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Simplistic to Modern Applications of Statistics on Rail

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Abstract

Statistics are the basis of much, if not most, decision making. Advertising agencies use statistics as do railway companies. Simple data manipulation is usually adequate though sophisticated techniques are available. A somewhat detailed analysis for costing a long railway tunnel is given with an OOM estimate for one across the Caspian Sea. A brief examination of some of the extreme risks are also given, including recent unusual ones that have occurred. Two large but unusual fire risks which will impact the supply of electricity to trains are stated. In addition, two novel new routes in the UK have been examined and an outline of the necessary new data needed before advanced statistics can be employed has also been stated.

Keywords: bridges, Caspian Sea, data analysis, rail tunnels, tri-mode rail tractor locomotives, typical failure model.

1 1ntroduction

Many mathematical modelling techniques exist but few engineering applications require excessive sophistication. For the few situations that are complex, most can be resolved using modern digital computers as these enable simplistic models to be employed, which coupled with a knowledge of Maclaurin’s theorem and its limitations can solve most problems. If time is not critical, leaving small laptop computers to operate overnight or at weekends can be effective. One method for solving simultaneous differential equations known as “the method of characteristics” can be used with laptop computers if time is available but it does need continual observation as it is easy for the computation to become unstable.

Here an outline of statistical methods to predict where detailed data is needed, when the bulk of the data in preliminary form only is available, is presented. This permits scarce resources to be concentrated, especially in studies, to those areas necessary to give acceptable results. Three examples over new rail routes are included with detailed analysis of one and outlines of the others.

2 Outline of Preliminary Costing Technique

For the first example, an order of magnitude (OOM) cost estimate for a fixed rail crossing of the Caspian Sea is presented. This would be part of the alternative rail route between Shanghai and Germany that did not involve the Trans-Siberian railway [1, 2]. Currently the crossing uses ferries.

When estimating tunnel costs, significant information is usually required and this typically includes:

(i) Tunnel length
(ii) Tunnel dimensions including the number of discrete tunnels
(iii) Geological conditions
(iv) Ground water conditions
(v) Traffic parameters, including critical train parameters
(vi) Lining strength, including any anticipated structural deformation and water leakage.

Even with this information, the final costs of long tunnel projects are often many multiples of the original estimate. Causing factors include inflation over the long time period to build the tunnel, currency movements, key skill shortages and geological surprises. Some examples of cost overruns are

(i) Channel Tunnel: Initial estimate = 7.1 US$ billion and final cost = 14.7 US$ billion
(ii) Seikan Tunnel, Japan. Initial estimate = 5.4 US$ billion and final cost = 7.46 US$ billion
(iii) Solan Tunnel, South Korea. Initial estimate = 0.9 US$ billion and final cost = US$ 10 billion

Using statistical analysis to estimate a preliminary OOM cost, certain key parameters have been employed and these are:

(i) Tunnel length
(ii) Number of tunnels
(iii) Cost of scheme in various currencies
(iv) Date of costings which is used for inflation estimation and currency exchange rate.

From the final costs of a large number of road and rail tunnels, the average costs in million US$ per single track kilometre (STK) of tunnel length, are presented in Table 1. From these units, the single tunnel and twin tunnel costs for a Caspian crossing have been developed. The single tunnel is for one railway track, and the twin track includes for an additional smaller service tunnel such as exists in the England / France Channel Tunnel.

		Road	Road Mod	Rail	Rail + Road	Rail + Road Mod
	Arithmetic Mean	125	205	230	205	220
	RMS Value	215	300	295	175	250
	Stand'd Deviation	170	220	245	195	230
	Single Track Costs	US$ billion				66
	Twin Track Costs	US$ billion				175
	Table 1: Average Cost of Various Tunnel Types in MMUS$ / single track km					

The column headed "road" shows the averages obtained from road tunnel values only. Since the table is intended to calculate the cost of a rail tunnel, the column headed "Road Mod" is included and this contains a factor to relate it more accurately to a rail tunnel. The "Rail" column is based on rail tunnels only. "Rail + Road" and "Rail + Road Mod" are based on the combined total number of data points for each. To be included in the sample space, the criteria used is a minimum tunnel length of 10 km. An extension to include more data points would involve large diameter water tunnels with suitable factors to adjust for rail cost additions or metro line tunnels adjusted for the deletion of the underground stations themselves

	Location	Country	Completion	Length (km)	Tunnels
	Mont d'Ambin Base	Switzerland	2032	57.5	2
	Brenner Base Tunnel	Switzerland	2032	55.0	2
	Shanghai Airport	China	2025	60.5	2
	Yigung Tibet	China	2030	37.9	2
	Kurahn Tunnel	Austria	2026	32.9	2
	Simmering Base Tunnel	Italy / Austria	2030	29.3	2
	Thane Creek Tunnel	India	2028	21.1	2
	Alia Tunnel	Italy	2030	19.9	2
	Benlung Tunnel	Malaysia	2027	18.0	2
	Chiltern Tunnel	UK	2033	16.0	2
	Table 2: Some Long Tunnels Under Construction				

Many long tunnels are under construction, and many more are planned. Some have been delayed due to geopolitical considerations in the Middle East, Ukraine, India and the Far East. Examples under construction are listed in Table 2. Longer ones are in the conceptual design phase.

Figure 1: Approach Road Complex to a bridge

One simplification factor which exists for rail tunnels is that the approaches are seldom complex, hence the cost of the tunnel can be isolated from these and other works. This is seldom feasible for road bridges as can be seen in Fig 1 hence estimating their cost is significantly more complicated. It demands historical data which may not even exist. The figure shows a complex road junction, a suspension bridge and a long, piled support bridge or series of bridges.

Due to the uncertainty associated with OOM costs for sub-sea tunnels, and the political desire to avoid underestimates at a very early study stage, some preliminary overly high estimates have been made. The estimates for a possible bridge or alternatively, a tunnel between Scotland and Northern Ireland, a sea distance of some 44 km, are US$ 440 billion for the bridge and US$ 275 billion for the tunnel respectively. The Irish Sea Bridge has been known as the Celtic Crossing. Though such links have merit, these cost numbers produced strong adverse reactions [3].

3 Miscellaneous Associated Risks

There are many "not so obvious" potential sources of errors or omissions associated with the total costings of rail routes and these include those associated with "fire" and "availability of power" once the route has been selected. Statistical analysis is frequently the basis to allow for these items as well as the impact if they are not available.

The Buncefield fire in the UK resulted in the destruction of a large volume of hydrocarbon fuels plus the loss of storage capacity. This fire lasted for many days with the storage capacity itself being out of commission for several months. This storage capacity supplied fuel for most of London's airports as well as the transport hydrocarbon fuel outlets for most of the extensive hinterland around north London.

More recent examples of small power loss fires which had a large consequential impact include the electrical fire at London Heathrow airport and another at a container port in Iran.

Even more recently, a failure of the electrical supply in the Iberian peninsula occurred which involved the loss of 15 GWe electricity generating capacity from many power generating units. These stations shut down, assumed progressively, over a period of approx. five seconds. The rail networks that used these power sources were in turn shut down. This electrical capacity loss represented approx. 60% of Spain's available electricity generation capacity and this loss, to a first approximation, had an economic cost to the Spanish economy, estimated to be 15.4 billion euros. The cause of this cascading loss is not yet stated and no mention of standby equipment failure has been made.

When determining standby items, ramp rate is important and this is outlined in section 4.0. The efficiency of this standby equipment is an important parameter. This is a balance between capital cost and anticipated frequency and duration of need. Interconnectors with other totally independent sources of supply help by minimising domestic standby units but it does assume that they are available when needed. This assumption has been proven false previously, fortunately on rare occasions.

A more unusual fire risk needing statistical analysis concerns bush fires in Australia. Under very hot still ambient conditions, eucalyptus vapour is released by the gum trees and appears as a purple haze above the trees. Portraiture of this appearance was once very popular with a school of artists. The danger is that once ignited, these vapours can send a rapid flame front (flash) over several kilometres making fire breaks virtually irrelevant. Photographs from above may permit correlation of appearance with direction of fire spread and its intensity and thus provide statistical data for usable analysis.

4 Ramp Rates

Ramp Rate is the maximum permissible change in electrical load (increase or decrease) that any generating plant can accept. It is expressed as % MW energy / minute or % change per minute. For combustion engines, certain components are hot and have limited tolerance to rapid temperature changes which occur as the load changes. This is important for CCGT stations especially for the larger high efficiency units which have high pressure (hence thick wall) components. The ramp rate of some generic designs is given in Table 3.

For wind renewables, back-up must be fast. Much R&D is being spent on utility batteries to reduce their size, cost, weight, re-charge rate, efficiency as their rate is from a few seconds to a few minutes. These may be the only solution for wind "back-up" especially if the current philosophy of employing interconnectors is inadequate. Utility ramp rate is improving following feedback from field experience but is still in the range 50 % / minute.

Station	Min. Load	Ramp Rate	Hot Start	Notes
		% P / minute	Hours	
Hydro	Standby	413 %	0.0015	Dinorwig Pump Storage
Fuel Cell	1 %	35 %	< 1 hour	Min. load need = 2 %
Hydro	5 %	15 %	0.1	
OCGT	10 %	50 %	0.05	Aero-deriv. Gas Turbine
OCGT	20 %	20 %	0.25	Heavy Frame GasTurb.
CCGT	20 %	8 %	2.0	Gas fuel
Steam	30 %	7 %	3.0	Gas/oil fuel
Steam	30 %	6 %	3.0	Coal fuel
Steam	40 %	4 %		Supercritical - gas fuel
Nuclear	50 %	2 %	24 +	

Table 3: Ramp Rates and Minimum Loads

One feature of nuclear stations is their size. Hence an EPR of 1.6 GWe with a 2% ramp rate can have a perturbation of 32 MWe / min. A marine version of the large aero-derivative machine such as the RR Trent with an output of 40 MWe, a 50 % ramp rate will have a perturbation of approx. 20 MWe / min. The former produces negligible carbon dioxide whereas the latter produces ~ 27.5 Te / hr whilst generating 40 MWe. For a nominal output using two machines to give roughly the same ramp rate of 32 MWe / min, this equates to a carbon dioxide output from the two machines of 46 Te/hr. The cost and time for introduction between the two is enormous at GBP 49 billion plus 12 years for nuclear and GBP 500 million plus two years for OCGT respectively.

5 Political Aspects of Energy Selection

Coal in the UK was consumed mostly in steam power stations which when last used in large quantities averaged a thermal efficiency of approx. 35 % [4], [5]. This value compares with natural gas in CCGT stations whose efficiency can be 60 to 65% LHV and this improvement is very important. Substantial electricity supply is required for the modern railway.

The thermal efficiencies of various electricity power stations are given in Table 4. The table shows that for a normalised 1,000 MWe power station, it would reject 1,785 MWth as a coal fired unit, 2,300 MWth as a family of SMR, 1,560 MWth as an EPR but only 555 MWth as a large CCGT unit. If the stations use river water for their cooling towers, the CCGT sets would reject the lowest quantity of heat into it, but emit 2.38 MM Te/yr CO_2 per 1,000 MWe generated. This greenhouse gas contributes to global warming. All four nuclear station designs in the table emit negligible amounts of CO_2 over their lifetime hence their contribution to global warming from power generation is minimal.

	Normalised power output all cases is **1,000 MWe.** Equivalent Heat Rejected. Internal energy usage to be deducted for all stations.				
	Type of Station	η %	Rejected Heat MWth	MTe CO_2 Emissions	Examples of Units
1	Coal Utility	35.8	1,795	6.83	Ratcliffe-on-Soar
2	Pembroke	34.5	1,900	6.45	Orimulsion (study)
4	Drax 2,000 MWe	38.0	1,630	6.10	Coal to wood conver.
	SMR	30.3	2,300	Nil	Small Mod' Reactor
	PWR	33.3	2,000	Nil	Sizewell B
	EPR	39.0	1,560	Nil	Hinkley C
	AGR	40.7	1,460	Nil	Heysham B
3	Supercritical	44.6	1,240	3.43	Hrasdan 5 - 93 % η, gas
	OCGT 9HA-02	44.0	1,270	3.47	Gas fired unit
	CCGT 2+1 Stm.	64.3	555	2.38	GT = 2 * GE 9HA-02

Table 4: UK Power Station Heat Rejection Comparisons

Notes:
(i) Most UK coal fired power stations operating between 2010 and 2024 had thermal efficiencies in the range 33 – 36 %. Ratcliffe-on-Soar was the last utility sized station in the UK to close.
(ii) The values in Table 1 exclude parasitic losses.
(iii) Emissions' values are based on 320 days /yr operation
(iv) The combustion carbon dioxide emission is assumed to be negated by associated timber growth as given in item 4 in the table. The number for carbon dioxide emission approximates to that associated with timber supply. The component associated with wood preparation is 0.22 MTe/yr.
(v) Hrasdan 5 has a standard, Russian designed, gas fired supercritical boiler

Rejecting large amounts of thermal energy into inadequate cold sinks causes environmental damage. The state of the River Trent when coal fired power stations used its waters for their cooling towers or rejected their heat directly into it gave cause for concern. The considerations when selecting power generation methods, emphatically include political decisions as to which generation method is least damaging to the environment given that there is no ideal option. An estimate of carbon dioxide emissions for each option is also given in the table to help explain this. The nuclear stations have the highest capital cost and the gas fuel stations the highest unit fuel cost. Costs and availability of the different fuels must be considered.

Energy use is part of a modern civilised society but energy waste is not. Energy conservation is definitely needed. Technology selection and undesirable product disposal, especially for the nuclear generation option, most definitely has need of responsible decision making.

The conclusion from Table 4 is that the selection process for electricity generation now becomes more complex as carbon dioxide capture methods are available but these impact efficiency and fossil fuels are expensive. CCUS is feasible - the reduction in thermal efficiency is approx. 4.0 % assuming that a local carbon dioxide depository is available. Most publicly anticipated ones are the older offshore hydrocarbon fields.

Carbon dioxide disposal is not straightforward due to the properties of the gas. Early work on Ekofisk field's carbon dioxide injection programme, suggests that the scheme has merit despite the properties of carbon dioxide at high pressures and low temperatures (sea bed temperature in the North Sea is roughly 4 °C). The initial success of the programme was confirmed by temperature measurements at the edges of the field.

6 Thermal Pollution

Heat emissions from power plant can be a significant cause of environmental damage [6]. The course of the River Trent was once referred to as Megawatt Valley, as 13 coal-fired power plants used the river for cooling duty or water makeup for the cooling towers. Between its source and its discharge into the River Humber, the water temperature was raised on occasions, by more than 5°C. In the 1980s, the River Trent was one of Europe's most polluted rivers being second only to the River Rhine and in the UK, the last coal-fired plant was Ratcliffe-on-Soar which closed in September 2024.

A bigger concern now, for the River Trent however, is chemical pollution from its tributaries, run-off from farmland, and unchecked sewage spills. As these, inter alia, promote algae growth, de-oxygenate the water and kill wildlife, the governing water authority was fined in September 2024 for discharging sewage into the river.

The problems associated with thermal pollution is true for many rivers. The River Roding in east London is generally clean and has few traditional pollutants but at certain locations under overload conditions, there are significant pollutant releases and this river ultimately discharges into the River Thames. This situation exists with other small rivers discharging into the Thames as well as direct discharges which many believe will be ameliorated by the new Themes Water Authority sewage tunnel.

In Europe, Vattenfall's 1,650 MWe Moorburg plant near Hamburg was only permitted to operate at full load during the winter months to limit the temperature rise of the river Elbe. This restraint has affected its profitability, and despite only commencing operations beginning in 2015, the station shut down in 2021.

The head waters of the Boulder Dam include Lake Mead and these waters are suffering from low precipitation. In addition, high evaporation rates exist due to high ambient temperatures. To complicate matters further, as it flows through Arizona and California there is water extraction mainly for agriculture but also a little for power generation. The river, though used as an aqueduct, is not covered so that finally at Yuma, the water flow as it enters Mexico is very low. This is the subject of international friction and dispute. More efficient use of water is essential and this is now commencing but it is mainly driven by the high supply cost of clean water to the consumers in California.

The net result is that there are severe restrictions on power generation from anything that uses these waters.

7 UK Rail Routes as Examples to Help Determine Weak Links

Here we consider two typical novel routes and present a technique for evaluating system availability to help optimise both sub-system designs and potentially also sparing policy. It follows a similar route as used in optimising offshore platform design where topside space and equipment weight is critical and real estate cost is high and can be measured in terms of millions of US$ / m^2 [7]. Here, rail optimising land usage is also critical, due to difficulties in obtaining any new land itself and legal / procedural delays and costs which can arise from any change in land and pseudo land use (e.g. bridges).

The aim of any study is to assess the system availability and the associated loss of use for the life of the facility by developing an overall reliability model from a set of components whose individual reliability parameters are known. By predicting the potential operational failure rates of equipment, the following were performed:

(i) Optimisation of equipment sizing from the aspect of downtime and its effect on profitability (i.e. oversizing of equipment to account for downtime such that the target average figure is achieved in an economical manner).

(ii) Optimising of equipment sparing from the aspect of total installed investment

(iii) Optimising of equipment sizing sparing from the aspect of maintenance and running cost at full and part load conditions.

(iv) Data generated can be used for various load scenarios in an economic analysis. The details here are aimed at freight use as there is generally zero tolerance on late passenger trains.

The data obtained is often used for maintenance facilities and spares inventory but that is discussed elsewhere. Modern rail equipment is beginning to carry condition monitoring equipment which can be downloaded online at specific rail locations [8]. It is an area of serious development.

The mathematical model employed to predict the availability assumes that the failure probability density function for times to failure, f(t), and times to repair, g(t), were of exponential form. This can be expressed by the Cumulative Failure Distribution Function, F(t) and the Cumulative Repair distribution function, G(t) as:

$$F(t) = \int f(t).\,dt \quad \text{and} \quad G(t) = \int g(t).\,dt$$

where $f(t) = \lambda \exp(-\lambda t)$ and $g(t) = \mu \exp(-\mu t)$. The factor λ is the constant equipment failure rate and the factor μ is the constant equipment repair rate. The use of the exponential probability functions is common with electronic components but their use here with freight trains is an unusual application. It is justified as the objective is to identify areas where scoping data is adequate and unique areas where more detailed data is needed thereby optimising use of scarce study resources.

The two novel routes considered here are:

(a) Cambridge to Cranfield to Oxford to Reading

The suggested Cambridge to Oxford to Reading route can be considered essentially in two parts. The Oxford to Reading component is well used already. In addition, there is the recent introduction of the Oxford to Bicester to Marylebone route which was in the pre-commissioning process using DMU some 18 months ago and this route is now proven successful.

The long process of route proving with new trains and rolling stock will eliminates the majority of early failures except for the rolling stock itself and signalling which dominate the early statistics. These latter items are being improved continually and the upgrades are limited only by budget and access restrictions. In terms of the day-to-day activity, lost time for delays is minimal but the overall statistics, in terms of achieving targets, is only some 70 % +.and these can be influenced significantly by single items, such as a derailment on the track. These large events can be identified by inspection and formed the basis of the mathematics in [7] which in turn evolved from the development programme of the WW2 German V2 rocket.

The original suggested route, as well as this one, will benefit from the latest trains in terms of decarbonisation such as the Alstom (Coloradia) iLint which uses a hydrogen fuel cell. Its "availability" in the UK will need to be determined.

The route from Cambridge to Oxford, hopefully via Cranfield (there is a university located there) will involve some new routing. In addition, some of the original right-of-way has activities on the land, hence land use decisions must be made which can take elapsed time. Assuming that the complete route, either to Reading or to Marylebone, London is to the latest proven standards, targets of 95% + will be achieved. This sounds good except that the old, well proven Shinkensen train in Japan, has regularly achieved the corporate target of 99% of trains arriving at their destination within one minute.

(b) Immingham to Hull to York

This concerns the possibility to develop a route involving the conversion of an existing road bridge to a shared, but very limited rail use, rail bridge. Road traffic only would exist most of the time but at night the bridge would be cleared of road users and a very limited number of freight trains would use it before returning it to road traffic only use.

Ammonia is produced in the UK to a limited extent. Importing additional large Quantities of it are being examined. For example, it is possible to import ammonia into the UK on South Humberside, take it at night over the modified Humber bridge when there is no other load on the bridge, thus keeping the train's transit time short and simultaneously minimising the load on the bridge. The train would then connect into the Northern rail network and thence on into Scotland.
A suitable tri-mode locomotive such as the Class 93 already exists. It has 25 kV power supply using pantographs which permit it to cruise at speeds of around 100 mph (160 km/hr). Electrical power at 25 kV would not be installed on the bridge for safety reasons. It would revert to its 25 kV electrical supply some distance away from the bridge using its 1000 HP diesel engine on the bridge and its approaches. A large battery pack is available also to provide power where neither a 25 kV supply exists

nor the diesel unit is permitted to operate. Such situations occur near manned premises. The Class 93 train has been trialled on UK routes for over one year and it is planned to send it abroad for finalised testing and general improving. Detailed statistics should result. Currently the Class 99 will be tested abroad before being trialled in the UK. The benefits of the Class 93 and Class 99 for UK use were suggested at the conference in [1].

As an ammonia distribution train there are many factors associated with the cylindrical Ammonia containers themselves, including the onboard HVAC units. On wagon condition monitoring [8] and any train or trackside data collection then becomes feasible. Once all the components are proven, overall results should exceed 95% as most of the route already exists and a total route upgrade will be initiated if a significantly novel activity such as this proposed use of a major existing suspension bridge is accepted.

This example is included as it is comparatively easy to provide a secure marine route between the Humber ports and the ports of Rotterdam and Antwerp from where the ammonia can be loaded. Protection of the UK North Sea hydrocarbon assets are already in place.

8 Conclusions Including Priorities

Movement of liquids in long trains is very common in some parts of the world. Tengiz crude was once exported from Kazakhstan by train freight wagons and a similar situation existed in Quebec, Canada. A crude oil train there once derailed and it resulted in a substantial fire. In the UK, rail safety is very high, significantly better than that of road. Furthermore, motorways are better than other roads with a statistic that motorways support 20 % of traffic yet experience only 5 % of accidents.

A recently quoted statistic for a large number of new build houses in London, stated that it would cost 43 times that for the same quantity in the West Midlands and 36 times that for the same quantity in Greater Manchester. These numbers look strange until one includes the statement that the numbers involved were in the tens of thousands. The UK has a very limited amount of land so that the “low cost” option of using virgin farmland must be excluded especially as housing and work opportunities must be related.

London is still an economic powerhouse with the UK having roughly 2 % of the world economy but only 1 % of the population. As part of harnessing and growing this economy, an innovative rail network is essential and two examples of the above have been given.

Other possibilities for using the next generation of trains includes the “Peaks and Dales Railway” [9] and the “North Downs Railway” [10]. Where traffic density is low hydrogen fuel cell drives with batteries is now an option and where medium density traffic on existing routes exists, hybrid electric battery trains are being evaluated [11]. All this is part of UK rail decarbonisation, which is part of its modernisation. For an engineer this offers an exiting future with statistics being a large part of this.

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