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Examining Hydrocarbon Fuels for Transport in a Decarbonised World

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Abstract

With rising average ambient temperatures, including the gradual melting of the icecaps, the occurrence of global warming is demonstrable. It is currently being addressed in the UK by energy conservation and decarbonisation, part of which is the use of renewables, nuclear generation facilities, and low/ zero carbon fuels such as hydrogen. A comparison of energy use between trains and road vehicles is made. Decarbonisation of trains is comparatively straightforward and is progressing in the UK albeit slowly with the use of electric trains on high density and/ or high speed routes. Use of high speed routes permits reduction of aircraft use on short flights. For minor train routes hydrogen as a fuel is practicable. The use of EV is better for small road vehicles with hybrids for vans and light trucks being suggested. The use of diesel fuels for HGV is recommended and the justification for this is outlined. Also presented for the UK, is the estimated emissions from combustion engines. These have been successfully reduced to the point that brake and tyre emissions have become a significant fraction of reported particulate emissions' values.

Keywords: CO2e, emissions, electrification, fuel cell, hydrogen, HGV, high speed trains.

1 Introduction

Global warming is being addressed in many countries by energy conservation and decarbonisation. Bloomberg estimates that Europe must spend US$ 32 billion to achieve carbon nett zero by year 2050 [01]. However, in the short term in the EU, natural gas will be needed in quantity with liquid hydrocarbons in declining demand. For the UK, extracting indigenous hydrocarbons for fuels in controlled quantities, provides energy security, tax revenues, supports infrastructure development and if this infrastructure is manufactured within the UK, provides employment. Through the latter's taxation, further sums are injected into the economy.

Even if carbon dioxide release is deemed non-critical, other combustion emissions such as CH_4, PM_{10}, SOx, are known to be injurious to health thus optimising efficiency minimises heat rejection, saves revenue and is ecologically essential where localised heat rejection into lakes and rivers causes problems by enhancing algae formation. These difficulties can be addressed by a combination of energy economy, nuclear power, use of renewables and the ingenuity of hydrocarbon extraction and use.

Where use of hydrocarbons is needed, e.g. for OCGT and CCGT electricity generation stations which offer low cost, high thermal efficiency and reasonable ramp rate for generation of electricity, methane is the ideal fuel. This is available as the dominant component in natural gas and as UK gas from offshore gas fields becomes depleted, LNG is being imported from many sources including the USA. For electricity generation, gas imports are stabilising due to energy conservation and the gas's displacement by renewables. LNG is temporarily in deficit and to overcome this shortage, many new facilities are being built which is leading to a projected oversupply. Potentially a large fall in prices will occur, hence currently a large spread of future prices exists. Typical USA export to the UK is expected to be 173 MTe/year in 2030 and 625 – 685 MTe/year worldwide in 2040. Projected EU imports will grow from 55 MTe/year in 2023, to 57 MTe/year in 2024 and 65 MTe/year in 2025.

2 Transport Energy

2.1 Trains and Road Vehicles

Much energy within the western world is consumed by transport activities with shipping, road vehicles and trains dominant. Some countries such as the USA have a significant component from air activities. Here we are comparing trains and road vehicles, as the latter dominates energy consumption and emissions statistics. Addressing decarbonisation of this energy is complex, with electric drives being used for both trains and cars. Trains are simpler as they run on fixed routes and much external electrification of supply in western Europe has already been undertaken. Road vehicles have significant flexibility and electric vehicles (EV) usually employ batteries. Trams and trolley buses using fixed electrical supply have also been introduced. However, batteries for EV have low energy density compared with equivalent diesel units hence EV are usually heavier. For HGV which frequently operate near their road weight limit, the relative increase in fixed weight reduces payload and affects energy consumption.

Battery technology is under continuous development with experimental trucks and trains in operation and if long term results are successful both technically and economically, these will be introduced on a larger scale. As HGV contribute such a small fraction of the total quantity of carbon dioxide emissions in some countries, HGV in those countries should be excluded from the general decarbonisation process. They should continue to use diesel as a fuel for a future period which allows staggering/ delaying "decarbonisation" of freight movement and permits new technology to be developed allowing more complex options to be assessed. For trains the situation is more complex as we are close to the limit of current battery technology but fuels such as hydrogen are a realistic option as the safety statistics for trains are significantly better than for road vehicles.

2.2 Energy and Emissions (UK)

<u>Table 1 – Basic Energy and Emission Metrics for UK</u>

(a) Energy Units [02]
Energy Consumption = 108 GJ/capita
Electricity Generation = 16 GJ/capita

(b) Electricity Generation Source Breakdown [02]

Gas = 38.5 %	Wind = 26.8 %	Nuclear = 15.5 %
Biomass = 5.2 %	Coal = 1.5 %	Solar = 4.4 %
Imports = 5.5 %	Hydro = 1.8 %	Storage = 0.9 %

(c) Energy Use Breakdown for hydrocarbon fuels [03]

Petrol = $4.56 * 10^5$ TJ	Diesel = $9.17 * 10^5$ TJ
Jet Fuel = $4.02 * 10^5$ TJ	Gas Oil = $1.97 * 10^5$ TJ
Fuel Oil = $8.4 * 10^5$ TJ	Others = $3.47 * 10^5$ TJ
Refinery = $1.21 * 10^5$ TJ	

(d) Energy Vehicle Breakdown [03]

Cars & Taxis = $4.08 * 10^5$ TJ	Light Goods = $2.21 * 10^5$ TJ
HGV = $2.56 * 10^5$ TJ	Buses & Coaches = $3.5 * 10^5$ TJ

Road Freight = 32 %	Bus = 2 %
Rail = 2.6 %	Water = 2.3 %
Air = 1.6 %	Motorcycle = 0.5 %

(e) Frequently for greenhouse gas emissions, the term CO2e is employed for its description. This is the sum of the major greenhouse gases of which the carbon dioxide component dominates. For the UK, the split of CO2e between the various sectors is approximately [04]:

Transport = 26 %	Energy = 20 %
Business = 18 %	Agriculture = 11 %
Residential = 16 %	Remainder = 5 %
Waste Management = 4 %	

(f) CO2e Emissions for the Transport Sector (MTe) [04]

Cars & Taxis = 5.7 MTe	HGV = 2.1 MTe
Vans = 1.8 MTe	Shipping = 5 MTe
Buses = 3 MTe	Others = 5 MTe
Inter. shipping = 6 MTe	Inter. aviation = 13 MTe

2.3 Energy for Trains

The estimated total energy consumption values for the UK are 7.32 EJ for 2022, EU are 58.1 EJ and the World are 604 EJ. Their rail component used for recent years is given in Ref [05]. Table 2 shows the energy and emissions for the UK only for electricity and diesel fuel drivers [06].

Table 2: Energy Consumption and Emissions for trains (UK)

(a) Passenger Trains

Year ending April	2020	2021	2022	2023
Electricity Energy (GJ)	15.1	13.2	13.3	13.1
CO2e (kTe)	1 087	868	795	717
CO2e (gm/km)	442	425	358	
Diesel Energy (GJ)	16.9	12.6	13.9	14.1
CO2e (kTe)	1 313	977	1 080	1 061
CO2e (gm/km)	1 382	1 422	1 400	

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(b) Freight Trains

Year ending April	2020	2021	2022	2023
Electricity Energy (GJ)	0.25	0.23	0.23	0.21
CO2e (kTe)	18	15	14	15
CO2e (gm/km)	301	251	211	
Diesel Energy (GJ)	6.1	5.4	5.9	5.7
CO2e (kTe)	475	422	443	419
CO2e (gm/km)	669	648	598	

2.4 Energy for Road Vehicles

Table 3 shows the total energy consumed by road transport with associated carbon dioxide emissions [07]. The carbon dioxide emissions from road transport and the HGV component are also stated and the relative UK component is not high. It is not suggested here that HGV exemption from decarbonisation fuel change is a universal panacea nor that it should go on indefinitely especially as carbon dioxide emissions are large for HGV in countries such as USA. HGV emissions in the USA, both in absolute terms as well as a percentage fraction are high, and they compose a smaller fraction of vehicle units compared with cars. HGV however tend to be driven longer distances than cars. Cars represent a very large fraction of many economies and are ideal for situations where comparatively short journeys occur. Therefore, EV are suitable here as their battery capacity and range does not automatically need to be large. For long journeys where charging facilities are inadequate or unreliable, the use of hybrids must be considered. together with means to ensure that preferential battery use occurs. Hybrids have an on-board power reserve in the liquid fuel which is useful when / where inclement or adverse weather conditions such as heavy snow and/ or traffic congestion can be expected or any times where fuel consumption is expected to be abnormally high.

The maximum all up weight of road vehicles depends on factors such as permissible axle load and all up weight. Though batteries have higher weights than their range equivalent hydrocarbon units, the electric motor plus its transmission weight is frequently less than the weight of a diesel engine plus its automatic transmission which partially compensates for the energy load carried. The latest generation of long distance HGV have high welfare loads such as HVAC and ICE and these must be considered when comparing overall energy needs.

There are also unique problems associated with EV which have large batteries and relatively high energy density, including the availability of suitable materials of construction and the infrequent but nonetheless important issue of battery fires [08]. Frequency of fires is related to issues which usually only occurs with the extremes of transport such as electrical battery assisted bicycles and hybrid powered buses. Long distance battery EV HGV will face the same problems as hybrid buses due to restrictions on space or weight which will impact their range, especially if they need to stay within restrictive weight limits.

When considering the decarbonisation of freight transport there are many factors to be considered. Smaller engines on HGV may be more economical in terms of energy use but issues of handling and safety can arise. This may be route sensitive like trains. For many engine suppliers, the maximum power output of their diesel engine range significantly exceeds that of their gasoline engine models making larger engine comparisons difficult. For one supplier, their large diesel engine was 560 kW compared with 240 kW for their large gasoline engine. Fuel consumption of HGV in operation can vary markedly and this can make large changes in emissions. A study in Scotland for a fleet of HGV, including 44 Te articulated vehicles, which went a combined distance of 11 250 000 km in one year, showed an estimated improvement in fuel consumption by introducing cab streamlining from 2.1 km/l to 2.3 km/l and this improved further with different driver training to 2.5 km/l [9]. This reduced the estimated carbon dioxide emissions from 14 000 Te to 12 900 Te then to 11 000 Te in the year. By careful route selection, a further 115 Te carbon dioxide was eliminated by minimising engine idling. This gave significant financial saving which at today's fuel costs would be some US$ 950 000 together with improved engine life and reduced maintenance costs.

Table 3 Overall Energy Consumption and Carbon Dioxide Emissions

Country	**USA**	**Canada**	**UK**	**EU**
Energy (EJ/an)	93	13.9	7.3	60.1
Components of Transport Fuels (EJ/an)				
Gasoline	16.3	1.48	0.60`	9.54
Diesel	7.86	1.20	1.21	2.66
Diesel HGV	5.60	1.16	0.26	0.43
CO2 Emissions (millions Te/annum)				
Total for Country:	4 700	527	338	2 728
Gasoline	1 154	105	42.5	677
Diesel	542	82.8	83.5	184
Diesel HGV	387	80	18	30
Percentage CO2 from HGV				
as % of Transport emissions	22.8	42.7	14.2	3.48
as % of Country emissions	23.0	15.2	5.3	11.1

2.5 Other Emissions excluding CO2

Hydrocarbon fuel engines have other emissions to carbon dioxide including NOx, CO, PMx. More crucially there is a significant difference between new engines and those from engines which have driven high mileages and/or many hours of operation [03]. Predicting the impact and cost of emissions on the environment is difficult and an early estimate is given in references, and it includes their wide confidence limits [10].

2.5.1 Particulates

$PM_{2.5}$, PM_{10} are particulates in products of combustion with PM_{10} dominant in engine exhausts. $PM_{2.5}$ is mentioned here as it is believed to be more harmful to humans but it is more plentiful in other sources.

In the UK, annual emissions of PM_{10} fell by 79% to 143.9 kTe between 1970 to 2021, before then increasing by 8% between 2021 and 2022. $PM_{2.5}$ emissions were 83.2 kTe in 2021. The road transport fraction of all PM_{10} emissions in 2021 was 12% of the overall PM_{10} figure. Exhaust PM emissions have decreased since 1996 by roughly 90%: other PM sources (e.g. brake dust) have fallen by roughly 10% of the PM_{10} + $PM_{2.5}$ figure [11].

2.5.2. Oxides of Nitrogen

NO is a dominant form of NOx emissions but can form into NO_2 in the atmosphere. Between 1970 and 1990 the emissions were roughly constant laying in the band 2.5 to 3.0 million tonne. After 1990 the emissions decreased almost linearly each year reaching 677 kTe in 2021 when the road transport component was roughly 180 kTe [13]. NOx is reduced by catalysts especially when used with additives, e.g. Adblue, to very low levels. The effectiveness of catalysts is temperature dependent and some indication of this is given in reference [14].

2.5.3. Methane

Methane is a potent greenhouse gas, and a significant quantity was released in leakage from the natural gas grid. Landfill sites are another major source. In 2020 Methane emissions were 13% of total GHG emissions and estimated at 52 MTe CO_2e [15]. Trace quantities of methane can be found in exhausts depending on the engine's operating conditions and these are readily oxidised by catalysts.

2.5.4. Oxides of Sulphur

SOx only occurs if sulphur compounds are in the fuel [16]. For road vehicles, the sulphur limit in diesel fuel has progressively reduced over recent years from 500 ppm (Euro II) to 50 ppm (Euro VI) with ultra-low sulphur fuels of 10 ppm being available now (year 2024) [17].

2.5.5. Carbon Monoxide

Carbon monoxide (CO) is a product of incomplete combustion from hydrocarbon fuels and exists in very limited quantity in HGV exhausts as these usually have diesel engines. Any CO there is easily oxidised to carbon dioxide with catalysts.

2.6. Tank Capacity for HGV

If it is essential to achieve 100% decarbonisation, a suitable fuel for road vehicles is hydrogen. Table 5 gives an indication of the full hydrogen tank weight for several storage pressures for a typical 40 Te truck. Many simplifying assumptions have been made to give identical range comparison and any solar panel boosts is excluded. The hydrogen requires energy to make and distribute. The 200 bar g pressure may not be realistic for road vehicles for safety reasons. The 50 bar g pressure is ideal, but the theoretical tank sizes are very large: multiple small units are needed to fit the space available.

The data for the equivalent diesel and gasoline trucks (full of fuel) to carry these loads is also included. Their range on high capacity tanks permits filling in the lowest cost regions saving both money and time for stops. This has produced an unofficial standardisation of tank capacity.

If the introduction of hydrogen is planned to become widespread, retaining diesel engines in HGV and subsequently replacing them with hydrogen IC engines will involve minimum change to the existing maintenance infrastructure and this can be upgraded as superior technology is introduced.

Table 5 HGV Tank Statistics for Range = 2 500 km

Hydrogen Pressure:	**50 bar g**	**100 bar g**	**200 bar g**
Tank Dia / Length (m)	4 off * 1.2 / 8	2 off * 1.2 / 8	2 off * 1.2 / 4.1
Weight (Te)	8.7	8.3	8.0

For hydrocarbon Fuel: Gasoline = 1.1 Te & **Diesel** = 1.0 Te

For a 44 Te articulated truck, the tractor plus trailer is roughly 19 Te giving a revenue generating payload of 25 Te. If a truck engine weighs 1 100 kg, its exhaust with all emissions reduction features weighs 120 kg plus gearbox and this is compared with an equivalent EV truck whose electric motor plus fuel cells weighs 2.6 Te, then the nett loss in payload is some 5 to 7 Te with a hydrogen system.

In terms of EV trucks and vehicles using batteries, the current generation of large EV articulated vehicles in California, USA, have batteries which weigh over 10 Te. The control systems and other necessary equipment weigh significantly less than their diesel engine equivalent but recharging these large vehicles is time consuming and frequent suitable charging points are not universally available.

2.7 Decarbonisation for Trains

The use of hydrogen with trains is well documented [06, 18, 19} The Coloradia iLint and the Hydroflex models are operational examples, and they have the same benefits as DMU in being comparatively independent of energy supply, refuelling at fixed remote locations. They employ fuel cells to produce electricity rather than internal combustion engines. Fuel cells produce minimal NOx as they operate at such low temperatures with unit values as given in Table 6 assuming natural gas as the fuel. Fuel cells using higher hydrocarbons exist and they also produce minimal undesirable emissions. To a first approximation the figure for NOx in Table 6 is applicable to a fuel cell operating on hydrogen

Table 6 Fuel Cell Operating on Natural Gas

NOx =	8 600 μ gm/MJ	SOx = 12.9 * 10^{-3} μ gm/MJ
Particulates =	1.29 * 10^{-3} μ gm/MJ	CO = 86 * 10^{-3} μ gm/MJ
Total H/C =	8.6 * 10^{-3} μ gm/MJ	

Many fuel cells produce waste heat which in some sizes is large and at sufficient temperatures to be used in combined cycle or CHP mode. Typical cells used with trains would use this heat for welfare purposes and the comparatively low temperature cells reject at 23 °C to 70 °C depending on cell load. This needs to be heat exchanged with the space to be heated. The quantity of heat available again depends on cell design and for the simpler units is typically 1.27 kWth per kWe of output. Unlike IC engines where significant albeit reduced heat is available at low loads, the available heat from a fuel cell at low load is very low and may need thermal support. Depending on service, IC engines may be preferable using hydrogen fuel, but their emissions will be significantly higher as these are combustion devices.

Both fuel cell powered EMU, and conventional DMU, are designed for comparatively short routes with regular stops. For some applications fuel cell EMU with auxiliary IC engines are realistic and may be necessary as fuel cells can need a long time to achieve full load - longer than IC engines. In addition, if hydrocarbon fuels are employed for the auxiliary device the latter's fuel carried will occupy minimal volume as it has a higher energy density.

For longer distance fast routes, electric trains are better both for passenger and freight and a typical freight model is in Fig 1. This employs 25 kV electricity supply via pantographs for most of its routes with diesel drives for local activity especially in freight yards. For fast passenger service, trains on routes such as HS1 and the future HS2 are well proven. For freight shunter activity, battery trains are under development but in the short term diesel units still work well.

3 Conclusions

A comparison between trains and long distance vehicles for decarbonisation has been made. For trains in the UK, electrification is the option for long distance routes and high capacity metropolitan lines. Hydrogen is an option for infrequently used routes and subject to further improvements, batteries are ideal for local applications. Other combustion fuels will be available in the future, and if steam boilers are used with steam turbines, may even help future refinery design. One example under design development is a converted former BR Class 60 diesel engine (conversion to steam) for freight applications.

Foe HGV, diesel should be retained as an interim fuel in the UK if only due to logistical problems associated with its replacement. Improved efficiency of diesel production is needed in the refineries of the future, and this will be associated with the projected changes in refined product demand. These upgrades will support diesel's retention.

For hydrogen, the question is cost (both fiscal and of energy for its production), and its widespread availability. Development work will always be needed on the components of hydrogen systems especially if the hydrogen economy evolves to the point of hydrogen's use in heavy industry, e.g. steel making. Already hydrogen grids exist in the USA and future ones are being developed in the EU.

Hydrogen fuelled systems for vehicles tend to be heavy as do large battery systems, and these impact the payloads despite the weight penalty associated with heavy modern diesel engines. In addition, from the high energy density of hydrocarbons, it is easier to accommodate the welfare loads associated with modern means of transport. Improvement in diesel and internal combustion engine design, together with improvement and development of steels, seals, valves, and other items for containment of high pressure hydrogen need continue.

All the above, point to the benefits of the high energy density of hydrocarbons when compared to other energy sources. Despite the necessity for decarbonisation brought about by global warming, selective use of hydrocarbons should be retained in countries such as the UK when their relative emissions are low such as with HGV.

If an efficient high speed train network with more than adequate capacity were to exist between the major population and industrial centres, then aircraft capacity can be reduced between these centres. This will reduce overall CO2e emissions and save fuel as with current technology, aircraft will usually be less energy efficient than equivalent surface transport.

Aircraft offer fast transport especially if their airports can be rapidly accessed. A realistic high speed train network would help eliminate the need for the extension of currently overcrowded airports so that they can concentrate on long distance air traffic. Low density routes which are not realistic with trains could still employ specialist aircraft.

References

[1] New Energy World (Energy Institute) May 2023 – Bloomberg

[2] ESO February 2023 (from 2022 data)

[3] Dept. Energy, Security and Net Zero, UK Energy in Brief, 2023.

[4] Gov. UK – Dept. of Transport, 2023

[5] "China's Iron Silk Road", Lloyd, S.A. and Atteridge, W.J., RAILWAYS 2022, Edited by J. Pombo. Proceedings of the Fifth International Conference on Railway Technology: Research, Development and Maintenance, Civil-Comp. Conference, Vol. 1, Paper 23.4. Civil-Comp Press, Edinburgh, UK 2022, DOI: 10.4203/ccc.1.23.4.

[6] Office for Rail and Road (Gov UK), Nov 2023

[7] HGV Check

[8] "Britain's e-bus ticking time bomb", Darren Boyle, 2 Mar 2024. Daily Mail On-line Live.

[9] "Freight Savings in a Scottish Haulage Fleet"; Ian Mitchell. Dept of Transport and Scottish Government, 2010.

[10] "Air Quality Appraisal Damage Cost Guidance". Updated 2021. Dept. of Environment and Rural Affairs.

[11] "Emissions of Air Pollutants in the UK – Particulate Matter (PM10 and PM2.5)". Dept. for Environment, Food & Rural Affairs, Gov.UK. Updated 12 Dec 2023

[12] "Emission of Air Pollutants in the UK – Nitrogen Oxides (NOx)". Dept. for Environment, Food & Rural Affairs, Gov.UK. Updated 12 Dec 2023

[13] "Reduction of NOx Pollution Emissions from Gas Turbines on North Sea Platforms"; Lloyd, S.A.; Energy World, April 1992, 17.

[14] "United Kingdom Methane Memorandum" – Dept. for Business, Energy & Industrial Strategy with Dept. for Energy Security & Net Zero, Gov.UK. 19 Nov 2023.

[15] "Emissions of Air Pollutants in the UK – Sulphur Dioxide (SO2)". Dept. for Environment & Rural Affairs, Gov.UK. Updated Dec 2023.

[16] "Diesel Sulfur content impact on Euro VI soot free vehicles: Consideration for emerging markets". Yihao Xie, Francisco Posada, Ray Minjares. Working Paper 2020-11. The International Council on Clean Transportation, 2020.

[17] "Thoughts on Use of Hydrogen to Power Railway Trains"; Atteridge, W.J. and Lloyd, S.A. Proc I Mech E Part A: J Power and Energy Part A, 1 – 11, 2020. DOI: 10.1177/0957650920912086.

[18] "Hydrogen as a Rail Mass Transit Fuel"; Lloyd, S.A., Lloyd, B.D. and Atteridge, W.J.; Chapter 5 of Railway Transport Planning and Management, edited by de Luca, S., Di Pace, R., Fiori, C., DOI: 10.5772/IntecOpen.99553.