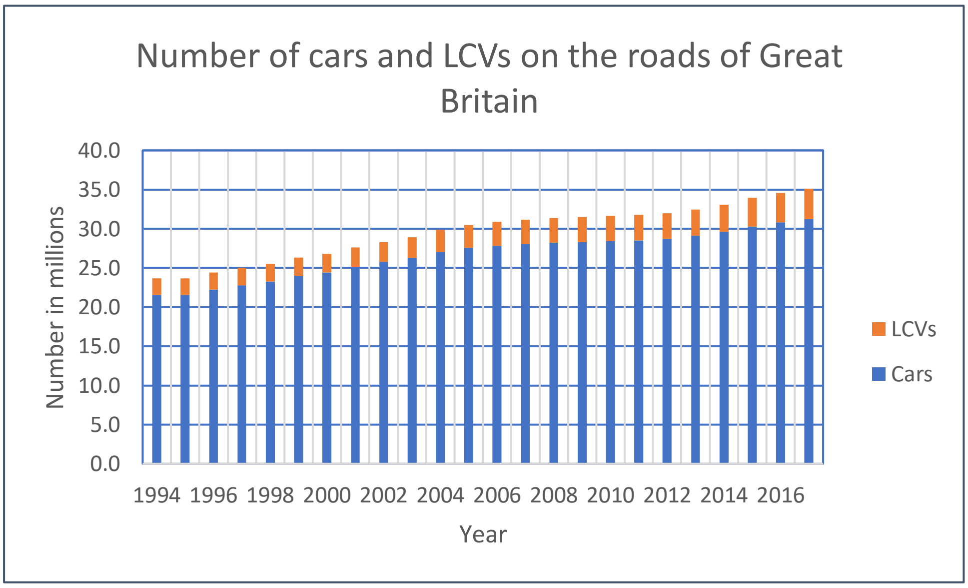
Hybrid, plug-in hybrid, range extended electric cars and purely electric will dominate new car production from 2030

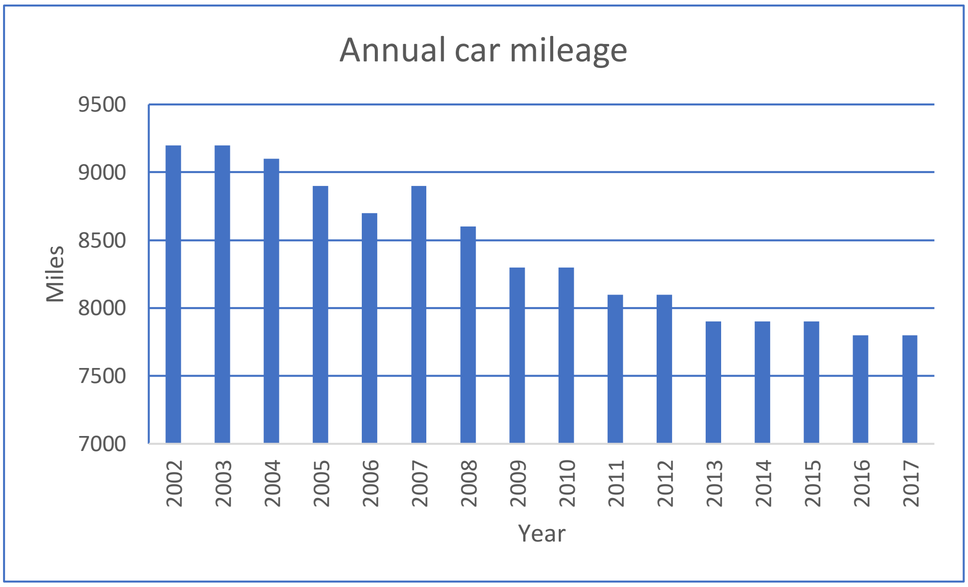
Issues with ***purely electric*** cars will include availability of public charging infrastructure and charging time.
Issues with ***hybrid*** cars include the 'dead weight' of effectively carrying two engines.
Issues with ***all*** battery powered cars will include availability of scarce materials such as lithium and cobalt

Some of these issues will be overcome by use of hydrogen fuel cells to generate electricity.

Annex: Supporting Information






Annual car mileage
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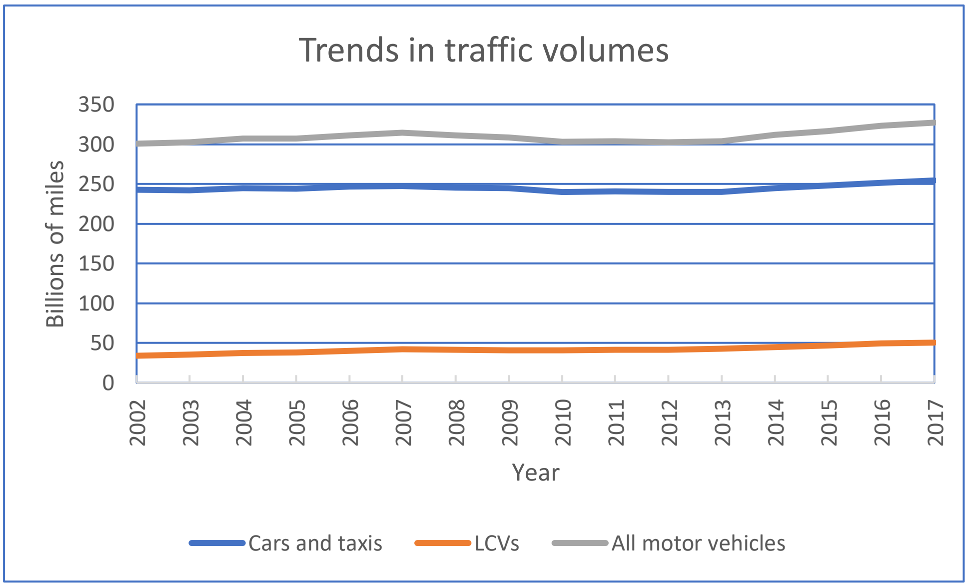
Trends in traffic volumes
350
300
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Billions of miles
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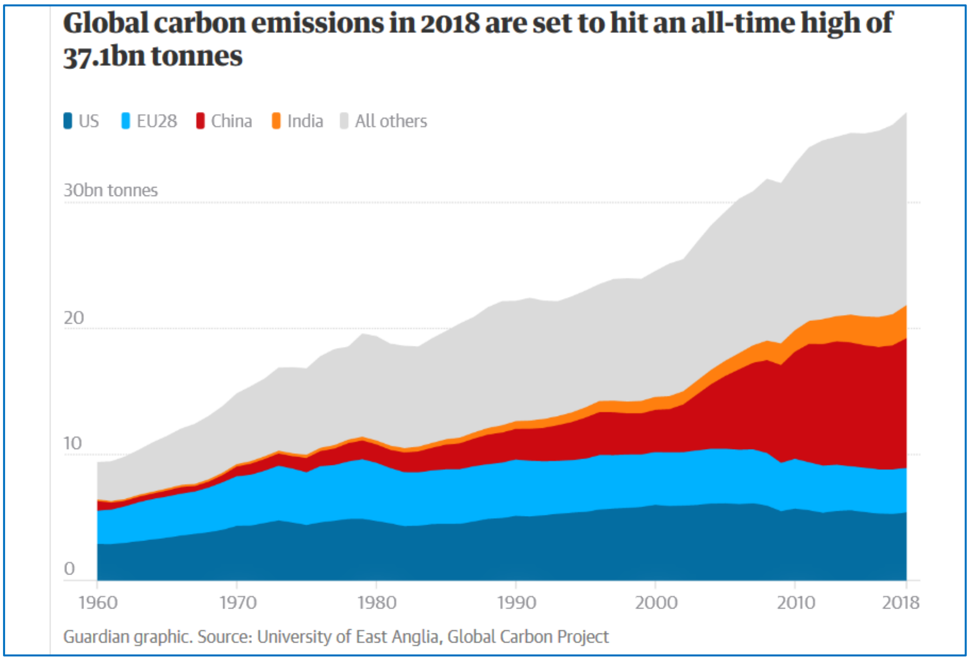
Cars and taxis
LCVs
All motor vehicles


Global carbon emissions in 2018 are set to hit an all-time high of 37.1bn tonnes
US
EU28
China
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All others
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1960
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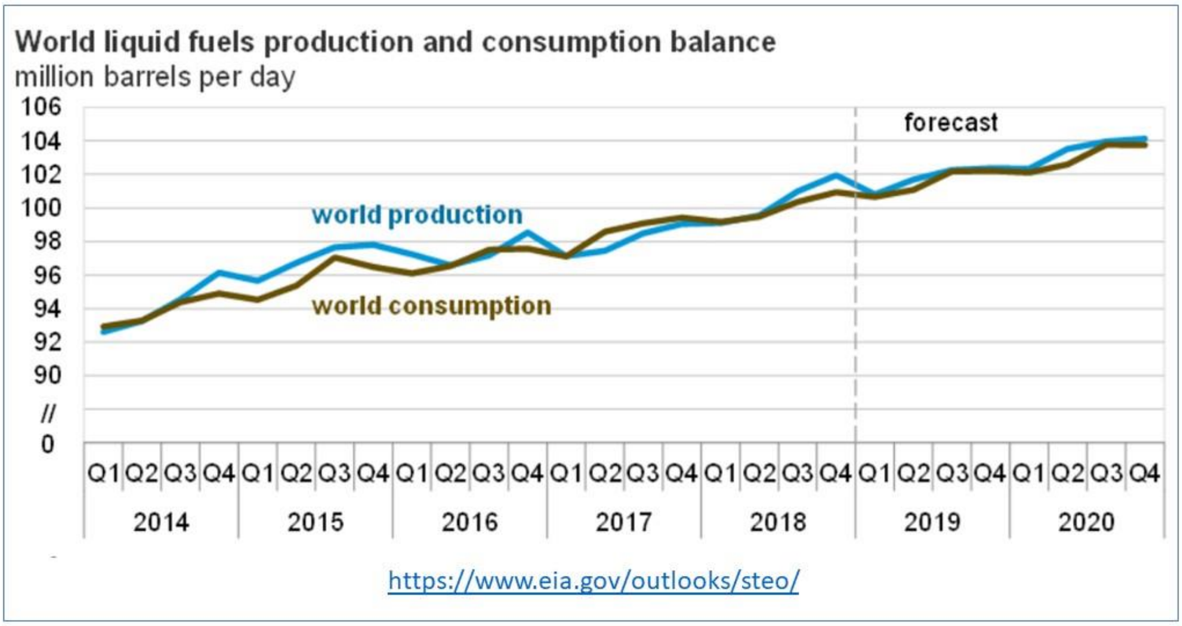
Guardian graphic. Source: University of East Anglia, Global Carbon Project


World liquid fuels production and consumption balance
million barrels per day
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104
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forecast
world production
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https://www.eia.gov/outlooks/steo/