ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

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Rail Transport

HIGHLIGHTS

■ **TECHNOLOGY STATUS –** This brief focuses on heavy rail transport; for information specific to light rail and trams, see ETSAP T09 Public Transport. Rail transport plays a significant role in fulfilling global demand for passenger and freight overland transport, particularly in industrialised nations. In 2005, rail transport accounted for around 6% of passenger transport, and just under 60% of overland freight transport worldwide. Present day rail transport is powered mainly by diesel fuel (particularly freight rail) and electricity (particularly for passenger routes with high traffic volumes); overall in 2006 around 31% of global rail transport was electrified, with almost all of the remainder powered by diesel fuel. Around 85% of rail energy consumption is used for traction energy. Technologies to reduce diesel-powered traction energy include diesel-electric motors, which can include regenerative braking, and using a series of smaller engines (‘genset’) that can be stopped and started to react to engine power demand. Electric rail is 15 - 40% more energy efficient than diesel rail, and has no direct emissions, but requires extensive infrastructure that can only be justified on a cost-basis for busy routes. High-speed electric trains are becoming widespread and offer an alternative to short-haul aviation. There is scope in all types of rail transport to reduce energy and emissions through improving aerodynamics and reducing train weight, and by reducing the non-traction loads, particularly passenger comfort functions. Alternative fuels, such as hydrogen and biodiesel, offer further potential in reducing emissions from rail transport (as alternatives to conventional diesel), but a fuel supply chain is less well developed.

■ **PERFORMANCE AND COSTS –** Rail transport is inherently energy efficient when transporting large volumes of passengers or freight on a fixed route even at relatively low load factors. IEA estimates global averages for carbon intensity of passenger rail to be 30 - 60 gCO_2eq/pkm (compared with 200 - 270 gCO_2eq/pkm for air transport), and carbon intensity of freight rail to be 15 - 40 gCO_2eq/tkm (compared with 190 - 300 gCO_2eq/tkm for long distance trucking) For this reason, shifting passenger and freight demand onto rail from other modes (in particular short-haul aviation and long-haul trucking) is often considered an effective way to make transport more carbon efficient. There is scope for further improving the energy and emissions performance of rail transport, but most technical measures are only presently cost-effective in new rolling stock (i.e. retrofitting outside of refresh cycles is usually uneconomic). Electric rail is typically 15 - 40% more efficient than diesel rail, but only lines that run at least 5 - 10 trains per day are economically suited to electrification. Reducing auxiliary loads on passenger rail, and using a separate auxiliary power unit on freight trains to reduce engine idling, result in energy savings of 4 - 8%. A 10% weight reduction can result in energy savings of up to 8%; savings are significantly higher for trains that accelerate and brake often (i.e. frequent stopping services).

■ **POTENTIAL AND BARRIERS –** Many national governments are prioritising rail investment as a route to decarbonisation of their transport system. For this reason, it is expected that globally rail transport volumes will increase into the future. IEA scenarios project a 20% increase in freight rail volumes to 2050, and an almost doubling of passenger rail volumes in the same period. Investment in high-speed rail is particularly prominent at present, with nations such as China rapidly expanding their high-speed passenger network. The International Union of Railways has set a target of a 50% reduction in specific energy consumption from rail in the period 1990 - 2050. However, the long service lifetime of rail rolling stock, together with the economic barriers to retrofitting new technologies, mean that there are limited opportunities to improve the train fleet in that time period. In addition, current trends for safety and comfort standards may mean that some of the energy efficiency improvements expected are offset against features that increase train weight and energy consumption. Infrastructure is also a major barrier, and cost, when considering rail efficiency improvements; for more information, see ETSAP T14 (Rail Infrastructure).

TECHNOLOGY STATUS – In most countries, heavy rail transport (i.e. excluding tram and urban light rail public transport, which is covered in ETSAP T09 Public Transport) accounts for a modest proportion of both passenger and freight transport volume. In 2005, rail accounted for around 6% of global passenger transport, and just under 60% of global overland freight transport (this excludes shipping) [1]. However, there is considerable variation between countries. Passenger rail is particularly well suited to transporting high volumes of passengers between large population centres (e.g. major cities), whilst freight rail is a very efficient way of transporting bulk goods over large distances [2]. Approximately 85% of energy consumed by the rail sector is providing traction energy to trains [3]. The vast majority of rail transport is powered by diesel fuel or electricity [2]. Electricity has a lower, but increasing share globally, rising from 17% of rail sector energy use in 1990 to 31% in 2006 [1]. Some regions already have well developed electric rail networks; in Europe, for example, 80% of passenger and freight rail movement is electric-powered [3].

Trains (diesel or electric) can be powered either by a **locomotive** at one or both ends of the train with unpowered carriages in between, or by **multiple power units** distributed along the length of the train (also known as railcars, diesel multiple units/DMUs or electric multiple units/EMUs). Locomotives are more commonly used for freight trains due to their flexibility in operation, whilst the lighter, more efficient multiple units are favoured in modern passenger rail.

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Technologies currently in use and those with the potential to impact train energy consumption are discussed below. It is worth noting that a large number of operational and system-based measures also exist with the potential to reduce train energy consumption substantially (examples include ecodriving, parked train management, and energy efficient traffic management), but are not discussed here.

■ **Diesel Rolling Stock** utilise one or multiple diesel internal combustion engines to provide motive power to the train, either in locomotives or in multiple power units. The vast majority of freight rail transport use diesel locomotives, since they provide the flexibility to travel long distances over varying infrastructure [4]. The proportion of diesel trains used in passenger rail varies widely by country; in Europe only 20% of passenger rail transport is powered by diesel [3]. Diesel engines are commonly used in series with electric motors (**diesel-electric**), the engine acting as a generator to power the motor. This has the advantage of keeping the engine at its optimum operating point without the need for extensive gearing or transmission equipment. A further advantage is that it enables **dynamic braking**, in which the electric motor is used to provide resistance to the wheels in braking, saving wear on normal friction brakes. Ordinarily the electricity generated is dissipated as heat by resistor banks; however some recently developed locomotive trains store the energy in batteries for use in acceleration (**regenerative braking**) [5]. Diesel freight locomotives in particular can spend a significant amount of time idling (especially those used to shunt trains in a freight yard), as the scale of the engine makes it impractical to shut it down regularly. This is very inefficient from an energy use perspective; one way to overcome this is to use '**genset**' locomotives consisting of a set of smaller diesel engines that can be easily shut down and restarted as the train power demand varies [5]. Taking this a step further, **hybrid locomotives** are available that have on-board battery storage to power electric motors, with a smaller diesel engine that only kicks in when the batteries need charging [6]. Another option to reduce engine idling is to employ an **auxiliary power unit** – a much smaller generator which powers auxiliary train functions, allowing the main engine to shut down when no traction power is required.

■ **Electric Rolling Stock** draw electrical energy directly from an external line (either an electrified rail or an overhead wire, known as a catenary) and use these to power electric motors. Both AC and DC current can be used, though AC is favoured for longer distance lines as it can be transmitted with lower losses. Electric trains can either use locomotives or a multiple unit (EMU) arrangement where driven wheels are distributed under carriages along the train. The latter has the advantage of being lighter and more suited to regenerative braking, but is less flexible as train lengths cannot be varied.

Electric trains have a number of advantages over diesel equivalents. They are considerably more efficient (requiring around one-third of the energy input of diesel trains [7]), and emission-free, at the train level [4]. Even when electricity generation and transmission losses are taken into account, electric trains require around 15% less energy input than diesel trains on a "well-to-wheel" basis [1]. Emissions from electric rail originate from the electricity generation industry, where there is substantial scope for cost-effective abatement [2]. Electric motors are also lighter and more compact than diesel engines, meaning the trains are lighter and have a higher proportion of useable space. Furthermore, the reduced complexity of an electric motor means that they are typically more reliable and cheaper to maintain. The significant drawback with electric trains is that they require significant expenditure and maintenance of electricity infrastructure (see ESTAP T15 Rail Infrastructure). This means that typically the economic case for electrification can only be made on lines that see high traffic volumes (5-10 trains per day) [1]. A recent development are dual-mode **hybrid drive trains**, which are able to utilise partially electrified track by having an electric drive train capable of receiving power from electrified lines, backed up with a diesel generator that enables operation on line sections that are not electrified.

■ **High Speed Passenger Rail** utilise trains that are capable of running at service speeds greater than 200 km/h (120 mph) or 250 km/h (150 mph) [8] depending on the source of the definition. Modern high speed trains can run at up to 350 km/h (215 mph) on dedicated track [9]. Such trains are electrically-powered, usually in multiple units taking power from overhead catenary lines. High-speed trains do not differ in fundamental technology to equivalent conventional EMU trains. However, they employ more advanced materials and technologies to minimise the increase in energy consumption to 10 - 30% more than conventional trains (see Table 1 for details). Lightweighting and aerodynamics are particularly relevant to high speed trains. In addition, both the traction and load bearing equipment (principally the train bogies) must be of a higher specification to cope with the increased stresses of high speed operation.

■ **Weight and Drag Reduction** are two of the most powerful ways to reduce train energy consumption [10]. Weight reduction is particularly effective for trains that are frequently accelerating and braking, whilst drag reduction becomes more significant for trains that travel long distances with few stops, or travel at high speeds [4]. Weight reduction can be achieved by reducing the weight of individual components or by re-designing the train as a whole. Reducing train weight has the additional benefit of reducing wear to the train and infrastructure [11]. At speeds over 200km/h, aerodynamic effects dominate train resistance [12];

reducing this requires aerodynamic shaping of the train nose and tail, shrouding bodies and catenaries and reducing skin friction on the train body [11]. Covering empty freight cars and shaping the end cars aerodynamically reduces the aerodynamic drag of freight trains, which can still be significant despite the lower average speeds [6].

■ **Regenerative Braking** can be used to recapture energy that would ordinarily be lost when slowing the train. Energy is recovered by coupling a generator to the train wheels, and can be stored in a mechanical or electrical storage device (such as a flywheel or battery), or returned to the catenary line for use by other trains [5]. The latter is most common on electrified lines, but electrical infrastructure can present a practical barrier to its implementation (particularly on DC lines where maximum voltage levels and short circuit detection may prevent regeneration). Regenerative braking has the greatest potential where the train duty cycle involves a high proportion of acceleration and braking, such as frequent-stopping passenger services [12]. The maximum current efficiency of the complete regenerative braking cycle is around 75%; for this reason it is preferable to reduce the train mass as far as possible to minimise the energy needed for braking and acceleration in the first instance [11].

■ **Auxiliary Loads** such as lighting, heating and air conditioning can be a significant source of energy demand. Auxiliary loads vary depending on the ambient operating temperature and level of comfort function installed on the train; a study in the UK found that auxiliary loads comprised around one-fifth of train energy consumption on average [13]. Reducing these loads by using more efficient components and management systems can save around 4% of train energy use in some applications [10].

■ **Hydrogen Fuel Cells** are an alternative to conventional diesel engines that are being investigated in several countries including Japan, the US and Europe [14]. They offer an option for ultra-low emission trains in situations where line electrification is not technically or economically feasible [14]. Fuel cells convert a fuel (usually hydrogen) into electricity via electrochemical oxidation. The electricity can then be used to power the train via an electric motor. Fuel cells could also be used as an auxiliary power unit, to provide low-emissions power for auxiliary loads when traction power is not needed. See T07 (Automotive Hydrogen Technology) for more details on hydrogen fuel cell technology. Current technical hurdles include improving the lifetime of fuel cells and efficient portable storage of hydrogen. The sustainable production of hydrogen would also be a challenge.

■ **Biofuels** offer a route to further reducing the life-cycle GHG emissions of diesel-powered trains. Biodiesel can be blended with conventional diesel and used with little or no engine modification (at blends of up to 20% biodiesel) [15].

PERFORMANCE AND COSTS – Rail transport is inherently energy efficient on a passenger-km or tonne-km basis. A 2008 report from the International Union of Railways stated that trains are 2-5 times more energy efficient than road, inland shipping and aviation [3]. This is supported by a recent US report that found that freight railroads are on average four times more energy efficient than trucking [16]. The IEA estimates global averages for carbon intensity of passenger rail to be 30-60 gCO$_2$eq/pkm (compared with 200-270 gCO$_2$eq/pkm for air transport), and carbon intensity of freight rail to be 15-40 gCO$_2$eq/tkm (compared with 190-300 gCO$_2$eq/tkm for long distance trucking, and 2-55 gCO$_2$eq/tkm for maritime shipping) [2], [17]. Actual relative energy and emissions performance is highly dependant on specific routes and systems used and on the achieved freight loading / passenger occupancy factors. There are also significant differences in the characteristics of rolling stock in different regions, e.g. between US, European and Japanese trains. The performance of passenger and freight rail in different geographical regions is indicated in Figures 1 and 2.

However, substantial energy-saving potential still exists, much of it cost-effective due to resulting fuel savings [10]. **Auxiliary power units** on diesel trains to reduce engine idling can reduce train emissions by 4 - 8% [4].

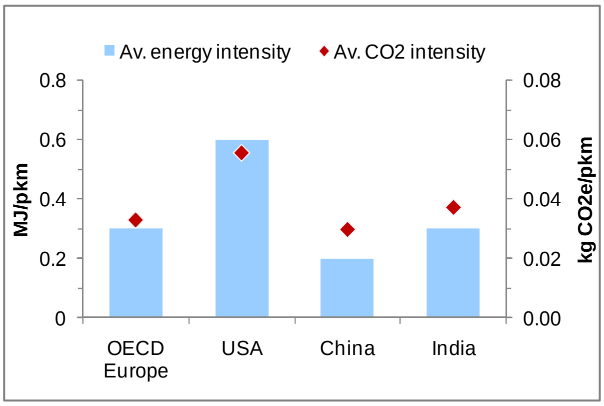

Figure 1 – Energy and CO$_2$ intensity of passenger rail [2]

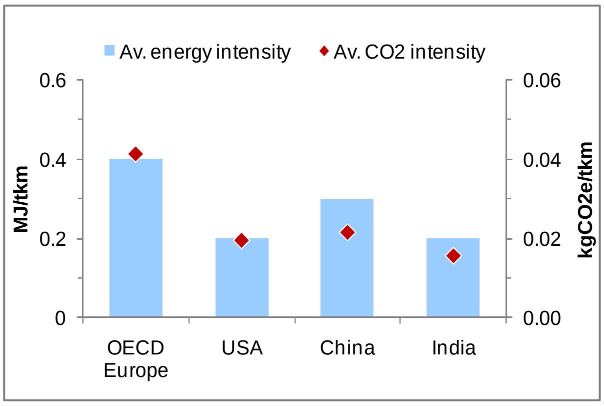

Figure 1 – Energy and CO$_2$ intensity of freight rail [2]

Electrification results in energy savings of around 15-40% over diesel passenger rail [1], [10], and the infrastructure investment required can be offset against the fuel and maintenance cost savings and benefits of reduced emissions. Electrification can be cost-effective for sections of line that run more than 5 - 10 trains per day [1]. For freight rail, where long sections of track with low traffic may make electrification uneconomic, **regenerative braking** with onboard storage can reduce train energy consumption by up to 15% [18], and for passenger rail estimates range between 10 - 20%, depending on the duty cycle [10]. In passenger rail, a **weight reduction** of 10% can result in energy savings of 0.5 - 1% for high-speed trains; 2 - 3% for long distance/conventional trains; 5 - 7% for suburban trains and 6 - 8% for urban trains [4]. Current **high speed rail** trains are around 15% more energy efficient that the previous generation, but still use around 20% more energy than their conventional electric equivalent [11]. To recoup the high costs of high speed rail, they rely on attracting high patronage (high service frequency and occupancy) and revenue. Volumes of at least 6 – 12 million passengers per annum are usually required for a high-speed link to be economic [9]. Reducing **auxiliary loads** (primarily heating and cooling) on passenger rail services give potential energy savings of around 4%, and are cost-effective, though the payback time is long [10]. The energy efficiency of **Hydrogen fuel cells** is strongly dependant on the process used to create hydrogen; however at the vehicle level fuel cells are around 2 - 3 times more energy efficient than diesel combustion engines [14]. There are, however, technical issues around fuel cell reliability and lifetime, and the production and storage of hydrogen, that need to be resolved before fuel cells are suitable for widespread use in the rail transport sector.

Costs vary significantly depending on specific applications, and are not reported in the literature [10]. However, typical payback times for some technologies are detailed in Table 2, assuming they are incorporated into new trains. Retrofitting to increase efficiency and reduce emissions is generally not cost-effective for most technologies [6].

A significant proportion of the overall cost of rail is in infrastructure – ETSAP T15 (Rail Infrastructure) provides more detail. This is particularly relevant to electrification and dedicated high speed rail track, both of which require substantial infrastructure investment.

POTENTIAL AND BARRIERS – Because of its already high energy efficiency and potential for very low emissions under electricity grid decarbonisation scenarios, both passenger and freight rail are seen to offer opportunities to reduce emissions by modal shift from more energy and carbon intensive modes [1], [2]. In particular, countries that have high proportions of private car transport and short-haul aviation could look to shift demand to conventional or high speed passenger rail, and certain freight currently shipped by heavy trucks could be shifted to freight rail. For this reason, future scenarios for sustainable mobility see volumes of both types of rail transport increase globally – by some 20% for freight rail and more than doubling for passenger rail in the period to 2050 [2].

Many countries have already begun investing in enhanced rail transport infrastructure. China, in particular, has invested large sums in recent years, and now has one of the largest high-speed rail networks in the world [2]. Current Chinese construction projects will almost triple the length of high-speed line by 2012 [9]. The USA and OECD Europe also have plans to extend their high-speed infrastructure [9].

The International Union of Railways has set sustainability targets for improving rail's energy performance. They are targeting a reduction of specific CO_2 emissions from train operation by 50% in 2030 compared with 1990 (measured per passenger-km and gross tonne-km), and to be carbon free by 2050. At the train level, they have set a target of a 30% reduction in specific energy consumption by 2030, and a 50% reduction by 2050 (against 1990 levels) [19].

However, there are barriers to both the widespread uptake of rail and to its continued technological development. The first is the long lifetime of rail rolling stock – trains have a typical service life of 30 - 35 years [10]. Many energy saving technologies are not cost-effective in retrofit [6], and hence there is limited opportunity to improve the efficiency of existing rolling stock until they are replaced. Furthermore, the market for new rail rolling stock is small compared to other transport vehicle markets – this makes it more difficult to recoup costs from researching and developing new models and technologies. Technological advancements are therefore often reliant on improvements made to related technologies in other sectors. Magnetic levitation (MagLev) technology, first used in Beijing, is an example of technology innovation that has been adapted for use in the rail sector.

In addition, if current trends in safety and passenger comfort standards continue, lightweighting and energy reduction measures may be partially offset against safety and comfort features that increase energy consumption and weight. The growing demand for high acceleration and top speed may further offset improved efficiency [20]. Investment in infrastructure will also be required in order to improve train efficiency, and to realise the increase in rail transport volume that is anticipated [4]. This is covered further in ETSAP T15 (Rail Infrastructure).

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Table 1 – Summary Table: Key Data and Figures for Baseline and Alternative Rail Vehicles

[7], [10], [11], [21], [22]

Baseline Vehicle: Diesel locomotive		
	Intercity	**Regional/Suburban**
Energy Input	Diesel	
Base Energy Consumption (g/seat-km) [7]	7.3 [a]	8.3 [a]
Base Energy Consumption (MJ/seat-km) [7]	0.316 [b]	0.360 [b]
Technical Lifetime, years [10]	30-35	30-35
Capital Cost, overnight, Euro/unit	N/A	N/A
O&M cost (excluding fuel), €/unit-year	N/A	N/A
Electric multiple unit		
	Intercity	**Regional/Suburban**
Energy Input	Electricity	
Current Generation vehicle Energy Consumption (MJ/seat-km) [7]	0.108 [c]	0.126 [c]
Next Generation vehicle Energy Consumption (MJ/seat-km) [11]	0.101 [d]	N/A
Technical Lifetime, years [10]	30-35	30-35
Capital Cost, overnight, €/unit	N/A	N/A
O&M cost, €/year	N/A	N/A
High Speed Rail		
	European	**Japanese [e]**
Energy Input	Electricity	
Current Generation vehicle Energy Consumption (MJ/seat-km) [22], [23]	0.140	0.104
Next Generation vehicle Energy Consumption (MJ/seat-km) [22]	0.119	0.085 [f]
Technical Lifetime, years [10]	30-35	30-35
Capital Cost, overnight, €/unit [22]	15,000,000	N/A
O&M cost (excluding fuel), €/unit-year [22]	900,000	N/A

a) Average value for European trains; b) Average value for European trains, based on a calorific value for diesel of 43.333 MJ/kg; c) Average value for European trains, based on an energy unit conversion factor of 3.6 MJ/kWh; d) Estimated performance of Hitachi Super Express, based on an energy unit conversion factor of 3.6 MJ/kWh; e) Based on Japanese Shinkansen trains made by Hitachi ; f) Based on reported performance of the N700 series Shinkansen compared with the 700 series currently in service [23].

Table 2 – Summary of Energy Reduction Options for Rail Transport

[4], [10], [18]

Description	**Energy reduction potential (%)**		**Payback period**
	Low	**High**	
Passenger Rail			
Weight reduction	1	8	Medium
Reduced aux loads	4	4	Medium
Improved aerodynamics	1	7	Med – Long
Line electrification	20	40	Long
Regenerative braking - AC	10	15	Long
Regenerative braking - DC	0	5	Long
Freight Rail			
Hydrid w/ energy storage	0	15	Medium
Auxiliary power unit	4	8	Medium