Energy efficiency strategies for rolling stock and train operation

1 Mass reduction

Typical passenger trains have specific weights between 400 and 800 kg per seat[1], but some high speed trains such as the German ICE 2 have values as high as 1100 kg/seat. Although there are some railway-specific limits to light-weight efforts, such as side wind stability, the Japanese Shinkansen (537 kg per seat) and the Copenhagen suburban trains (360kg per seat) may serve as benchmarks for light-weight in high speed and local service respectively[2].

Two types of lightweight efforts are to be distinguished:

- *component-based* lightweight design which focuses on the elements of the system "train" without any changes to basic principle of the train configuration
- *system-based* lightweight design which tries to find the weight-optimised solution for the whole system

Component-based lightweight design

In the field of component-based lightweight design, the use of new materials or innovative traction components offer substantial potential for mass reduction. Figure 1 helps to identify the most promising areas for lightweight efforts by giving the mass distribution of a typical MU.

In past years aluminium *carbodies* have replaced steel constructions to a large degree and can now be considered as standard in new stock for regional and high speed lines. Future developments in car-body construction point in the direction of carbon fibre materials.

Many state-of-the-art *propulsion components* are lighter than their predecessors, such as the IGBT replacing the GTO. Some innovative concepts such as the medium frequency transformer promise further progress in this direction.

Most of these measures can only be realized in new stock. Refitting measures usually allow to cut the weight of *interior equipment* only (seats, coach panels etc). There are a number of promising measures in this field. Especially the developments in sandwich structures and other composite materials offer interesting options for cutting the weight of interior panelling.

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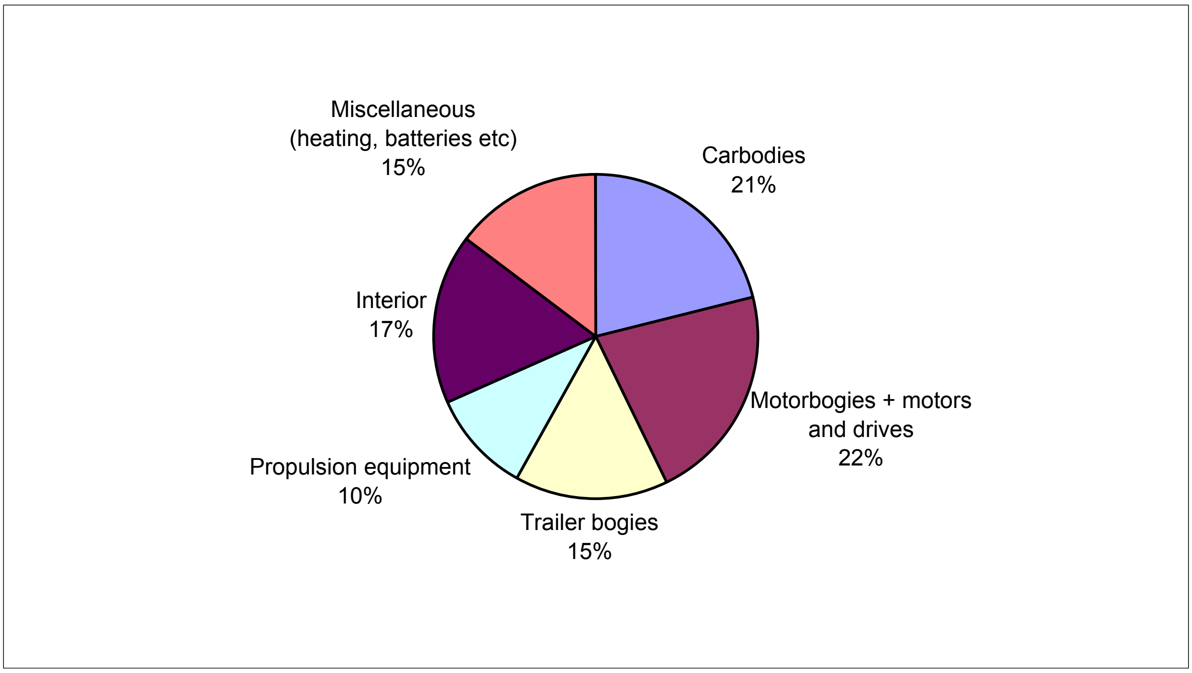
[1] Since the service offered by railways is not so much carrying a train, but rather carrying people or freight, the relevant figures such as energy efficiency will usually be given per seat or per ton.

[2] It has to be pointed out that mass per seat is also owed to space utilisation, an issue addressed in section 3.

Figure 1: Mass distribution of a modern MU (total mass: 92,7 tons)



Source: Euro Transport Consult 1997

System-based lightweight design

For the mass reduction of bogies which account for over one third of the train weight, several innovative and conventional concepts exist. However, they usually entail changes in the whole system design of the train and have to be considered as system-based lightweight design.

Jacob-type bogies have been in use in railways for decades. Whereas conventional stock consists of individual carriages resting on two bogies each, articulated trains with Jacob-type bogies consist of a fixed composition of coaches with consecutive cars resting on shared bogies. This reduces the number of axles per train length and thus overall weight.

Another option is replacing conventional *2-axle bogies* with single axle bogies. For suburban and regional vehicles modern curve-steered single-axle running gear exists and is successfully in use (e.g. the new Copenhagen S-trains[3]). More radical changes of the conventional train configuration have been proposed. At DB AG the technological feasibility of an "integral long vehicle" similar to the Spanish TALGO has been studied[4]. In recent years there have been growing efforts from mechatronics to study active suspension technologies for railways based on sensors, controllers and actuators. *Mechatronics* could revolutionize suspension technologies and considerably reduce train weight. Developments in this field range from electronically controlled single-axle running gear to wheel-sets with two

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[3] Dompke, Brunnecker 1998

[4] Schenk 2000

independently rotating wheels instead of a common axle and directly-steered wheel-pairs.

Mass reduction	
Technologies/strategies	**Example**
Aluminium car-body Articulated trains (Jakob-type bogies) Fibre reinforced polymers Light coach interior equipment Mechatronic innovations for future running gear Sandwich structures Single-axle bogies	*New generation of urban trains Copenhagen*[5] For the new generation of Copenhagen S-trains, a Siemens / LHB consortium developed a train meeting ambitious light-weight requirements in close co-operation with DSB. A number of measures was realized to reduce train mass while raising the number of seats per train. These included ➢ single-axle running gears (KERF) ➢ aluminium car-bodies ➢ sandwich floors & other These measures **reduced mass per train length by 15 %**. At the same time wider carbodies (3200 mm) allow to increase seats per train length by 29 %. As a result **mass per seat is 357 kg, a 34 % reduction** compared to the previous generation of Copenhagen S-trains. Mass reduction along with other measures **reduced energy consumption by 60 %**. It has to be stressed however that these values are partly owed to the fact that the previous S-trains were over 30 years old and therefore offered big improvement potential.

2 Aerodynamics and friction

Air resistance

Aerodynamics is of great interest for railway operation, not only for energy considerations but also for noise reduction, safety of high speed operation, and passenger comfort. Energy considerations especially come into play as railways plan to increase the speed of high speed trains to 350 km/h within the next decade. Given the present state of high speed technology, raising top speed from 280 km/h to 350 km/h would increase energy costs by about 60 %.[6]

The air drag experienced by a travelling train is determined by two features: its external geometry and its surface roughness. Virtually all outer parts of a train contribute to its air resistance. The individual shares however vary considerably with train length and train design. Figure 2 gives a typical situation for a long high-speed train. It shows that more than 70 % of the drag is due to bogies and wheels and surface friction from sides and roofs. It has to be stressed that the importance of the

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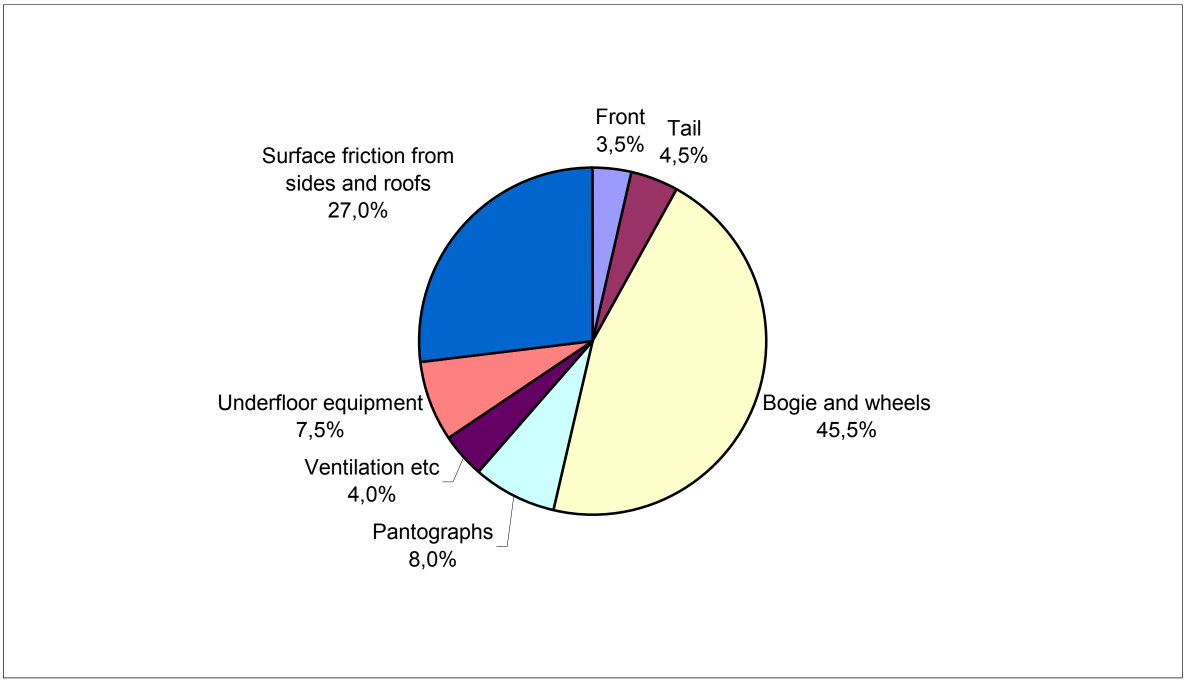
[5] Source: DSB

[6] Schulte-Werning et al. 1998

front and tail ends is much less than commonly believed. They do however have more relevance in very short trains (1-3 vehicles)[7].

Figure 2: Percentage share of the aerodynamic drag by the different parts of a typical high speed train with 14 coaches



Source: Andersson, Berg 1999, as presented in Fors 2001.

For high speed *passenger trains* a number of constructive measures have been proposed. For example, the influence of bogies can be substantially reduced by shielding them with an exterior cover. Such a measure alone is proven to cut the train's air drag by about 10%. Since a major part of the air resistance is due to so-called separations (transitions between laminar and turbulent flows), the aerodynamics of sides and roofs can be effectively improved by avoiding sharp changes in the vehicle's surface geometry. Measures include covering the underfloor equipment, streamlining the lateral coach design, optimising windows, doors and the transition between coaches as well as coating the train surface with an aerodynamically smooth material.

Freight trains, although travelling much slower than high speed trains, also use a high share of their energy intake for overcoming air drag. This can be mainly attributed to the aerodynamically unfavourable shape of freight trains: the space between cars is not shielded, many cars have no roof or cover and are often empty which maximises air drag. Studies indicate for example that due to aerodynamics a locomotive pulling open empty cars (in level topography) consumes more energy than one travelling with heavy load.

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[7] Fors 2001

There is a number of conceivable measures to improve the situation. Covering open cars or putting freight waggons of different heights into the aerodynamically optimised order could save in many cases more than 10% of energy consumption.

Friction

Mechanical friction comprises all the dissipative effects of wheel-rail interaction, mainly:

- Linear friction caused by dissipation in the wheel-rail interface
- Curve resistance is the additional resistance in curves due to increased frictional forces in curves.

The sum of the two effects usually accounts for less than 10% of a train's energy consumption.

Rail lubrication aims at reducing lateral friction between rail and wheel. This is especially effective in curves but can also be applied on tangent tracks.

Since linear friction is proportional to train mass, reduced friction is an automatic side effect of *light weight* efforts.

Aerodynamics and friction	
Technologies/strategies	**Example**
Aerodynamic optimisation of pantographs Aerodynamic ordering of freight cars Bogie fairings Covers for open freight cars Lubrication of wheels and tracks Streamlining of head and tail Streamlining of train sides and underfloor areas Virtually coupled trains	*Fairing of bogies*[8] In most of today's high speed trains the bogie area is uncovered up to the height of the wheel. In order to minimise air drag, bogies may be covered with smooth and streamlined surfaces. Bogie fairings have been used in the Japanese Shinkansen 500 series for some time. In Europe a research project involving the new multi-voltage ETR 500 high speed train of Italian FS revealed a considerable reduction of air drag. Tests demonstrated that **bogie covers cut running resistance by 10%**. Given that running resistance accounts for 60-70% of the energy demand for high speed service (including passenger comfort), **the saving potential of bogie covers is 6-7%**.

3 Space utilisation

The relevant figure being mass per seat, reductions cannot only be achieved by making a vehicle lighter, but also by fitting more seats into it. The latter can be done by

- raising vehicle height (double-decked stock)
- raising vehicle width (wide-body stock)

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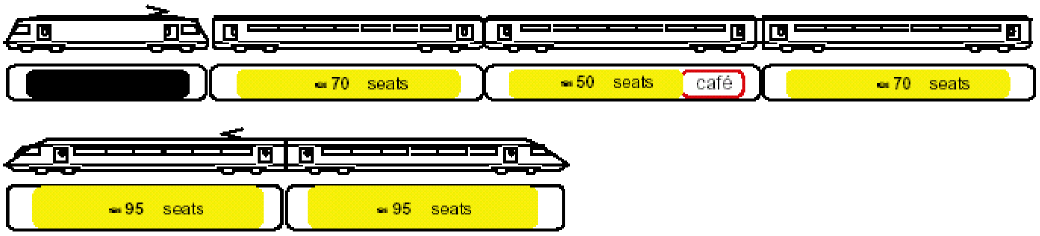
[8] Source: Schulte-Werning, Matschke 1999, calculations by IZT

- extending seating to parts of the train previously reserved to other purposes (eliminating locomotive by using MU stock or replacing restaurant by mobile bistro in the train)

Double-decked stock is already in wide-spread use on regional lines. There are also some examples for double-decked high speed trains (Shinkansen, TGV). Introduction in this area however meets more obstacles, since passenger comfort plays a more important role in long-distance service. There are also some timetable problems due to longer boarding periods at stations.

The main obstacle for *wide-body stock* is infrastructural compatibility (platforms in stations, trains passing on adjacent tracks, signals and other track-side equipment). Trains with car-bodies 3200 mm wide or wider are in use on some suburban lines. For the corresponding insular networks, infrastructural compatibility can be ensured at a reasonable expense. This is usually far more difficult on main lines, let alone international traffic, where wide-body stock usually collides with interoperability requirements. Despite these problems many experts recognise a clear potential for wider trains.

Figure 3: An extreme example of space utilisation: train length of wide-body EMU vs. loco-hauled train for equal seating capacity



Source: Andersson et al. 2001

Whereas freight trains still have the conventional constellation of a locomotive pulling cars, in passenger service there is a widespread trend towards replacing loco-hauled trains by *multiple units* (MUs). In MU stock the traction equipment is located below the floor in a decentralised fashion along the coaches. This way locomotives are replaced by coaches with a small driver’s unit at one end, thus yielding much lower mass per seat. The length reductions are impressively shown by Figure 3. In addition, the need for fitting motors and transformers into the limited space under the floor has been and still is a major driver for mass-reduced traction components. Replacing a restaurant by a regular coach is another effective means for decreasing mass per seat. Many operators fear however that with such a measure travelling by train could lose attractiveness with such measure.

Space utilisation	
Technologies/strategies	**Example**
Elimination of dining car Double-decked stock Wide-body stock Multiple units (MUs) vs. loco-hauled trains	*TGV Duplex*[9] Since 1996 SNCF operates the TGV Duplex, a double-decked train developed by GEC Alsthom on some of the busiest high speed lines such as Paris – Lyon. Besides clear economic benefits (low initial investment per seat etc) TGV Duplex has very low weight per seat and good energy efficiency. Compared to an equivalent single level TGV the Duplex version has 45% more passenger capacity, with train mass reduced and energy consumption being virtually unchanged. As a consequence, **mass per seat is reduced by 36% and energy consumption per seat-km by almost 30%!** Surprisingly, SNCF claims that passenger comfort is better than in normal TGV due to more space between seats. Presently 30 out of 300 TGVs are of Duplex type. With ongoing procurement this figure will soon rise to 80 out of 350 (~23%).

4 Reducing conversion losses

4.1 The electric case

Figure 4 shows the distribution of losses over the individual components of the power train for an ICE 3 EMU as compared to a Re 465 loco-hauled train.

Transformers are usually the more efficient the heavier they are. So dimensioning this component always involves a compromise between efficiency and mass. As an alternative to conventional transformers, two innovative concepts are discussed: the HTSC transformer which dramatically increases efficiency by using superconducting material, and the medium-frequency transformer which saves mass and losses by exploiting the fact that induction increases with frequency.[10]

In the field of *inverters* the main efficiency advances lie in power electronics. With IGBTs replacing GTOs, efficiency of these components in new stock has generally improved.

Asynchronous *traction motors* have become the uncontested standard solution in electric railway technology. In long-term perspective, permanent magnet motors may prove an interesting alternative to asynchronous motors in some areas.

Gears play a minor role in traction losses. There is R&D going on to develop a direct traction motor, e.i. one without gears. Permanent magnet motors and transversal flux motors are potential candidates for such a wheel-mounted construction[11].

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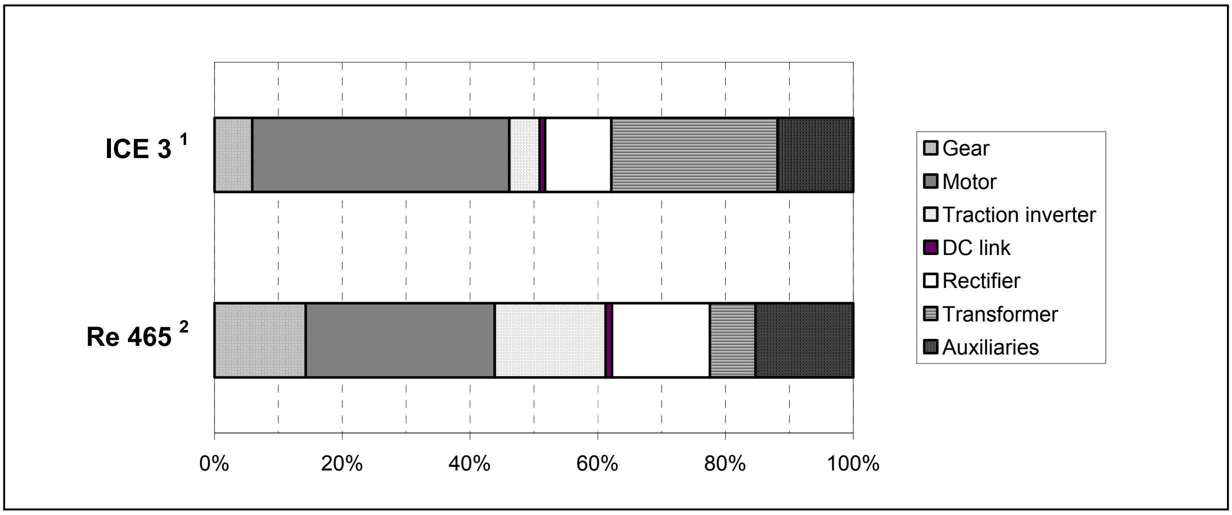
[9] Source: SNCF

[10] Kunz, et al. 1999

[11] http://www.bahntechnik.de/berlin/antriebstechnisc.html and Matsuoka (1997)

Figure 4: Energy losses for two trains (German ICE 3 EMU and Swiss Re 465 loco-hauled train) and respective operational patterns



Source: [1] Klose, Unger-Weber 2000

[2] Meyer, Aeberhard 1997a

Auxiliaries comprise a wide range of components and functions connected with traction (such as ventilation, brakes etc.). The energy share used for auxiliaries, especially coolers, is rather small for vehicles running at maximum load, but may rise to quite substantial levels for operation at lower power[12]. This offers some efficiency potential by introducing demand-operated solutions[13].

Apart from innovative traction components which will be available mainly in mid- or long-term perspective, considerable efficiency potential lies in intelligent control algorithms for the individual traction components.[14] A modification of the corresponding traction software is often a cost- and energy-efficient option.

Reducing conversion losses in electric traction

Technologies/strategies	**Example**
Transversal flux motor Optimisation of traction software Medium-frequency transformer HTSC transformer IGBT Wheel-mounted permanent magnet synchronous motor Switch-off of traction group	*Optimisation of traction software*[15] The power electronics of modern electric stock is operated by an on-board computer. The corresponding software is fixed by the manufacturer and usually not modified by the railway operator. However this software often offers potential for optimisation from an energetic point of view and can be modified afterwards in co-operation with the producer. The principle consists in changing the setpoints

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[12] Slattenscheck 1997

[13] Bänziger et al. 1995

[14] Meyer, Aeberhard 1997a

[15] Source: Meyer, Aeberhard 1997a

Ventilation control (in new stock) Ventilation control (retrofit) Loss reduction by optimised power intake	of relevant parameters such as voltage in DC link, magnetic flux in motor or pulse pattern in traction inverter. All the target values of these parameters have to be simultaneously optimised. The **theoretical saving potential** of such a measure can be **as high as 15%**. In practice, an ex post software improvement will **typically raise energy efficiency by 1-3 %** depending on vehicle and degree of software optimisation already realized by the manufacturer. For large series (such as DB's BR 101) even a small improvement potential of only 1% can economically justify such a measure. Software optimisation measures have been realized on the Swiss Re 465 locomotives.

4.2 The diesel case

Engine technology

Diesel engine technology has developed very dynamically in recent years. The main breakthrough in fuel economy was brought about by direct injection technology improving the energy efficiency of diesel combustion engines by 15-20%. This has been achieved by

- improvements in injectors (with multiple orifices and two-stage injection) and
- higher injection pressures (as a result of improvements in injection pumps and electronic control)
- The development of common rail technology has yielded some further improvements in injection technology.

Given high average ages of diesel fleets and the high power classes required, direct injection engines are only starting to diffuse into railway markets. Re-engining (replacing engines in old vehicles) programmes can substantially speed up this process.

The option of running diesel engines on regenerative fuel[16] ("bio-diesel") such as rape oil methyl-ester, has been studied by railways, but scepticism prevails at present due to ambivalent environmental impact and lack of production capacity for generalised use.

Transmission

The mechanical power produced by the combustion engine can be transmitted to the wheels in several ways. In rail vehicles three transmission types are generally in use:

- electric transmission

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[16] Natural gas is also discussed as an alternative fuel. Since it needs modified engines it will be discussed separately in section 6.

- hydromechanical transmission (also called "hydraulic" or "Voith" gear)
- mechanical transmission

Most heavy locomotives are diesel-electric. In Central Europe hydraulic transmission also plays an important role. For DMUs all three types are in use. From an energy efficiency point of view, electric and mechanical transmission present some advantages over the "Voith gear" as can be seen in Table 1. Modern diesel-mechanic vehicles with 16 speeds are very energy-efficient and can be considered for DMUs in a wide range of operation contexts.

If combined with an energy storage unit, diesel-electric power transmission becomes a very energy efficient traction technology as well. This issue will be addressed in section 5.

Table 1: Comparison of transmission systems in diesel traction

	Diesel–mechanic	**Diesel-electric**	**Diesel-hydraulic (Voith gear)**
Engine efficiency	equal	equal	equal
Transmission efficiency	~95%	~85%	~85%
Possibility for optimum engine load	high	high	low
Potential for recuperation	low[17]	high	?

Source: DSB

Auxiliaries

The auxiliaries (air compressor of the diesel cooling system, generator etc.) consume additional energy. The redesign of auxiliaries is expected to offer substantial optimisation potential but very little data is available in this field.

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[17] Some diesel-mechanic trains actually exploit regenerative braking to some extent. As an example the mechanical transmission of the DSB IC3 train set stays engaged under normal braking. This way the engine is motored by the running train. There is no fuel consumption, but the auxiliaries (air conditions, generator, air compressor) are powered by the engine.

Reducing conversion losses in diesel traction

Technologies/strategies	Example
Re-engining of diesel stock (replacement of engine) Diesel-mechanic transmission Biodiesel Fuel or oil additives for diesel traction Upgrading of engines Future developments in diesel technology Common Rail	*Upgrading of existing engines*[18] Due to the long useful life of railway vehicles there are a lot of old diesel locomotives around with a fuel economy far from optimised. They can be upgraded in order to improve injection and compression characteristics. Starting 1995 German DB AG has refitted a series of older locomotives. Apart from substantially reduced emission, **fuel economy was improved by 6%**. The measure is estimated to pay off in 4 to 5 years.

5 Regenerative braking and energy storage

The energy put into accelerating a train and into moving it uphill is “stored” in the train as kinetic and potential energy. In vehicles with electric traction motors (this includes electric and diesel-electric stock) a great part of this energy can be reconverted into electric energy by using the motors as generators when braking. The electric energy is transmitted “backwards” along the conversion chain. This is known as regenerative braking and widely used in railways. However, the use of dynamic braking does not necessarily imply that the recovered energy is used to save energy. Diesel-electric trains will often have dynamic brakes to save the braking pads and the recovered energy is just dissipated in brake resistors.

Energy recovery is especially powerful on local and regional lines with frequent stops. Nevertheless, even on high speed traffic regenerative braking offers potential for energy efficiency.

Although regenerative braking is in wide-spread use in many countries, there is still a great potential for increasing the share of recovered energy. The following obstacles for regenerative braking can be identified:

- Receptivity of catenary: Energy recovery is only an option whenever another train in the system can use the energy at the same time. The probability for this depends on train density and possible transmission distance. The latter is rather small in DC and 50 Hz AC systems and fairly big in 16 2/3 Hz systems.
- Old stock: many older vehicles are not equipped with dynamic (=regenerative) brakes.
- Braking power: For 3-phase motors the braking power is roughly the same as the tractive power. Whereas for MU trains with many powered axles this is usually sufficient for braking, loco-hauled trains, especially heavy freight trains, have to fill in the missing power by mechanical (or other dissipative) brakes.

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[18] Source: Schmidt 1996

- Operation concept of drivers' cabin: To a certain degree, the operation features of the drivers' unit can be more or less favourable for regenerative braking.
- Drivers' acceptance: Some drivers are more inclined to use regenerative brakes than others.

Efforts to promote the use of regenerative braking address one or various of these impeding factors.

If the technological conditions for regenerative braking are given, drivers' training and incentives can raise awareness and motivation for using regenerative brakes.

DC systems can be made more "receptive" for energy recovery

- by equipping substations with thyristor inverters. This makes them "reversible" and allows to feed back energy into 3-phase supply grid (an option especially relevant for DC systems).[19]
- by storing energy until it is needed by other trains. The storage medium can be installed on-board or in substations. There has been substantial progress in storage technologies such as flywheels, powerful batteries and super-capacitors over the last years with further improvements to be expected.

By means of energy storage diesel-electric vehicles can be converted into *hybrid vehicles* running on the power either generated by the diesel engine or released from storage medium. This facilitates an on-board energy management with two main efficiency features:

- The diesel engine is decoupled from demand variations of traction motors. This way the combustion engine can be run at point of maximum efficiency and surplus energy can be stored for later use.
- Braking energy can be recovered and stored on-board. This way diesel-electric traction can combine the advantages of both electric (energy recovery) and diesel traction (autonomy).

Regenerative braking and energy storage

Technologies/strategies	**Example**
Diesel-electric vehicles with energy storage Regenerative braking in 16,7 Hz, 15 kV systems Radio-controlled double traction in freight trains Regenerative braking in freight trains On-board use of braking energy in diesel-electric stock Revision of limit value for longitudinal forces in the train Inverter unit for DC substations On-board energy storage in DC systems	*Stationary energy storage in Cologne light rail network* Since 2000 an energy storage system is tested in service in the Cologne local transportation network. The flywheel with an maximum energy content of 6,6 kWh and a maximum power of 600 kW was installed in a substation of the DC supply grid. Braking energy which otherwise would have been lost in brake resistors is stored and can be used later for an accelerating train. Comprehensive tests demonstrate that energy storage **saves about 24 % of the total energy consumption**. Additional cost effects can be

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[19] Moninger, Gunselmann 1998

Stationary energy storage Fly-wheels (storage technology) Batteries (storage technology) Double-layer capacitors (storage technology) Superconducting Magnetic Energy Storage (storage technology) Regenerative braking in DC systems Regenerative braking in 50 Hz, 25 kV systems	realized due to the fact that energy storage reduces power peaks and thus the energy price.[20] However, due to technical difficulties (not specified in detail), the fly-wheel storage has been given up and is no longer operating.

6 Innovative traction concepts and energy sources

Today’s railway transport is entirely supplied by electrically and diesel driven vehicles. In mid-term perspective, pressure on diesel traction could grow, mainly due to tightening European emission standards on diesel engines. Since electrification is economically not reasonable in many cases, alternative concepts for autonomous traction might be needed in future railways. Different solutions are discussed in this context, but the most promising are undoubtedly fuel cells and natural gas propulsion.

Fuel cells generate electrical energy by converting hydrogen and oxygen into water. This electrical energy of this process can be used to drive a traction motor. The fact that fuel cells operate with almost no harmful emissions makes them a very interesting technology. However the overall energy balance is extremely dependant on the energetic pre-chain, e.i. the way the hydrogen is produced. In addition, technological and financial hurdles for a railway application are still high.

Natural gas propulsion is another alternative to diesel traction. Natural gas produces less harmful emissions and less noise than diesel fuel. Since the energy density of natural gas is low compared to diesel, the fuel has to be compressed (=CNG), liquefied (=LNG) or adsorbed (=ANG). The main technological problems lie in low power output and bad fuel economy of existing natural gas engines.

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[20] Godbersen, Gunselmann 2001, calculations by IZT

New traction concepts and energy sources	
Technologies/strategies	**Example**
PEM fuel cell Natural gas Hydrogen engine Gas turbine	*CNG railcar at SNCF*[21] SNCF realizes a project on natural gas propulsion involving a railcar running on compressed natural gas (CNG). Simultaneously, the emerging technology of adsorbed natural gas (ANG) is explored. Natural gas is seen by SNCF as today's best short-to-medium-term option for replacing diesel traction. Main benefits are seen in ➢ less emission ➢ less noise ➢ less smell and smoke

7 Non-conventional trains

Discussion about alternatives to the conventional wheel track system of trains has been going on for some time. New concepts normally seek to overcome some of the major limitations of railways, namely the speed limitations of the wheel-track and pantograph-catenary systems, the heavy on-board traction equipment and the immense air resistance in high-speed traffic.

The *Transrapid (or Maglev)* clearly dominates the European discussion on alternative train concepts. Its high speed (400 km/h and more) makes it hardly comparable to any other means of ground transportation. As far as energy efficiency is concerned, some studies indicate that it may be more efficient than track-borne high-speed traffic, as long as equal velocities are compared (which is obviously not possible for maglev top speed). The biggest obstacle lies in the high costs and incompatibility of the infrastructure. An even more ambitious concept is the one pursued by the Swissmetro, which envisions maglev high-speed trains running in partly evacuated underground tubes.

Innovative train concepts	
Technologies/strategies	**Example**
Magnetic levitation technology (maglev) Swissmetro	*Swissmetro*[22] Swissmetro is a magnetic transportation system running inside partially evacuated underground tubes. The system could achieve speeds between 300 and 500 kilometres per hour, which comes close to the lower range of short-haul air traffic. Some experts see Swissmetro as an environmentally very attractive alternative to both air and high-speed ground transportation, since noise pollution and energy consumption as well as negative impacts on residential areas and the

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[21] Chabas et al. 2001

[22] Ernst et al. 2000

	landscape could be substantially lower.

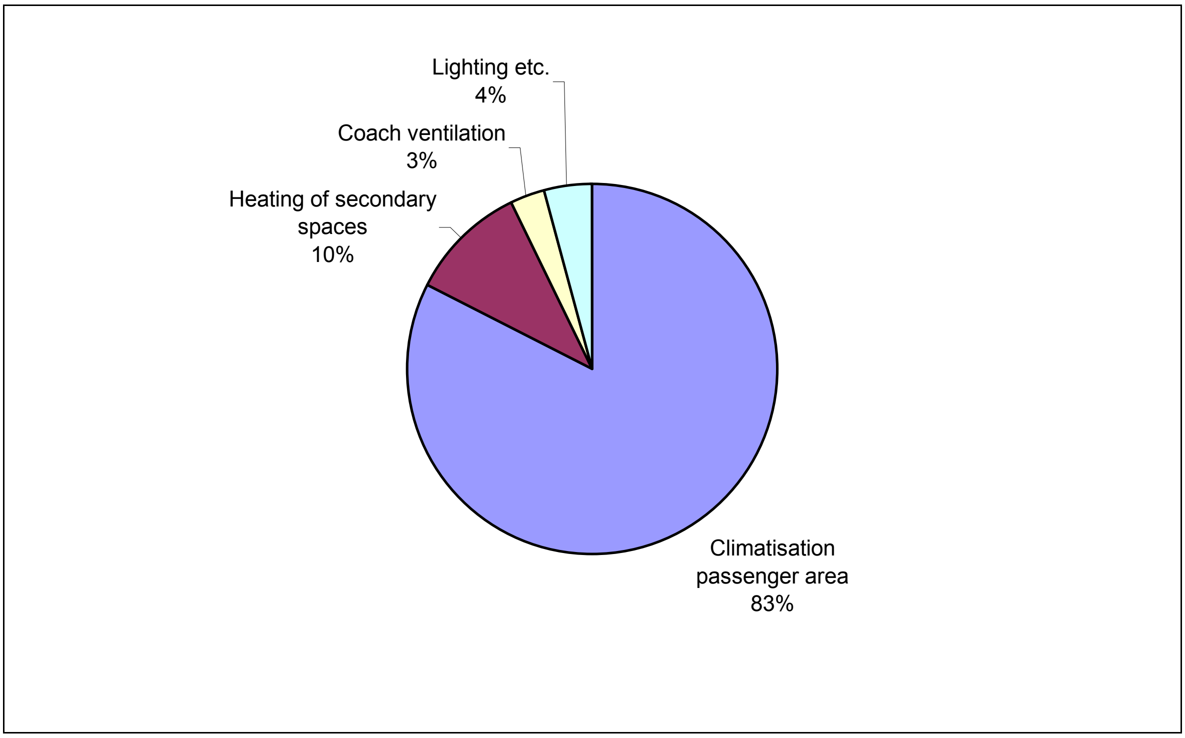
8 Reducing energy consumption for comfort functions

Comfort functions during service

Apart from energy needed for train motion, passenger trains consume energy for comfort functions. In Central and Northern European countries, this energy usually accounts for about one fifth of the total energy consumption of a train during service.

Since air-conditioning (heating in winter and cooling in summer) accounts for the biggest share of comfort energy, the total demand for passenger comfort highly depends on the region (e.g. Italy vs. Norway) and season. Figure 5 shows the situation for very low (–20 °C) or very high (+40 °C) outside temperature. For temperatures in between the energy needed for heating or cooling is lower, being zero for approximately 12 °C.[23]

Figure 5: Energy demand of comfort functions for extreme outside temperatures (- 20 °C or + 40 °C)



Source: Knau 1993

Air-conditioning has to replace heat lost in two ways:

- heat transmission through walls, doors, windows and ceiling of car-body

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[23] These figures refer to occupied coaches. For 15 °C outside temperature, coaches have to be cooled already since every passenger contributes to heating with about 100 W.

- heat lost by ventilation. About 20 m^3 of fresh air are typically added to a passenger coach per seat and hour. For a coach with 80 seats, this means 1600 m^3 of air to be heated or cooled to room temperature every hour.

These heat losses can be reduced by different approaches. Heat transmission can be minimised by coach insulation (which is to some extent possible by refit measures). Heat lost through ventilation can be reduced by a demand-controlled operation of the fresh air intake. In such a system ventilation is regulated according to actual occupation rather than number of seats. This can be realized by means of CO_2-sensors.

Other concepts aim at the heat source rather than the heat demand. Waste energy produced by under-floor traction equipment in MU stock can be used to heat passenger coaches. In many cases, the amount of thermal energy produced this way is sufficient to supply all the heating energy needed. The use of waste heat can be facilitated by heat exchangers. This is already realized in many DMUs but not yet in EMUs. Future concepts using the Organic Rankine Cycle (ORC) could even permit to produce electric power for comfort functions from waste heat.

Optimisation of comfort functions during service

Technologies/strategies	**Example**
Coach insulation Modification of target temperature in passenger coaches Smart windows Improved operation control for air-conditioning ORC technology to use waste heat in MUs Heat exchangers to use waste heat in MUs CO_2-based demand control for coach ventilation Excess ventilation	*CO_2-operated ventilation* In order to ensure air quality passenger coaches are ventilated with 20 m^3 of outside air per hour and seat. This system is not very efficient since for low occupancy the ventilation is excessive. CO_2-concentration in the air is a good indicator for the number of passengers actually present. Installation of CO_2-sensors and a control circuit for ventilation therefore allows a demand-oriented and energy efficient ventilation of passenger coaches. A pilot project realized in NS Reizigers showed that **climatisation energy may be reduced by 20%. Correspondingly, total energy consumption is reduced by 3-4 %.** Demand-oriented ventilation is an attractive option for new stock but may also be installed in some older stock. However retrofit measures are not always economically feasible. Technological challenges lie in: ➢ sensor stability: state-of-the-art CO_2-sensors suffer from strong drift and have to be calibrated regularly ➢ additional bad air sensor: CO_2 is a good indicator for occupancy but should be combined with a sensor for bad smell (VOCs etc) in order to improve air quality even more. Corresponding sensors exist for houses but do not yet meet railway requirements.

Comfort functions in parked trains

Parked trains consume considerable amounts of comfort energy:

- They have to be heated and lighted when accessed by cleaning personnel.

- Trains must already be heated up when passenger service starts in the morning.
- A certain minimum temperature has always to be maintained in the coaches in order to avoid freezing of toilets etc.

In practice the energy consumption of parked trains is much higher than actually needed for the purposes described above. Due to planning and organisational hurdles trains are often heated all night leading to huge energy demands in winter. In some cases this energy demand amounts to about 10% of the entire energy consumption of the train.

There are several ways to tackle this problem such as an automatic control of comfort functions in order to limit heating to those time periods when it is actually needed. These measures are usually very cheap compared to the huge savings in energy costs. Their implementation often conflicts however with existing operation and organisation schemes.

Comfort functions in parked trains	
Technologies/strategies	**Example**
Control of comfort functions in parked trains Coupling of parked trains for common energy supply	*Automatic control of comfort functions in parked trains* Parked trains are usually heated overnight in order to guarantee comfort functions at service start. In countries of Central and Northern Europe this consumes considerable amounts of energy. Swedish SJ has developed an automatic control (called PLC - Programmable Logistic Control) to tackle the problem. The system optimises the use of electricity so that heat and light is minimised during parking hours, but automatically switched back on well before service starts again. At the end of service, coach temperature is lowered to 12° C, and raised again to service temperature one hour before service start. The system is currently tested in a pilot project involving 4 coaches. The **saving potential** of the measure is expected to lie **between 3 and 5 % per vehicle** (with respect to total energy consumption).[24]

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[24] Source: SJ, calculations by IZT

9 Energy efficient driving

Given a train with a certain „hardware“ (mass, aerodynamic profile, traction equipment) and a trip from A to B, energy consumption is far from being fixed. Since the number of stops and subsequent accelerations as well as the average speed have an immense influence on the train’s energy demand, one has to look at the driving pattern, the so-called „trajectory“, i.e. the speed over time diagram.

This pattern is not only influenced by the *time-table*. Even for a given driving schedule, there is still room for optimisation by an energy efficient *driving style* or by increased *traffic fluidity*.

9.1 Time-table

From a theoretical point of view, the energetically most efficient trip would be one at low speed and with no intermediate stops. For obvious reasons this is not an option for railway operators. Time-table planning is driven rather by customer orientation and cost efficiency than by energy efficiency. Nevertheless, there is not always a conflict between an energy efficient and a customer-oriented time-table.

Here are two examples:

- Time-tables usually provide certain time buffers (also called recovery margins) which are added to the calculated minimum travelling time in order to allow for unpredictable delays on the way without compromising on punctuality. Elasticity of average energy consumption with respect to buffer times is very high, i.e. slightly increased buffer times lead to strong reductions in energy consumption, especially if original buffer times were low (<5% with respect to shortest time driving strategy). Buffer times are also a key factor for punctuality and surveys demonstrate that most passengers give higher importance to punctuality than to minimum reductions in travel time. As a consequence, there is optimisation potential for both energy efficiency and service quality.
- On many lines there exist low-speed sections that could be removed without major costs. This would not only reduce travel time but also reduce energy consumption since the deceleration and subsequent acceleration caused by speed limits on short parts of the line usually overcompensate the energetic effect of reduced air drag in speed limit sections.

Time-table	
Technologies/strategies	**Example**
Energetic optimisation of timetable	*Timetable optimiser as part of the Siemens Metromiser* Siemens and the Technical University Berlin have developed the Metromiser, a driving advice system for light-rail, suburban and metro systems. The Metromiser consists of two components: an on-board unit (OBU) and the timetable optimiser (TTO): The timetable optimiser is an off-board based software program checking the energy efficiency of timetables. Using basic data (acceleration, rolling behaviour of the train, topology, passenger flows etc) it draws up a new energy-optimised timetable fitting in with the existing running schedule of the railway network.

9.2 Reduced standing times in stations

The boarding time in stations has a strong impact on punctuality. This is relevant for energy efficiency because delays reduce the potential for energy efficient driving. There are several conceivable causes for delayed departure at a station:

- "Internal" railway reasons
- High passenger numbers leaving or entering the train
- Passengers looking for the "right" car (according to their seat reservation)

The situation can be improved by introducing better platform information systems indicating the exact position of the individual cars. A different approach is taken by the concept of consciously delayed trains explained in the example below.

Reduced standing times in stations	
Technologies/strategies	**Example**
Systematic train delays	*Strategy of consciously delayed trains*[25]
Passenger information to reduce boarding time at stations	After passenger boarding, trains frequently have to wait more time in the station until the timetable permits departure. This is a waste of precious time given the importance of time buffers for energy efficient driving. The strategy of consciously delayed trains is intended to exploit the time periods usually wasted in stations. The train is driven according to a “shadow” schedule, which is identical to the official schedule at the main stations but slightly delayed at the intermediate stations. This way the driver can immediately leave the station after passenger boarding and has more buffer time for energy efficient driving strategies. The delays (< 2 min) can be chosen small enough in order not to bother passengers. Punctuality at the main line stations is ensured.

9.3 Driving advice systems

For a given time-table there are still some degrees of freedom for the driver. In fact, if the driver runs at the allowed top speed whenever possible and then brakes at maximum braking power directly before the station, the train will arrive before time. Within certain limits this time buffer permits a more energy efficient driving style, provided that no unexpected stops occur on the way.

There is a variety of energy efficient driving strategies making use of time buffers. The most important ones are:

- *Coasting:* The driver shuts off the traction motors as early as possible in order to reach the station on time. This avoids braking and leaves deceleration to air resistance and friction.

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[25] For details see: Euro Transport Consult 1997

- *Continuous speed optimisation:* A more sophisticated approach is one where the speed pattern of the remaining part of the trip is constantly optimised and speed recommendations are calculated for the driver. The resulting driving strategy may include reducing the train speed before entering a steep downhill grade in which the train will accelerate due to gravity. Algorithms exist which even take into account the load dependence of the efficiency of traction equipment.

Depending on their experience and skill, many drivers have always used timetable buffers to run part of the trip with idling motors. Today, driving advice systems exist which calculate (and continuously update) the optimum driving strategy much more exactly than any driver could. They are based on train position (GPS or other), train, track and timetable data as well as algorithms to calculate driving recommendations.

Driving advice systems	
Technologies/strategies	**Example**
Energy efficient driving strategies Energy efficient driving by low-tech measures Driving advice systems in suburban operation Driving advice systems in main line operation Driving advice systems in freight operation	*German driving advice system ESF* In co-operation with Hannover University, German DB AG developed a driving advice system called ESF (Energiesparende Fahrweise). The system gives coasting advices based on track and train data, timetable, position and time. Continuous speed optimisation could also be given by ESF but is presently not activated. The savings to be realized strongly depend on timetable, operational situation and degree of energy efficient driving previously realized by drivers' skill. An **average saving potential of over 5 %** on German ICE has been confirmed by tests and calculations.[26] A pilot on ICE 1 and 2 was realized in 2001. At the end of 2002 ESF is planned to start in all ICEs. There are however some problems as far as availability of track data is concerned. Exact structure data of the entire network is needed in a reliable and convenient digital version in order to successfully run the new electronic timetable method (EBuLa) which is also required for ESF.

9.4 Traffic fluidity

As previously described, energy efficient driving is only an option for trains running ahead of time. This requires that no unexpected stops and delays occur on the way. The condition becomes more and more difficult to realize in today's railways since existing infrastructure has reached its capacity limits in many countries. Traffic fluidity is a major issue for energy efficiency since any additional stop (and subsequent acceleration) along the way requires additional traction energy. Such train conflicts are especially relevant in bottlenecks of the infrastructure, such as junctions and lines with high traffic density.

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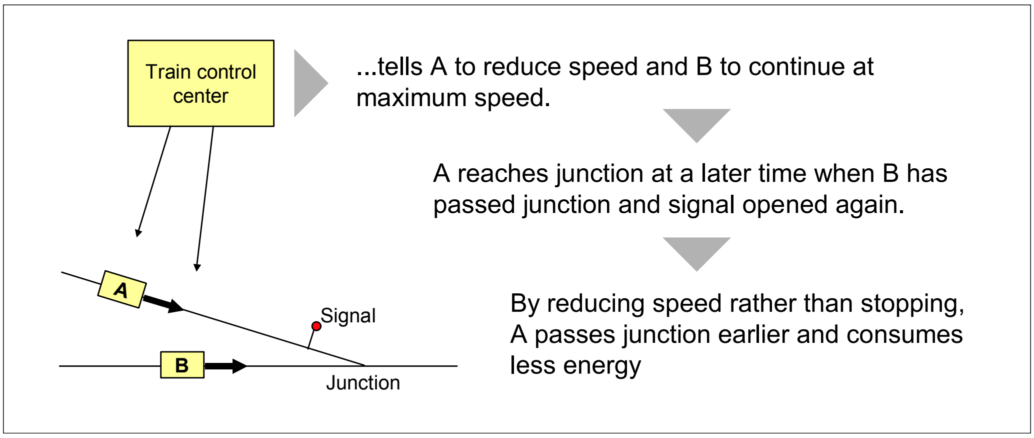
[26] Sanftleben et al. 2001

Figure 6: En example for the integration of traffic situation into driving advice system



Source: IZT

Since traffic fluidity is concerned with train interactions, it needs to be addressed by a systemic rather than a single-train approach. The advent of powerful simulation programmes, mobile communication networks and advanced telematic solutions offer a huge potential for systemic optimisation of train operation and train control.

Train conflicts may be eliminated or alleviated by strategies such as:

- Infrastructure expansion: Building new tracks is the "easiest" way to eliminate capacity problems and increase traffic fluidity. In short term perspective, this is usually not an option due to high investment costs. From an environmental point of view, strategies with less area consumption are clearly preferable.
- Integration of traffic situation into driving advice system: If the exact position of all trains in the controlled area is known at the train control center, train conflicts leading to signalled stops may be foreseen at an early stage. The speed regime of the involved trains may then be modified in order to avoid the conflict or reduce its effects (delays, energy consumption through stop-and-go driving). An example for such a situation is shown in a simplified manner in Figure 6. Obviously such a system requires IT tools to support decision making at the control center as well as a communication channel between the control center and the train (GSM or other).
- Moving block: Replace static train control and signalling by more dynamic approaches. Moving rather than fixed block control is a promising approach, which is however still far "down the track".
- Demixing and speed harmonisation: Marked speed differences between trains running on the same track increase the probability of train conflicts (outside junctions). Speed homogeneity on a given line may be raised either by traffic separation (slow freight and regional trains don't use the same lines at the same time) or by speed harmonisation (making freight trains and regional trains faster in order to avoid conflicts with high-speed traffic).

Traffic fluidity	
Technologies/strategies	**Example**
Optimisation of train operation by control center Moving block Automatic train control Demixing of railway infrastructure Speed harmonisation	*Impact of traffic situation on energy consumption* A study[27] made by ETH Zürich, Adtranz and SBB in 2000 revealed a considerable influence of traffic situation on energy consumption. Measurements realized on IC-2000 tilting trains running between Luzern and Zurich demonstrated that those trips affected by unexpected stops at signals showed an **energy consumption 10 – 15 % higher** than unimpeded trips. This indicates the big saving potential offered by traffic fluidity measures.

10 Load factor and flexible trains

Due to the unfavourable ratio of dead weight over total weight, the energy demand of a *passenger train* is virtually independent of the load factor (number of passenger-km in relation to seat-km). This is the reason why raising occupancy probably offers the biggest potential to save energy per passenger-km.

Of course, this is mainly a task for the marketing department. Since marketing strategies for railways would be an entire study in itself, they will not be covered by the EVENT project. There are however more technological ways to increase the load factor, such as adapting train length to passenger numbers in a more flexible manner. Since in MUs the traction components are distributed along the train, the cars of a given set cannot be decoupled. This tends to reduce flexibility of train length. On the other hand, short train-sets can be ordered in order to recover some of the modularity in train formation typical for loco-hauled train operation. Short train-sets offer two main benefits which are both relevant for energy efficiency:

- Capacity can be adapted to variable demand (e.g. rush-hour vs. late evening in suburban transport)
- Trains can split up in two train-sets at a certain point of the route to serve two destinations. Passengers do not have to change trains and the operator saves costs.

In the *freight sector*, the specific advantages of rail are ideally exploited by long trains transporting heavy low-value mass goods from point A to point B. The specific advantages of road transport are best realized by small high-value goods that have to be transported in small quantities.

During the last decades, the latter type of freight has constantly increased while mass goods have lost importance. For smaller amounts of cargo the conventional production system in railways has been the one illustrated in solution 1 of Figure 1. This system is cost and time-consuming since the individual units have to be coupled and decoupled at shunting points and often have to wait until enough units have gathered in order to form a long train on the main relation. These problems are one of the reasons why the modal split has changed in favour of road transport.

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[27] Meyer et al. 2000

A major challenge for freight traffic is posed by the different starting points and destinations to be served. The bundling and separating of train freight takes too much time and is too expensive to meet today's logistics requirements.

The most obvious solution to this problem is to make freight trains more truck-like, i.e. replace long loco-hauled trains by smaller units with a high degree of modularity and flexibility.

These shorter units can be realized in different ways:

- Short conventional loco-hauled freight trains
- CargoSprinter consisting of multiple platforms, the end ones of each group are powered by a small diesel motor. The intermediate platforms are unpowered. Several of these trains can be linked together and run in MU (multiple unit) configuration.
- Individual self propelled freight cars: Each wagon is powered and runs independently (usually requiring driverless operation).

Flexible train concepts	
Technologies/strategies	**Example**
Self-propelled freight cars Modular train sets for passenger operation	*Growing modularity in German ICE generations* Whereas ICE 1 in typical formation is a long train with a locomotive ("Triebkopf") on each end, the ICE 2 is a so-called half train with a locomotive on one end and a small driving unit (without installed power) at the other end. Two half trains can be combined to a full train comparable in length to the ICE 1. To a certain extent this vehicle concept allows for an adaptation of train capacity to actual demand. For example on the service Berlin-Cologne the full train (2 half trains) is split up into two half trains which continue on different routes. In the case of the ICE-T tilting train, flexibility has been pushed even further. The train was ordered in two sizes: one 5-coach and one 7-coach train-set.

11 Measurement and documentation of energy consumption

Measuring or calculating energy consumption does not save energy by itself. A better knowledge of energy consumption will provide however valuable data to identify potential for optimisation as far as regenerative braking, energy efficient driving or stopping patterns are concerned.

Energy consumption can be measured most effectively by means of *energy meters* installed on trains. They allow for an exact monitoring not only of energy intake, but also of recovery rate (by regenerative braking). Energy meters are also an essential condition for energy billing, an issue gaining growing importance in liberalised railway markets. Only if private train operators have to pay for the energy actually consumed rather than a system average, they do have an incentive to use energy efficient stock or apply regenerative brakes.

Instead of measuring the energy actually consumed in service, one can calculate the demand with modern simulation tools. The results may be collected in a database of traction consumption in order to provide relevant data for a number of purposes including timetable planning and determination of ideal train constellations.

Measurement and documentation of energy consumption	
Technologies/strategies	**Example**
Energy meters (electric) Diesel flow meters Database of traction consumption	*The TEMA project*[28] In 2000 DB Energie tested the installation of energy meters in several trains as well as data transmission and evaluation in the TEMA project. The meters measure both energy intake and recuperation energy. Energy metering is seen as an essential prerequisite for determining the influencing factors of energy consumption and monitoring the success of energy saving measures. Evaluation of individual sets of data shows that the energy consumption differs by up to 20% from one day to another. This underlines the importance of individual conditions for energy consumption. They are not taken into account by theoretical calculations and simulations presently used to determine energy consumption.

12 Management and organisation

Procurement strategies

Procurement strategies are one of the major factors determining future lanes of technology development. Manufacturers only produce what they can sell and only develop what they are confident they can sell in the future. This is not as trivial as it may sound. A number of innovations that could reduce LCC of rolling stock are not developed by manufacturers because the purchasing strategies of railways do not create any incentive to do so.

LCC are a part of most of today’s purchasing contracts, but often they are outweighed by initial investment when it comes to actually making a procurement decision. Some countries seem to give LCC more relevance than others. An analysis could show success factors for making procurement decisions more LCC-driven.

LCC and other energy-related quantities may be effectively optimised by creating incentives for manufacturers. For example, railways may agree with manufacturers on a so-called bonus-penalty system. A target value for some relevant quantity e.g. mass per seat is specified. If manufacturers do better than that they are rewarded by a price increment, if they do worse, there's a certain price reduction.

In order to make energy efficiency of new stock more transparent and comparable, a standard definition and declaration of efficiency is needed. At present manufacturers usually give efficiency of power train at maximum load, which tells little about losses

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[28] For details cf. Treige, Olde 2000

occurring in a real application context. A representative and verifiable reference cycle (like the F-cycle for diesel vehicles) has to be defined in order to allow railways to compare the energy efficiency of different products.

Procurement strategies	
Technologies/strategies	**Example**
LCC-driven procurement Reference cycle for energy efficiency Bonus/penalty rules	*Bonus/penalty rules at NS Reizigers*[29] In several recent rolling stock projects Dutch NS Reizigers decided to create an incentive for suppliers to reduce weight of supplied stock. An agreement was made with manufacturers fixing maximum weight as well as a bonus/penalty for each kg of weight reduction/increase beyond that target value. The amount of the bonus is based on the energy cost benefits NS Reizigers realizes as a consequence of the weight reduction.

Awareness of personnel and incentives

The energetic performance of railways is not only determined by “hardware” (rolling stock, infrastructure etc.), but also by human factors. Even the most efficient train equipped with regenerative brakes and a drivers’ advice tool for coasting has a bad energy performance if drivers are reluctant to make use of these features.

It is therefore crucial to raise energy awareness and motivation of personnel. This can be done by

- training seminars, information campaigns etc.
- monetary incentives (give drivers a fixed share of energy costs saving)
- non-monetary incentives (drivers’ competitions etc.)

It is important that these measures do not exert pressure or excessive control on those involved, since experience teaches that this tends to raise reluctance rather than motivation.

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[29] Dongen, Fiechter 2000

Awareness of personnel and incentives	
Technologies/strategies	**Example**
Incentives for drivers Training programs to raise awareness of personnel	*Contest "Energy optimisation of 'Metropolitan' trains"*[30] Parts of the personnel operating the 'Metropolitan' trains running between Hamburg and Cologne were invited to participate in a contest for saving energy in regular service. The drivers were informed about different saving measures (e.g. increased use of recuperation brakes) and the outcome of the measure was measured by means of on-board energy meters. The contest showed a strong influence of drivers behaviour on energy consumption as well as the effectiveness of measures to raise the awareness of personnel.

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[30] Source: Deutsche Bahn AG