Rail Infrastructure

HIGHLIGHTS

■ **TECHNOLOGY STATUS –** There is a vast range of rail infrastructure in use today, with a whole spectrum of possible energy consumption and efficiency performance. The most significant contributor to the life-cycle of rail infrastructure energy consumption is its construction phase. Naturally this depends on the size of stations, quantity of track and whether or not the rolling stock will be run on electricity or diesel. Electrified and high speed track is becoming more and more popular, partly because of their greater energy efficiency compared to diesel. This does however lead to greater infrastructure requirements and energy consumption, specifically in the form of overhead line equipment and larger, airport style termini.

■ **PERFORMANCE AND COSTS –** Infrastructure construction, maintenance and operation together contribute 13.5% to the total lifecycle emissions of electrified rail based on an EU average electricity generation mix. Operation of the rolling stock accounts for 82% and the remaining 4.5% is construction and maintenance of rolling stock. Maintenance energy consumption of electrified track is dominated by the railway itself and supporting substructure, at 39% and 38% respectively; stations contribute 12%. In terms of costs, the rail driveway can cost between €56,800 and €472,700 per track km, and a typical high speed rail station costs around €100m and takes two years to build. High speed rail infrastructure is leading the way in terms of performance efficiency and is attracting the latest technologies, but it is also the most costly. Substructures of gravel are only operational 79% of the time due to maintenance and substantiating of the ballast. This can be increased to 99% with ballastless track, although this is uncommon at the moment.

■ **POTENTIAL AND BARRIERS –** France, China and the UK are making steps towards sustainable stations, with plans and targets particularly focusing around installing solar photovoltaic cells on station roofs. Other options for reducing energy consumption mirror any commercial building, such as thermal insulation and low-energy lighting. Barriers to such developments are high capital costs, and in the case of upgrading existing stations, whether or not the structure is able to support renewable energy devices or new waste and water systems. In terms of the life cycle, transporting materials to the construction site by river or rail can also cut energy consumption, though this is restricted by the location of the infrastructure development. Improved signalling and communications technology claims to be able to save around 5% of in use traction energy, achieved by smoothing speed profiles and reducing conflicts.

TECHNOLOGY STATUS – Rail transport infrastructure may offer unexploited potential for energy efficiency improvement, such as the reduction of energy consumption of large railway stations, signalling equipment and electricity transmission for electrified rail. Further, considering life cycle emissions opens up more areas for improvement, such as the energy consumed in constructing rail substructures, tunnels or bridges, or process emissions from the materials used in the various components of a railway line. To provide context, Figure 1 shows the relative contributions of various components to the lifecycle GHG emissions from a railway. The figures are based on the carbon footprint assessment of the Eastern branch of the Rhine-Rhone LGV [1], adjusted to the EU electricity mix. The following subsections provide a discussion of the current status of each component of the rail infrastructure.

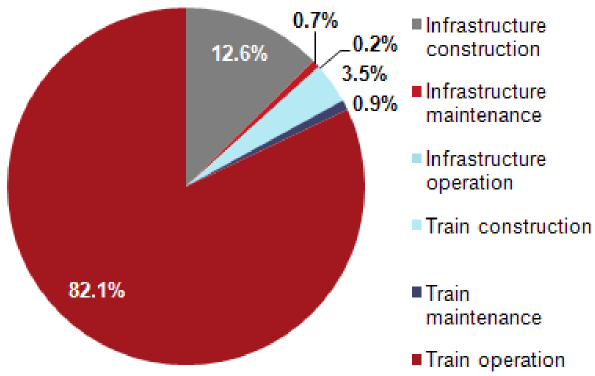

Figure 1: Life-cycle emissions from electric rail transport based on EU grid electricity mix [1]

■ **Permanent way and borders** involve earth works to support the track, drainage systems for water dispersion and perimeter barriers. Typical energy consumption (including earth works and energy embedded in materials from extraction and processing) ranges from 5,150 to 6,779 GJ / track km [2]. Junctions typically include a kilometre of track, and related land and earthworks. Rail in a rural environment simply requires bordering by post and wire fencing to stop trespassing, while urban routes often have acoustic side barriers [3].

■ **Ballast** is the support for the rail track, and is composed of tightly interlocked gravel pieces. Gravel ballast requires regular maintenance as pieces fall away under vibrations, and the support for the track needs substantiating. For high speed trains, greater quantities of ballast are normally required with larger stone sizes [4]. High speed trains may also require banked curves or super-elevation due to their maximum required curvature. Conventional trains however already employ tilting technology (e.g. Pendolino rolling stock in the UK) so banking would be avoided. **Ballastless track** or slab-track uses a continuous concrete bed with entrenched rails instead of interlocked gravel pieces and sleepers. This has specific uses in road crossings and tunnels, and has also been tried for continual stretches of rail but remains relatively uncommon.

■ **Track gauge** is the term given for the width between rails. Many countries have a combination of gauges

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owing to historically localised engineering and a lack of national, let alone global supply chains. Some countries, for example India, underwent a re-gauging to standardise the network in the 1990s [5], whilst many others avoid the costly overhaul. In Europe and Japan for example, lines with different gauges are used separately for conventional and high speed trains [11].

■ **Road crossings and culverts** (water pipes) in a rural environment tend to be less obstructive and less frequent than those in urban environments. Recent analysis by Network Rail in the UK assumes minor roads intersect with rail track every 2km in rural environments and every single kilometre in urban environments [3]. Road crossings are a necessary application of ballestless track explained above, where smooth concrete allows road vehicle crossing [4]. Major culverts require consideration every kilometre in densely populated countries such as the UK [3].

■ **Retained cut** or trench cutting, depends on the topography of the route. Rural plain line development in the UK would typically involve 2% retained cut. In an urban environment this is more likely to be around 50% to reduce street level disturbance [3]. If situated below the groundwater table, a retained cut has to be made waterproof, usually using water resistant concrete [6].

■ **Rail Tunnels** follow a standard horseshoe shape design, ensuring enough space is provided that air pressure build up is not dangerous if trains pass. For a twin track tunnel the width of the main section will be approximately 11m, with a height of 9m. This creates a typical cross section of 130m^2. Two emergency walkways may be fitted, one either side of the railway lines. To avoid the likely effect of groundwater on excavation, the tunnel level is designed to be above the groundwater table by several meters [7] Energy use related to embedded materials and construction ranges from 1,169 to 17,429 GJ / track km [2].

■ **Bridges** for rail can be two-span continuous bridges, long suspension bridges, lattice bridges or arch bridges [8]. Rail bridges can be combined with pedestrian or road bridges, saving on materials and energy consumption compared with constructing separate bridges for different modes. Some may even carry both rail and road on two decks, such as the 2.2km Tsing Ma suspension bridge connecting Hong Kong mainland with Chek Lap Kok international airport [9].

■ **Signalling and telecommunications** spans traffic management, automatic train protection systems and driver advice systems. Signalling train detection is the established technology used by signallers and automatic route setting systems to predict and manage conflicts between trains [10]. Telecommunications systems at a basic level provide the train driver with timetable information and other generic advice on paper or screen. The French paper-based system, and the German and Swiss electronic timetables, are examples of systems in widespread use today [10].

■ **Electrified Rail Infrastructure** for rural routes would require national grid network diversions every 30km and an electrical substation to correct the voltage every 10km. In an urban environment, connection to power becomes approximately three times more expensive because of high land values and obstructions inherent with the location.

■ **Overhead Line Equipment** (OLE), or catenaries, are used to deliver electricity to the train in electrified rail systems. Construction requires steel (71%), aluminium (10%) and copper (19%) which have respective embedded emissions per rail track km of 40.9, 15.3 and 11.8 tCO_2 equivalent [4]. **Electrified third rail** is an alternative to OLE and requires a wheel, brush or sliding shoe to draw direct current, which can then be returned through the wheels and via the standard rails.

■ **High speed rail infrastructure –** High speed rail definitions differ, but most common they refer to rail systems which are designed for a maximum speed in excess of 250 kph [4]. These speeds often involve the construction of new track, although trains which use them can also use existing tracks at reduced speeds. In Japan, the high speed trains, named Shinkansen, run on their own dedicated network with virtually no overlap with conventional rail. In comparison, the French TGV high speed trains often use conventional rail lines to increase their coverage of the country, although conventional trains do not use high speed lines to avoid congestion and slow down. Spain developed high speed lines (for their AVE services) on the same gauge as France, but had a conventional rail system running on a narrower gauge. To make more intensive use of the new lines, they have been developed with a third rail and operate as dual gauge lines. Italy and Germany have a completely open network, with high speed and conventional trains running on both categories of rail [11]. There are currently no high speed lines in the US, although proposals were put forward in early 2011 for investment of $53 billion over six years to improve rail services, including some high speed services [13].In China, high speed lines consist of a mix of upgraded conventional rail lines, newly-built high-speed passenger designated lines, and the world's first high-speed commercial magnetic leviation (Maglev) line [12]. **Maglev** is a new technology that suspends, guides and propels trains using magnetic levitation from a very large number of magnets embedded in the train and its guideway, which push and pull to move the train. It has come close to being implemented on a wide scale, however, no country currently uses such a system for inter city transport. The first and only major application of the technology is the Maglev service connecting Shanghai airport to Shanghai city in China.

PERFORMANCE AND COSTS - Compared to diesel rail transport, electrified rail transport is 15% - 40% more energy efficient, has no direct emissions and reduces overall CO_2 emissions by 20% to 30% [16]. Electrified rail can also reduce the operating costs of the rolling stock, with a 20% to 30% fuel saving and an estimated 20% saving in maintenance costs per vehicle mile (for passenger vehicles). Further, electrified infrastructure provides for higher levels of vehicle reliability and availability and lower leasing costs (see ETSAP brief T11 on Rail Transport for more information on rolling stock) [16]. However, the extensive infrastructure requirements mean that electrified rail is only cost effective for sections of line that run more than 5-10 trains per day [14, 15]. The Energy consumption per track-km of maintaining rail infrastructure is shown in Figure 2. Work for Network Rail in the United Kingdom has demonstrated that in high-frequency and high-occupancy contexts (e.g. the 600-km London–Scotland line) high speed rail (HSR) can provide further benefits

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over equivalent conventional electrified services in terms of energy consumption and GHG emissions per passenger-km. However, the development of new rail infrastructure is expected to be by far the most significant lifecycle component in terms of GHG emissions if the electricity system is highly decarbonised, as planned in the UK over the next 40 years. This emphasises the importance of minimising emissions from the construction of any new rail infrastructure, focussing on sourcing lower carbon materials and on end-of-life recyclability of components [4]. This is particularly relevant when significant project implementation times are considered (e.g. 10-20 years for the high speed plan in the UK). Long term plans exist in the European Union (to triple the length of high-speed network by 2030 and serve the majority of mid-distance passenger transport by 2050 [20]), in the United States (to build over 27,000 km of national high speed rail by 2030) and in China (to invest US$100bn per year over the next few years and reach 16,000 km of high speed track, running trains at 350 km/h [19]).

■ **Tunnel** excavation technology and costs varies hugely with different geological conditions. A range of tunnels built in Taiwan show typical rates of excavation between 30m and 250m per month [7]. Like excavation times, costs can vary hugely. The UK Highways agency estimates the average cost for a twin bore tunnel at €50m per kilometre [22]. However, this appears to be at the low end of the scale when compared with completed projects; Westerschelde Tunnel Construction in the Netherlands reports a figure of €110m per km [23], the Channel tunnel reached €251m per km by its completion [24], while the Gottard and Lötschberg were also around €100-120m per km [28].

■ **Bridges** have a wide range of costs depending on type, geological foundations, height and whether or not it spans water or land. The Tsing Ma bridge, because it was over water and because of its height, was extremely expensive at €325m per km [9]. The Vallarpadam Railway Link, India, was far cheaper at €12m per km [25]. The Danube Bridge in Bulgaria falls in the middle at €120m per km [26].

■ **Stations** with international high speed links are likely to cost in the region of €100m [27] and take around two years to build. A terminus however is likely to cost more. At the top end of the scale with integrated underground networks costs could reach €950m, based on the proposed Stuttgart Central Station [28]. These may take up to 10 years to build. A smaller twin track station on the other hand may cost around €15m, with upgrades to standard city stations such as modernisation and re-roofing costing between €2m and €5m [29]. Opportunities for energy efficiency measures in stations mirror those of commercial buildings and can include: reduced waste, increased renewable energy supply, more sustainable materials, minimised water consumption and greener ways to transport construction materials to and from site.

■ **Signalling and telecommunications** fitting of new systems with technology and software would cost in the region of €18k per cab. Maintenance costs thereafter would be €1.2k per cab per annum, which includes software licenses. A further €109 per year per vehicle on the network would be required to cover the costs of a control centre, including software development. However, analysis indicates that over 5% of traction

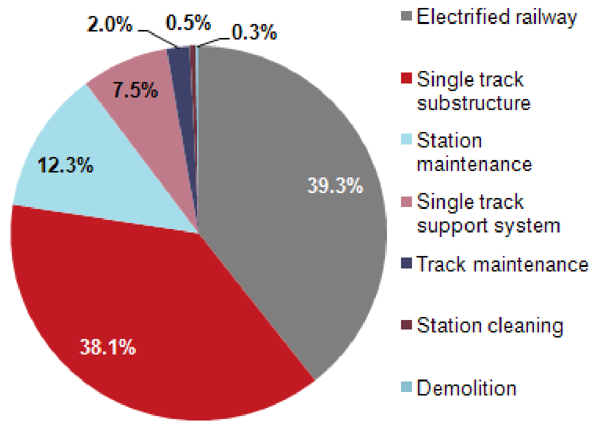

Figure 2 Split of maintenance energy consumption per track km for electrified rail [17, 18].

energy could be saved overall without increasing lateness. This would be achieved by smoothing speed profiles, reducing unplanned conflicts and improving timetabling [10].

■ **Ballast** replacement with ballastless concrete track, or slab-track, could increase track availability from 79% to 99% compared with gravel ballasted track by reducing maintenance time [30]. Today, however, traditional gravel ballast is prevalent because of its lower cost; the two perform relatively evenly in terms of embedded emissions [4].

POTENTIAL AND BARRIERS

■ **Rail Electrification -** Around half of the European rail network is electrified [31], so there is still potential for further electrification in a number of European countries. Even higher is the potential in other regions of the world). In countries like the UK and India, for example, electrified rail still only accounts for a third and a quarter of the network respectively. Given India has the fourth largest rail network in the world, there are clearly large benefits to be made from current electrification technology [32]. However, the cost-effective potential is likely to be a somewhat lower proportion as rail electrification requires costly extension of electricity distribution networks and substations at regular intervals along the route.

■ **New Track and High Speed Rail –** Building new track provides a big increase in track capacity, enabling frequent services and releasing capacity on the existing lines' conventional passenger services. Further, there is no interference with existing freight routes. However, new track is extremely costly, with sources quoting figures between €4 and €111 million per km of track. The lower estimate refers to rural track building without bridges, tunnels and on low value land, whilst the latter estimate involves intensive tunnelling under water such as for the Channel Tunnel connecting the UK to continental Europe [33]. High speed rail specifically using its own dedicated new infrastructure is extremely costly. A number of countries have upgraded existing track for higher speed, with tilting technology on routes with more curves. However, such trains do not normally run at speeds above 200 km/h so are not true high-speed services (i.e. typically those above 250 km/h).

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Their rationale is to upgrade services at relatively low cost in countries which have sufficient capacity to cope with increased divergence of speeds on routes shared with all forms of traffic. Most of the countries which adopted this strategy initially, such as Britain and Sweden, are now considering building dedicated high speed lines [33].

■ **Upgrading Existing Track -** Upgrading existing track is the core feature of the US's designated national high-speed railway corridors announced in 2011 [13]. The upsides to track upgrading (where possible) over new railways include considerably lower costs [3], lower financial risk (improvements can be introduced incrementally to see how demand responds to the investments), and shorter lead time. However, upgrading existing track may suffers from downsides compared with new track:

- Services may remain uncompetitive*.* Train speeds are lower than on dedicated track and so the '3-hour threshold' journey time – proven to be important to passengers - may not be achieved. Rail competitiveness may therefore be impeded versus air services over longer distances;
- Constrained capacity*.* Use of existing track may be severely constrained, with limited additional capacity available to be created. This means that high-speed trains have to mix with slower passenger and freight trains, limiting the number and efficiency of high-speed services that can be operated. This may also lower service reliability compared with services on dedicated lines [40];
- Technological upgrades*.* Use of existing lines for new rail systems such as high speed lines generally requires upgrades to signal interlocking to prevent conflicts at junctions and points, and OLE and telecoms equipment at the tie in location to be compatible with new route infrastructure and/or rolling stock [37].

■ **New Signalling and Telecommunications -** controlled centrally improve energy efficiency of trains both in motion and whilst stationary. Modern signalling systems are being deployed across Europe as part of the European Rail Traffic Management System (ERTMS) programme, which includes wireless communication between trains and central control centres. These links can be used to measure energy use and send instructions to trains to significantly reduce energy usage [35]. The latest systems can calculate energy efficient driving profiles, taking into account the features and availability of routes and the speed and acceleration of the train. Driving recommendations can then be sent wirelessly to the train, helping the driver to conserve energy. The UK Department for Transport believes that ERTMS-enabled lines will cover 50% of the UK by 2019 [36]. By 2034, the vast majority of the UK will be ERTMS-enabled. Energy use from lighting, heating and other services can be minimised with control centre intelligence whilst the train is stationary. Such systems can shut-down non-essential services more quickly than existing 'load shedding' systems. For example, if the system knows a train will be stationary for several hours the auxiliary services can be shut down immediately when it stops, rather than waiting for on-train electronics to automatically turn off [35]. Further benefits such as controlling acceleration to maximise the energy returned by regenerative braking and to minimise maintenance, are also possible. Within a few years, automatic train control (ATC) on mainline railways could provide the potential for many more energy saving opportunities [35]. All in all, signalling and telecommunication advances are believed to be able to reduce energy consumption by 10% [35,40].

Innovation in signalling and telecommunications may suffer from reluctance to adopt new systems [40] if train delays occur due to insufficient installation of new systems, if drivers are not appropriately trained, or if new automated train control systems are perceived as a threat to jobs. Some decision makers think that the possible reluctance of drivers puts too much uncertainty to the effectiveness and thus payback of the system. Further, the effectiveness of the system is reduced if train punctuality in the network is low [40].

■ **Stations –** Stations may improve their energy efficiency through measures that are similar to those of commercial buildings, as discussed earlier. There are also many examples of planned improvements in this area, with some examples below. King's Cross station in north London has plans to draw 10% of its energy from photovoltaic panels affixed to its roof, and Blackfriars will use the River Thames to transport its construction materials [38]. Nanjing South Railway Station will deploy 7MW of solar photovoltaic panels on its rooftop. The Nanjing South station is a major stop along the Beijing-Shanghai high speed railway [39]. In France, the SNCF are bound by the buildings strategy to reduce the energy consumption of stations by 38% by 2020. Plans involve equipping 500,000 m^2 of roofs with photovoltaic cells from 2010 onwards, following the example of the two new Besançon Franche-Comté TGV and Belfort-Montbéliard TGV stations. Plans are also to optimise the thermal insulation of the nation's railway stations by 2020 and equip all railway buildings with low-energy lighting before the end of 2011 [1]. Installing photovoltaic cells on station roofs is a popular way of reducing the emissions related with running stations. However, the technology is still costly and depends on local environment at the site of installation.

■ **Technology Innovation: Maglev –** Magnetic Leviation (Maglev) rail is capable of very high speeds and is most likely to prevail where there is sufficient traffic to justify both a new self-contained route and the existing one. A Maglev project was proposed in Germany to connect Hamburg and Berlin, but has then been abandoned. A Maglev project is still under discussion for a Tokyo-Nagoya route and in the Tokaido corridor in Japan [33], where analysys and research have shown that for speed above 330 km/h, the Transrapid Maglev has an energy advantage over conventional high-speed trains, in terms of energy consumption and in terms of land use per kilometre travelled. Further, the Transrapid accelerates faster and therefore does not need to reach as high of a maximum speed in order to achieve the same journey times. Comparing running times rather than speeds, the energy comparison will be even more favourable for the Transrapid [34]. The principal barrier to Maglev is that it is inflexible in terms of infrastructure because its trains are not able to make use of a section of existing tracks. Furthermore, the infrastructure (and trains) are extremely costly [33] and in certain conditions energy consumption per seat-km is significantly higher than high-speed rail. Very high network intensity and load factors are therefore necessary to offset these elements.

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Table 1 – Summary Table - Key Data for Components of Rail Infrastructure

Component Lifetime (years)	
Telecommunications and Signaling (including radios, cables and signal stations) [4]	30
Buidlings (Stations & Maintenance Centres) [4]	100
Rail [4]	Low: 30 - High: 35
Rail Driveway [4]	15 (Gravel) - 30 (Steel, Concrete) - -50 (High)
Bridges [4]	50
Tunnels [4]	100
Construction Energy Consumption (GJ/track km)	
Stations [17,41]	Small: 800 - Medium: 3,800 Large: 42,500
Track Substructure (including embedded emissions) [17]	Low: 2,200 - Medium: 4,600 - High: 9,400
Track Base (Including embedded emissions) [17]	Low: 5,200 - Medium: 6300 - High: 6,800
Track Substructure (excluding embedded emissions) [17]	3,085
Track Base (excluding embedded emissions) [17]	1,341
Tunnel [4, 17,41]	Low: 1,200 - Medium: 4,400- High: 17,400
Bridge [17,41]	Low: 1,200 - High: 10,500
In-Use Energy and Material Consumption	
Station electricity (Wh/passenger) [4]	9.7
Station heating (kWh/passenger) [4]	35.3
Points electricity (kWh / track km) [4]	840
Total Maintenance (GJ / track km) [4]	Low: 57 - Medium: 425 - High: 1,160
Station drinking water (cm^3/passenger) [4]	0.02
Capital Costs (2010 Euros)	
Rail Driveway (Euro/km) [42]	Low: 56,800 - High: 472,700
Points (Euro/unit) [42]	Low: 6,400 - Medium: 9,464 - High: 13,600
Telecommunications & Signaling (cost per in cab device for modern driver advisory information, energy management and regulation) [10]	Low: 6,000 - Medium: 18,000 - High: 36,000
Central control system (Euros per year per vehicle in network including payment for initial software development) [10]	109
Tunnels (Euro/km) [3]	125m
Summed capital costs of all rail components of a high speed line (Euro/km) [37]	Low: 4m - Medium: 25.5m - High: 111.5m
Summed capital costs of rail terminals for a high speed line per 500km (Euro/km) [37]	Low: 25.5m - Medium: 51.5m - High: 111.5m
Annual In-Use Costs (2010 Euros)	
Telecommunications & Signaling (incl. radios, cables, signs and signal stations) [3]	1,000
Station staffing costs (Euros/platform) [3]	918,000
Station maintenance costs (Euros/ platform) [3]	123,000
Head Quarter's Cost [3]	3,500,000
Track Maintenance (Euro/km) [41]	Low: 13,400 - Medium: 37,000 - High: 74,500

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