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New Thoughts on China's Iron Silk Road

S. Lloyd[1,2,3] and W. Atteridge[4,5]

[1]Energy Institute, London, United Kingdom
[2]Institution of Mechanical Engineers, London, United Kingdom
[3]Spindeep Limited, Spindeep Limited, London, United Kingdom
[4]Institute of Marine Engineering, Science & Technology, London, United Kingdom
[5]Brookson 5308G Limited, Shavington, Crewe, United Kingdom

Abstract

The East West rail route from China to Western Europe provides an intermediate level of energy cost, fiscal cost, and time of transit for goods between these continents with the relevant performance parameters sitting between those of shipping and air freight. Transit times have been reduced sufficiently to permit certain time sensitive goods to be carried. These metrics are developed further to give initial guidance on decarbonisation and reduction in other combustion emissions. An outline comparison between ships and trains for the extremities is presented for emissions and energy used.

There are rail gauge changes on the route which can present difficulties, but automatic wheel set adjustments exist. This process is satisfactory at low speeds, but a question mark exists for high speed use. Time lost at border crossings can be exacerbated if there is conflict between the nation states near the route. An alternative to the traditional route through Russia using a route through Kazakhstan and crossing the Caspian Sea is presented including many metrics. As distances are great, parameters included are relative fuel tank sizing for several fuels, outline of track capital costs and some comparisons with shipping.

Keywords: Caspian Sea, decarbonisation, diesel engine, emissions, fuel cells, Kazakhstan.

1 Introduction

The original Silk Roads were a network of trade routes between East and West, known for the transport of high value goods such as silks and spices [01,02]. One route went south to Isfahan, Persia. The original network of routes started during the Han Dynasty in China (130 BCE) and ceased operation in 1453 CE when the Ottoman empire closed it down. Today it is a rail route which extends from China's eastern seaboard to western Europe, and having been expanded over the past ten years, it is seen as a complement as well as competition to existing sea and air transport modes. The transits in each direction are approximately equal and substantial electrification of parts of the route exist already, despite having diesel price subsidies in China. The fuel in China is generally of a high quality hence maximising the train's range on the engine's tanks is important.

Metrics for energy efficiency in the freight sector are well documented [03] and shipping is usually the most efficient transport means but the shortest distance east to west is overland. Pipelines are efficient but only handle fluids and are included here for comparison only. Rail is discussed here in comparison with the other transport methods but for the rail link itself, many logistic problems exist such as the different rail track gauge between Russia and most European countries. Though transferring containers between flat-bed cars to suit rail gauge is an option, as is automatic wheel gauge change, with traffic density increasing, a more flexible, timely solution must be used. For certain long sections, e.g. through Kazakhstan, new rail links are being constructed but their capital investment is high; they still need to cross the Caspian Sea. A large investment in Caspian ports is underway which will partially solve the problems, but using ports is invariably slow compared to a direct trans-Caspian link. In addition, some decarbonisation of the existing rail route is being undertaken if only by the increased use of electric trains [04].

2 Methods

2.1 Transport Metrics

Table 1 gives typical values of important transport parameters in terms of NOx, carbon dioxide and other undesirable emissions produced for trains, shipping, and other regular transport means. Classic transport efficiency parameters such as Te*km/l for this route are given by Atteridge & Lloyd [04]. Aircraft are not discussed as their main attribute is speed of movement and relatively low fixed investment both of machine and land facilities. For most sea vessels, their fuel consumption increases dramatically over 14 knots, and this is reflected in the differences between comparatively slow, low value oil movement in bulk quantities to high value, fast container ships. Influence on future numbers will include implementation of IMO efforts to increase ship efficiency and reduce emissions. The parameters for shorter distances and bulk liquids are presented in Atteridge and Lloyd [05,06].

For pipelines, the numbers vary between capital and running costs as increases in pipeline diameter result in energy savings hence emissions reduction. The first step(s) in decarbonisation are energy use minimisation. Unless canals are available, freight transport options for small / discrete quantities of liquids and most other goods are essentially by road and rail with the former providing greater flexibility of route. Fast road transport routes, e.g. motorways, usually require greater land space than rail, except perhaps at the terminuses. Trucks are frequently more efficient in time and fuel used up to about 200 km range helped by their flexibility. This range may adjust a little with the improvements of battery / electric / green fuel vehicles and their wider transport fleet expansion.

Item	Te*km / **gm** NOx	Te*km / kg CO2	Te*km / kg CO2e
Trains	48	84	82
Container Ship	14	325	318
ULCC	25	568	557
VLCC	29.8	383	375
Pipeline	240	403	395
Trucks	17	30	29

Table 1: Freight Transport Metrics by Several Methods

For scoping the costs for infrastructure for trains, indicative unit metrics are presented in Table 2. Track and its electrification is given separately.

UK (Track)	$15 to 25 million /single track km (congested areas ~ 100 + million)
Europe	$17.5 million /single track km
UK & Europe (Electrification)	$1.1 to 2.8 million/single track km
France	$1.5 million /single track km
USA	$1.35 million / single track km

Table 2: Indicative/Approximate Costs for Track and Electrification (US$)

2.2 Ship's Fuel Needs

Ship designations are in Table 3 and Table 4 [07]. For container ships, the limit of "economies of scale" is due to technology constraints rather than size limitations. The draft of a fully laden VLCC tanker exceeds the anticipated draft of the next generation of ULCS and both usually employ common routes though the associated greater widths of ULCS may impose some route restrictions.

One problem with designing very large vessels is the availability of high output, compact, low maintenance, high efficiency engines. Diesel engines are fuel efficient, low maintenance low speed units, but are heavy, large and their noise is difficult to supress. Gas turbines have high outputs, are compact but have poor efficiency at part load unless special engines e.g. those using ICR (e.g. by Rolls-Royce) are installed. Most marine gas turbines and newer diesel engines demand distillate fuels though the older traditional ones burned heavy marine oils [08,09]. Efforts to improve shipping efficiency are ongoing such as bubble drag reduction which is being trialled on the container ship MSC Tessa which aims for a 3% to 4% improvement in fuel consumption by reducing hull drag. The steady growth with time in container ship capacity is shown in Table 5 illustrating economies of scale.

Categories	No. Containers	Abbreviations.
Ultra large container ships	> 20 000	ULCS
Very Large container ships	10 000 to 20 000	VLCS
New Panamax	10 000 to 14 500	NPan
Port Panamax	5 101 to 10 000	PPan
Panamax	3 101 to 5 100	Pan
Feedermax	1 101 to 3 000	Fmax
Small Feeder	< 1 000	SFeed

Table 3: Container Ship Designation

Categories	DWT Capacity	BBL Capacity	Abbreviation
Ultra Large Crude Carrier	320 000 +	3 million	ULCC
Very Large Crude Carrier	200 – 320 000	2 million	VLCC
Suezmax	120 – 200 000	1 million	SCmax
Alframax	80 –120 000	750 000	ACmax
Panamax	60 – 80 000	500 000	PCmax
Handy Size	10 – 60 000	< 345 000	HSCmax
Coastal Range		< 140 000	CBCmax
Inland Waterway		< 29 500	IWCmax

Table 4: Crude Tanker Designation

A container ship with 24 000 TEU would consume approx. 780 m^3 of marine fuel per day for a 21 to 26 day transit between Shanghai and London via the Suez Canal within a speed range of 20 to 25 knots. The route via the canal is approx. 23 300 km and via the Cape of Good Hope is approx. 28 500 km. The typical train route length avoiding passage through Russia is approx. 12 900 km (+ ferry 440 km).

Vessel	Capacity (TEU)	Year
MSC Irena	24 436	2023
MSC Tessa	24 116	2023
EVER A Lot	24 004	2022
EVER ACE	23 992	2021
MOL Triumph	20 170	2017

Table 5: Large Container Ships

2.3 Train Fuel Needs

Trains do not have the flexibility of ships. Their route is fixed. Energy, water and utility supply is usually determined after the route selection but in urban and desert locations the reverse may be more appropriate. For the route comparisons selected here, trains carrying 100 to 200 TEU are used with a rail route length of 12 900 km. At an average speed of 95 km/hr (assuming minimum delays at border crossings), the journey will take 6 to 7 days. This leaves a maximum potential of 15 days to be saved from an average transit time for ships of 24 days. For the more realistic average speed of 65 km/hr, journey times will be approx. 8 to 9 days as delays at border crossings can be severe. However, in 2020 a significantly shorter express route between Germany and China through Russia was inaugurated with a length of 9 400 km and a journey transit time of 10 to 12 days [10]. Its operation however has temporarily ceased due to geopolitical events in eastern Europe.

Fuel tank capacity for the large diesel engines on trains ranges from 7 500 litres to 15 000 litres but it is possible to use additional dedicated wagons to give extended range. For journeys such as this there will be several engines, possibly using different power sources – alternatively multi-fuel hybrids can be employed. Differential fuel costs are another consideration as to route used and engines selected, but as decarbonisation evolves, hydrogen is one possibility especially where electricity cannot be provided. Where new rail track is laid, route preparation itself is a major cost and broadening this route to accommodate a pipeline becomes a possibility: typical track costs only have been given in Table 2. A pipeline, if desired, can be laid near the track to minimise overall costs but its distance from the track would depend on many factors including safety considerations. Multiple merchant telecoms cables can be introduced trackside to produce a separate revenue stream as well as satisfying the railway's needs.

When making energy comparisons between trains and ships, one large container ship is roughly equivalent to 160 trains with the sum of trains' fuel consumption being 16 – 19 000 cubic meters of diesel equivalent compared with the ship consuming some 18 500 cubic meters of fuel if going via the Suez Canal or 20 000 cubic meters if travelling via the Cape of Good Hope. Significant electrification has already been introduced thereby reducing total emissions, but these benefits depend on the method of electricity generation and the number of generating stations. Fuel in tanks has minimal losses under normal circumstances but for an AC transmission system when estimating energy needs, losses are 2.0 to 4.0 % for transmission itself with an additional 1.0 to 2.0% for transformers.

2.4 Other Fuels and Energy Sources

Several possible fuels are available for trains with internal combustion engines. LPG has been employed and can be stored at essentially atmospheric conditions. LNG is an alternative fuel, but it must be stored at 160 K which involves a cooling load. Both liquified gases produce less emissions than diesel fuels especially when used with exhaust catalysts. These fuels have been used with fuel cells but still produce carbon dioxide though total emissions are reduced. Hydrogen with fuel cells gives negligeable emissions but with IC engines they are somewhat higher: carbon emissions are zero.

Ammonia has been examined extensively as another fuel option. It has a narrow flammability range (15 to 28%) [11], low calorific value and reaction rate but when mixed with small quantities of hydrogen, reaction rates improve [12,13]. Ammonia is toxic and unless controlled carefully when burned, can produce quantities of NOx.

It is usually stored as a liquid at atmospheric pressure and 240 K (– 33 °C) temperature. It must be carefully handled using fully trained personnel as exposure via inhalation causes panic symptoms and continuous exposure, if forcibly maintained, is fatal. Several engine suppliers are working to develop engines that overcome the difficulties with ammonia fuel.

The shipping company Maersk anticipates that three fuels will be used for shipping in the medium term until full decarbonisation occurs later this century and these are ammonia, alcohol, and biogas. The far eastern company MISC wants to introduce an ammonia fuelled tanker soon [14]. The energy density of hydrocarbons is significantly higher than other fuel options on a volume basis which increases the necessary fuel tank size. This is an important factor when converting vessels. The extra mass and volume can impact payload. Comparisons of several possible fuels is given in Table 6 with marine fuel being unity.

Fuel	MGO	LNG	DME	Biodiesel	CH_3OH	NH_3	L H_2	G H_2
Storage (° K)	288	105	288	288	288	240	23	288
Tank Size	1.0	2.3	1.8	1.0	2.3	4.1	4.6	235
LHV (MJ/kg)	44.3	48.6	28.9	43.9	19.9	18.8	118	120
CO_2 (kg/GJ)	77.8	55.7	49.1	74.1	69.1	<------ Zero ----- >		

Table 6: Relative Tank Sizes, Heating Values and Specific CO2 Values

For gas turbines used with ammonia fuels, it has been proposed that the ammonia is stored and delivered as a liquid which, on arrival, is locally cracked to produce hydrogen. Its transfer technology is simpler and the storage cost for ammonia is somewhat lower at roughly 1.0 US$ /kg compared to 30 US $ /kg for liquid hydrogen and more than 1 000 US$/kg for gaseous hydrogen depending on storage pressure. Burning the ammonia cracked to hydrogen has a lower propensity to produce NOx. However on this east-west route for trains with IC engines, an annual equivalent of 1.5 million cubic meters of diesel would be equivalent to 2.9 million tonnes of ammonia but as ammonia fuelled engines are usually slightly less fuel efficient than their diesel counterpart, approx. 3.3 million tonne of ammonia would be required.

Local passenger trains using hydrogen fuel cells have entered service in Europe with the hydrogen carried in pressure vessels (stored at 350 bar g) above the passengers [15,16] though here any larger quantities needed would be in purpose-built separately attached wagons. These when depleted would be exchanged at pre-determined stops. The Iron Silk Route is not an ideal first application for hydrogen as distances between refuelling stops can be large even though the longest distance travelled by a fuel cell train without refuelling is 2 800 + km [17,18]. This was achieved with the Stadler FLIRT H2, essentially a commuter train. If hydrogen delivery by pipeline is impracticable, the use of local electrolysers can be examined assuming ample water and renewable electricity supply exists. For freight trains, especially those travelling long distances, large fuel cells with associated hydrogen storage are needed. Suitable cells are under development for the large trucks used in open cast mines and one example is a 2.0 MWe unit on a platinum mine in South Africa [19,20]. If successfully proven there, these cells will have an application for long distance rail engines.

Battery powered trains using industrial scale batteries are another development. High power shunters in locations such as California are being tested already but for long distances the batteries need to be mounted on wagons behind the engine. Exchanging battery wagon(s) at intermediate stops and locally charging them using solar power or other renewable generated electricity is practicable. The development of ever larger wind turbines is ongoing. Long distance trains have powerful engines with nominal power outputs of 2.5 MW to 4.5 MW and research in decarbonising them by using batteries is being undertaken in several countries [21]. For trains of this size and power needs, regenerative braking becomes an attractive possibility.

2.5 The Future

A route through Kazakhstan and transit across the central portion of the Caspian Sea is attractive and would avoid Russian territorial waters to the North and Iranian territorial waters to the south. The Caspian Sea, a well-known barrier to east-west journeys, is an inland sea with many rivers flowing into it including the Volga, Ural, and Terek. Main water outflow is by evaporation, and this is presently high, made worse by global warming. Its salinity is 1.2%. The Caspian's length is 1 200 km, with a varying width which is roughly 320 km near one proposed train crossing point. Trans Caspian pipelines and electrical interconnectors may be developed for it in the future. The water depth in the northern part, which is heavily polluted, is only 5 to 6 metres, but the depth increases as one progresses south being 150 metres in the centre which is comparable to parts of the North Sea. The water depth increases further towards Iran being over 1 000 metres at its deepest part. The future transit options which include ferry, bridge and tunnel or a combination of all, is currently served by ferries. Low air temperatures exist in winter with water ways freezing and this can stop winter movements in the supply river systems. There is an air temperature gradient over the geographical plan of the sea being some – 10 °C in the North and + 10 °C in the South in winter, and average temperatures of 25 °C rising to a peak of + 44 °C in summer.

Long bridges and tunnels have already been built worldwide and some are noted in Table 7 [22]. The narrowest shore-to-shore point of the Caspian is some 210 km but 250 km should be considered for evaluations. Ferries are usually the lowest capital cost option for most sea crossings but for high traffic density routes where time is important, tunnels and bridges become attractive. Motive power for the external options is flexible but the tunnel option will use electricity, most probably with pantographs. Emergency diesel engines as used in mines could support elimination of an emergency tunnel [23] and English Channel Tunnel and other tunnel statistics will help in the making any engineering decisions.

1	Danyang-Kunshan Grand Bridge, China (Yangtze River Delta)	165 km
2	Changhua-Kaohsiung Viaduct, China (earthquake zone)	157 km
3	Tianjin Grand Bridge, China	114 km
4	Kila-Yaitu Viaduct, Japan	114 km
5	Cangde Grand Bridge, China	106 km

Table 7a: Long Bridges and Tunnels

6	Gotthard Tunnel, Switzerland	57 km
7	Tsuguru Strait, Hokkaido-Honshu, Japan	54 km
8	Channel Tunnel, England – France	50 km
9	Yulhyeon Tunnel, South Korea	50 km
10	Laerdal Road Tunnel, Norway	25 km

Table 7b: Long Tunnels

Crossing the Caspian is one hurdle. Others on the overall route include crossing the Caucuses, traversing Turkey whilst minimising routes through earthquake zones, and then crossing the Dardanelles or the Bosphorus. An east-west rail route across Turkey already exists but would most likely need reinforcement as it already has high traffic density.
The cost of Bridge 1 in Table 7 was US$ 10 billion, the estimated cost of the Hong Kong-Zhuhan-Macao bridge is US$20 billion, and the cost of the English Channel tunnel was US$ 14 billion, all built some years ago. The cost of this package will be high and will present many challenges, but it does offer an alternative if the Straits of Hormuz and Bab-el-Mandab are inhospitable, and the long routes via the Cape(s) is undesirable. As a further comparison, the cost of a China to Pakistan rail link, currently under development, is projected to exceed US$ 58 billion. The construction of this China to Western Europe rail link, avoiding Russian and Iranian territory, will be a major political statement. It will increase trade along its route and intermediate nations will benefit greatly. It could also be used for secure communications in parallel to the track.

2.6 Other Potentially Necessary Large-Scale Activities

Turkiye is almost totally an earthquake region, hence crossing the Dardanelles into Europe, requires careful study. Extending the rail route across the Balkans offers the possibility of increased Mediterranean development both for tourism and low pollution industry. A northern Turkiye route along the edge of Black Sea crossing the Bosphorus into Europe is another possibility. A Spain-Marocco tunnel(s) under the Straights of Gibraltar is being considered. There is much Chinese port construction activity in the eastern Black Sea, including the coast of Georgia, which may offer an alternative freight outlet for Chinese and other countries' goods in both directions, especially if special container wagons are developed suitable for Roll-on-Roll-off application and equipped for long distance travel. [24,25].
Other long routes uniting continents such as the one between Russia and Alaska and between Turkiye through Syria to Iraq and the Gulf present similar opportunities and challenges but all have huge geopolitical constraints.

3 Conclusions and Contributions

East-west trade activity has occurred for millennia though organised transit is usually considered as starting about the time of the recorded travels of Marco Polo. A series of rail links provides environmentally acceptable means of moving goods and services between each end and the stations along this route. Constraints exist everywhere but equal trading between friends, partners and neighbours is always beneficial. The considerations presented above offer constructive options to develop this concept in an energy efficient and environmentally acceptable way. The costs are high and may need world-wide sources of funds, but it would offer access to resource rich countries and provide them with equitable trading opportunities. If successful, long distance energy efficient surface travel from Europe into Africa becomes an option as many lessons will be learned from implementing the enlarged Silk Route.

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