EVENT
Evaluation of Energy Efficiency Technologies for Rolling Stock and Train Operation of Railways

Final Report

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1 Executive summary

Energy efficiency is a key challenge for today's railway companies for reasons of cost effectiveness and environmental competition. There is general agreement that there is considerable saving potential in railways both in the short and long term. In an effort to provide a reliable data basis and to enhance the knowledge transfer on energy efficiency technologies, the UIC commissioned the Berlin-based IZT to realize a two-year project on energy efficiency technologies and strategies for railways.

The key aim of the EVENT project is to provide a global state-of-the-art overview over energy efficiency technologies as well as relevant experiences and projects and to make this information easily available by means of a web-based database. The technological, economic and environmental potential of energy efficiency technologies is evaluated by means of a standardised evaluation tool. Furthermore, key success factors and impeding factors for technology dissemination are analysed and recommendations for implementation strategies are derived. The focus is put on the energy directly consumed by trains. The energy efficiency of stationary installations is not treated. Technology fields and saving strategies addressed range from the optimisation of traction technologies and weight reduction to systemic optimisation and management approaches.

Whereas technological improvements to rail vehicles will be rather incremental and require a long time for diffusion there are many promising short- and medium-term saving strategies aiming at an optimised control and use of present technologies or operational improvements. Many of them require only minor investments in new technologies and often rely on "soft" factors such as training programmes. An enhanced use of energy efficient driving strategies and regenerative braking are among the most promising measures. In long-term perspective the introduction of innovative traction technologies, the integration of energy efficiency targets into vehicle strategies and an optimisation of railways as a system will yield considerable further steps towards an energy-efficient (and cost-effective) railway operation.

The creation of favourable framework conditions turns out to be of equal importance as progress in R&D. This includes procurement strategies as well as well-defined financial interfaces between functional divisions of railway companies. The payback and profitability strongly depend on scale effects reached within or outside railway markets as well as on the future development of energy prices.

The findings of this study are intended to serve as a reliable data basis and reference frame for railway operators. National energy efficiency strategies may be derived by putting the output of EVENT into the context of specific national conditions and other challenges faced by railways such as deregulation and changing demand structures especially in the freight sector.
2 Summary

2.1 The EVENT project

Energy efficiency is an issue of growing relevance for the competitive position of railway companies. The reputation of railways as the transport mode of least environmental impact could dwindle in the future with negative consequences both for railways' market share and for its standing in policy making. In addition, deregulation and privatisation processes throughout Europe have increased the pressure on railway operators to be cost-effective and competitive within their networks.

There is wide-spread consensus among experts that the energy saving potential in railways is large. Most railway operators have embarked upon efforts to exploit this potential in one field or another. Systematic approaches are rare and knowledge transfer on energy efficiency technologies and measures is often sporadic.

The Subcommission Energy Efficiency (SCEE) of the CTR Committee of the UIC therefore commissioned the Berlin-based IZT to realize a two-year project on energy efficiency technologies and strategies for railways. The Railway Environment Centre of Deutsche Bahn AG was responsible for the Project Management. The key aim of EVENT is to provide a global state-of-the-art overview over energy efficiency technologies as well as relevant experiences and projects and to make this information easily available by means of a web-based database. The technological, economic and environmental potential of energy efficiency technologies and strategies is evaluated by means of a standardised multi-dimensional evaluation tool specifically tailored to the aims of this project. Furthermore, key success factors and impeding factors for the dissemination of these technologies in railways are analysed. Using the ample basis of evaluated data on technologies and framework conditions compiled in the course of the project, recommendations for implementation strategies and lanes of action for all relevant technology fields are derived.

The focus is put on the energy directly consumed by trains. The energy efficiency of stationary installations is not treated. Both passenger and freight transport and all relevant traction systems are covered. Apart from on-board technologies, saving strategies on the system level concerned with train control or traffic optimisation as well as management or organisational approaches are addressed in detail.

2.2 Technology fields and saving strategies

The energy consumed by a train can be split up into four main portions:

1. Energy needed to accelerate the train and move it up mountain slopes
2. Energy needed to overcome running resistance (friction and air drag)
3. Energy needed for on-board purposes such as comfort functions in passenger trains
4. Energy losses in traction or energy conversion equipment

All energy saving efforts in train operation aim at one or several of these items.
Weight is a decisive factor for the energy demand of a train. New materials and lighter traction components still offer some potential in this field. Apart from this component-based approach, the approach of system-based lightweight design aims at the weight-optimised solution for the whole system. This includes concepts such as articulated trains with Jacob-type bogies as well as more innovative approaches such as curve-steered single-axle bogies or future suspension technologies based on mechatronics.

In high-speed passenger trains and in freight trains air resistance is a key driver for energy consumption. Covering bogies with smooth fairings is the most promising measure to reduce air drag of high-speed trains. In freight transport there is a huge (theoretical) reduction potential to be exploited by covering open freight cars and introducing an aerodynamically favourable car order in train formation.

By optimising space utilisation, more seats can be fitted into a passenger train with only minor increases in train mass and air drag. The result is a considerable reduction in energy consumption per seat. Both double-decked and wide-body train design offer a quantum leap in overall energy efficiency. However, the compatibility with infrastructure and the gauge requirements of interoperability pose strong limitations especially on wide-body design. The replacement of locomotive-hauled trains by multiple units (MUs) is another promising means for increasing the number of seats per train length.

Today’s state-of-the-art electric traction components (AC asynchronous traction motors with IGBT inverters) are very mature and offer little potential for further energetic optimisation. However, substantial short-term improvements can be realized by optimising the control of these components and their interaction. In long-term perspective, quantum leaps in energy efficiency could be achieved by the next generation of traction components such as wheel-mounted drives or transformers based on superconducting material.

Main efficiency gains in diesel traction technology will come from the gradual transfer of recent advances in fuel injection and electronic engine management from automotive to railway markets. Long-term options for substituting diesel traction range from natural gas engines to fuel cells.

Modern rail vehicles with three-phase induction motors allow for the recovery of energy while braking. The actual recuperation rates are strongly influenced by the supply system and traffic density. While in most AC networks, the main barriers are non-technological, DC networks can be technologically upgraded to enhance recovery rates. Solutions range from stationary or on-board energy storage systems to inverter units in substations. In some state-of-the-art diesel-electric locomotives an on-board use of recovered braking energy is feasible.

The energy consumption of comfort functions represents a substantial part of the energy demand of passenger trains. The current degree of optimisation of these systems is arguably much lower than that of traction components and the theoretical saving potential is accordingly high. Promising measures include the revision of temperature target values, intelligent control tools for air-conditioning as well as a generalised use of waste heat from traction components. Intelligent control systems for parked trains may reduce the energy demand of stand-still periods considerably.

Energy efficient driving is one of the most promising strategies to save energy in railway operation. It covers a wide range of measures and approaches ranging from
instructions and training programmes for an "unaided" energy efficient driving style to sophisticated electronic driving advice systems (DAS).

In a system-wide perspective, a modern traffic flow management based on telematics offers huge theoretical saving potential by smoothening speed profiles and avoiding stop-and-go driving in bottlenecks. This covers a number of strategies such as moving block systems and linking on-board DAS to the control centre level.

The energy efficiency performance of any transport mode is strongly sensitive to the occupancy rate. The average load factor in railway operation cannot only be raised by marketing strategies but also by technological options, such as more flexible vehicle concepts allowing for an adaptation of train length to demand variations. In passenger service, short modular MU train-sets prove to be the most promising concept. In the freight sector, the situation is quite different. In order to respond to structural changes in freight markets, the vehicle strategy should aim at replacing long loco-hauled trains by smaller units with a high degree of modularity and flexibility.

Energy meters provide consumption data which are more reliable than those generated by simulation. An energy debiting system based on actual consumption creates an economic incentive for operators to save energy. Furthermore, energy meters are a powerful tool to improve the monitoring and communication of energy saving measures.

Important impulses for an energy efficient train operation may also come from management and organisation. Procurement departments can provide additional incentives for manufacturers to produce energy efficient stock. Training programmes and incentive systems may be set up to raise the awareness and motivation of personnel for energy efficiency matters.
2.3 Recommendations concerning individual technology fields

For the most relevant technology fields recommendations are given. They are classified by time horizon and ranked by priority. The following table shows an overview over the recommendations with highest priority. A brief description of the recommended measures is given at the end of this section.

<table>
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<tr>
<th>Short term</th>
<th>Medium term</th>
<th>Long term</th>
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<td>Study potential for brake energy recovery</td>
<td>Traction group switch-off</td>
<td>Integrate recovery and storage options in early development stage</td>
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<td>Re-engining/upgrading programme for the diesel fleet</td>
<td>Assess and test options to enhance recuperation rates in DC systems</td>
<td>Link traffic management to on-board driving advice units</td>
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<td>On-board use of recovered braking energy</td>
<td>Control of comfort functions in parked trains</td>
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<td>Optimise set values for temperature and ventilation</td>
<td>Energy meters</td>
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<tr>
<td>State-of-the-art features of air-conditioning</td>
<td>Driving advice systems for suburban lines</td>
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<td>Potential for energy efficient driving</td>
<td>Driving advice systems for main lines</td>
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<tr>
<td>Revise timetables and speed limits</td>
<td>Single-axle running gear</td>
<td></td>
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<tr>
<td>Assess operability of double-decked and wide-body stock</td>
<td>Aerodynamic ordering in freight trains</td>
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2.4 Implementation factors

The energy efficiency of railways is not only determined by the pace of technological progress but by a number of framework conditions inside and outside railway companies.

**Payback and profitability** are decisive factors for the technology implementation. The initial investment for innovative technologies strongly depends on scale effects reached within or outside railway markets. The payback of energy saving measures obviously improves with growing energy prices. However, the liberalisation of energy markets, concentration processes among energy suppliers and political instability in oil-producing regions make future price developments very difficult to predict.

The **deregulation of railway markets** will have indirect effects on energy efficiency technologies. Vertical disintegration, privatisation and intramodal competition of European railways will have both positive and negative impacts on the implementation of innovative technologies.

Many technologies cannot be introduced by railways themselves but rather have to be integrated by manufacturing companies into the design of rolling stock. It is therefore crucial that the **procurement** departments of railway operators offer clear incentives to industry to disseminate cutting edge technologies. A consequent LCC perspective combined with bonus-penalty rules are possible steps in this direction.
2.5 Conclusions

The energy consumption of rolling stock and train operation can be significantly reduced in short and medium term by optimising the control and use of present technologies and by operational measures such as energy efficient driving. In long-term perspective the introduction of innovative technologies, the integration of energy efficiency targets into overall vehicle strategies and the focus on more systemic approaches such as telematics-based traffic management will yield considerable further steps towards an energy efficient (and cost-effective) railway operation.

The creation of favourable framework conditions turns out to be of equal importance as progress in R&D. This includes procurement strategies as well as well-defined financial interfaces between functional divisions of railway companies.

The findings of this study will have to be broken down to specific national conditions to derive energy efficiency strategies for individual railway companies. National differences range from technical specifications such as the electric supply system (AC, DC etc.) to the specific fleet composition and policy context (degree of deregulation etc.).

Furthermore the challenge of energy efficiency has to be put into the context of other challenges faced by railways in the future. These include the liberalisation and privatisation processes in railways and changing demand structures especially in the freight sector.

2.6 Brief description of the most important technological recommendations

<table>
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<tr>
<td>• It is recommended to elaborate a detailed study on the technological <strong>potential for brake energy recovery</strong> in the fleet.</td>
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<tr>
<td>• If no systematic <strong>re-engining/upgrading programme for the diesel fleet</strong> is in place, operators should set up such a programme by identifying the most effective and profitable solution for each fleet segment.</td>
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<tr>
<td>• State-of-the-art diesel-electric technology allows for an <strong>on-board use of recovered braking energy</strong> at no additional investment cost. This feature should be integrated into future calls for tender.</td>
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<td>• The status quo of <strong>set values for temperature and ventilation</strong> should be evaluated taking both passenger comfort and energy efficiency parameters into account.</td>
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<tr>
<td>• Some <strong>state-of-the-art features of air-conditioning</strong> should be integrated into the specification sheets for passenger stock. This includes an intelligent control of coach ventilation and the use of waste heat in diesel railcars.</td>
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<tr>
<td>• The <strong>potential for energy efficient driving</strong> should be assessed. Especially in local networks drivers can exploit a great part of this potential without the need for timetable changes or sophisticated electronic advice systems.</td>
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• An **energetic revision of timetables and speed limits** is often feasible without increasing running time and can in some cases even improve punctuality.

• An unbiased **assessment of the operability of double-decked or wide-body stock** on parts of the infrastructure should be made. For insular solutions requiring the elimination of a small number of obstacles a cost-benefit analysis should be made. Those operators not using double-decked high-speed trains yet should develop design solutions together with manufacturers meeting all comfort and operation requirements.

**Mid term:**

• A study should be made on the potential implications of **traction group switch-off** in electric stock. As far as no principal barriers are identified, a widespread introduction seems feasible in mid term.

• A comparative study on the profitability and effectiveness of **different technological options to enhance recuperation rates in DC systems** is to be made. Pilot projects should be realized with the technological solution identified as most promising.

• Requirements for a **control of comfort functions in parked trains** should be identified systematically in order to develop and implement tailored solutions for all vehicles classes.

• **Standard metering equipment** ought to be a requirement for new stock. A step-by-step introduction of energy meters in old stock ought to be carried out. Future energy billing should be based on on-board measurements.

• **Driving advice systems (DAS) for suburban lines** should be introduced starting with pilot projects in areas with expected high potential. Suburban networks are especially well-suited for implementing DAS since technical obstacles are generally smaller than in main line operation.

• If availability of digital track data is critical, it is recommended to introduce **DAS on few selected main lines** which can be digitised "manually". This way the high economic profitability of such systems can be demonstrated without the need to overcome the obstacle of high initial investment.

• Modern curve-steered **single-axle running gear** is a promising alternative to 2-axle bogies in local and regional transport and should be seriously considered in future purchasing.

• The big theoretical saving potential of imposing an **aerodynamic car order in freight transport** justifies a close look at chances to overcome the barriers. R&D is recommendable to examine the corresponding potential offered by existing or future logistic planning and fleet management systems.

**Long term:**

• Calls for tender ought to give incentives to manufacturers in order to **integrate energy recovery and storage options into the concept development** as an integral element of future traction rather than a mere add-on.

• In long-term perspective a **link between the traffic management of the control centres and the on-board DAS systems** should be envisaged.
3 The EVENT Project

3.1 Motivation and project aims

The need for cost efficient operation as well as environmental competition with other transportation modes make energy efficiency an important issue for railways. There exists a large potential to reduce energy consumption by energy efficiency technologies. This applies both for rolling stock and train operation.

Most European railway operators are aware of this challenge and have carried out feasibility studies and pilot projects on innovative traction technologies and energy efficiency in train operation or even drawn up ambitious energy saving plans in recent years.

In order to make expert knowledge and technological experience in energy efficiency matters available across and between railway companies, the Subcommission Energy Efficiency (SCEE) of the CTR Committee of UIC commissioned the Berlin-based IZT to realize a two-year project on energy efficiency technologies and strategies for railways. The EVENT project was managed by the Bahn-Umwelt-Zentrum (Railway Environmental Center) of Deutsche Bahn AG.

The key aims of the EVENT project have been:

- to provide a global state-of-the-art overview over energy efficiency technologies relevant for both rolling stock and train operation
- to provide an overview over existing experiences and projects with railway applications
- to develop a standardised tool for evaluating the technological, economic and environmental potential of energy efficiency technologies
- to identify the key success factors and impeding factors for the implementation and application of these technologies in railways
- to develop guidelines and recommendations for implementation strategies and lanes of action.
- to enhance knowledge transfer between railway operators by means of a web-based database containing major parts of the project output including the evaluated technologies and projects

3.2 Project scope

When studying a system as complex as railways, it is essential to clearly define the boundaries of the object studied.

The EVENT project focuses on the energy directly consumed by trains (for traction and passenger comfort) and studies the involved technologies. This implies that the energy efficiency of stations, administrative buildings, track-side infrastructure, repair and maintenance of stock etc. is excluded from the study.

However as far as the energy consumption of train operation is concerned, the project takes a very comprehensive approach covering both passenger (local / regional / main line) and freight traffic and including different traction systems.
3.3 Methodology

The study has used a bottom-up approach which directly accesses the experiences made with energy efficiency technologies on project and regional level via interviews with experts from all relevant areas, the mailing of a questionnaire as well as a widespread analysis of relevant documents and the critical use of the results of related studies as well as a top-down approach for the standardised evaluation and assessment of energy efficiency technologies for railway applications by means of a multidimensional evaluation tool.

Key components of the applied methodology are briefly outlined in the following:

Data compilation

- Literature research: Relevant publications were searched in libraries (books, scientific magazines, PHD theses etc.) and on the internet (servers of research institutes and universities). The proceedings of the most important railway-related conferences were ordered (WCRR 1997 – 2001 etc.). A total of over 200 publications on relevant subjects was compiled and critically evaluated (cf. Bibliography in Section 9).
• **Mailing of a questionnaire:** In order to get a more systematic and comprehensive overview over the diffusion of energy efficiency technologies and their future potential as seen by individual European operators, a questionnaire was drawn up and sent to about twenty experts (including SCEE members) in seven countries. Besides purely technological questions, issues such as favourable framework conditions, co-operation and knowledge transfer etc. were addressed. One third of the questionnaires was returned covering five countries. The answers provided a wide range of valuable data on the technological potentials in individual countries as well as general views on policy framework, knowledge transfer between national railways and co-operation with manufacturers.

• **Expert interviews with railways:** Numberless guided interviews with experts from national railway companies were carried out to get a broad view on different implementation conditions and degrees of diffusion of individual technologies. IZT staff made journeys to meet railway experts in France, Denmark and Germany. Apart from these face-to-face interviews numerous telephone-based interviews were realized with most European railway companies. The subjects of these expert interviews ranged from technological details to success factors for energy efficiency in general.

• **Expert interviews with industry:** Several interviews were carried out with the three major manufacturing companies for railway technologies Bombardier Transportation, Siemens Transportation and Alstom. Face-to-face interviews took place in Germany and Switzerland and were supplemented by guided interviews via telephone. They focused not only on the potential of particular technologies but also on more general issues such as obstacles for R&D in niche markets etc.

**Workshop**

In order to discuss some of the first project results and elaborate promising implementation schemes with railway experts, IZT organised a workshop that took place in Florence on June 4, 2002. Besides SCEE members, additional experts from European railway operators and infrastructure managers, UIC, industry and railway focussed consultancies were invited in order to guarantee a comprehensive view on technology introduction and roll-out.

One of the key issues of the workshop was the elaboration of implementation schemes in some of the most promising technological areas. In small working groups these technology fields were discussed, success factors and barriers were identified and assessed and lanes of action were sketched. These results were submitted to further discussion with all participants. Outflow of this process were four lanes of action for the fields of energy meters, driving advice systems, energy recovery and comfort functions used to draw up the corresponding lanes of action in Chapter 8.

**Technology evaluation**

For the evaluation of energy efficiency technologies a dedicated multidimensional evaluation tool was developed and continuously refined during the project. The approach chosen includes “hard” (technological, economic etc.) as well as “soft” (e.g. acceptance, impeding factors, benefits) evaluation criteria. For each technology the
individual criteria comprise a detailed comment and a rating. This rating will be chosen out of a set of possible values to be assigned to an individual criterion.

The tool covers the following areas of assessment:

- **Description:** Detailed description of the technology including the possible fields of application

- **General criteria:** This covers a number of issues concerning the technological development and the potential and present degree of application in railways as well as a number of implementation factors such as barriers and success factors.

- **Environmental criteria:** In the environmental field, a clear focus is put on energy efficiency matters. Other environmental impacts are briefly treated as a separate criterion.

- **Economic criteria:** These cover a number of cost aspects such as the impact of the respective technology on vehicle and infrastructure costs. Furthermore scale effects and amortisation period are addressed.

- **Application outside railway sector:** This covers a number of criteria evaluating the performance of the respective technology in sectors other than railways. For technologies that have been transferred to railways rather than developed for railways, this offers additional information helping to estimate the technological and market dynamics of the technology in a general context.

- **Overall rating:** From the entire set of evaluation criteria an overall rating is derived. This includes a specification of both the overall potential of the respective technology as well as the time horizon for its introduction in railways.

The evaluation tool is carefully designed to keep the right balance between quantitative and qualitative criteria. While the former only entails the challenge of data compilation, a more qualitatively oriented evaluation requires additional efforts to ensure a reproducible procedure and to avoid unacknowledged biases. In the EVENT project the evaluation process was designed in a way as to minimise this problem. In a first step, a critical and comparative analysis of available literature was carried out. This phase was enhanced by expert interviews with manufacturers and railways. Based on this material, a first evaluation of the technologies was realized. In a third step, this evaluation was validated and refined by several internal and external feedback loops:

- a critical revision by other experts of IZT
- plausibility cross checks comparing the evaluation of different technologies
- an open round of critical commenting through a group of over 20 experts at UIC and national railways accessing the first draft of the database

### 3.4 The EVENT ComTool

Since the key aim of the EVENT project is to provide a reliable and easily accessible data basis and enhance the knowledge transfer between railway companies, the results of the project are not issued as a conventional project report only but are also put at the disposal of railways, manufacturers and other interested groups by means
of a web platform, the EVENT ComTool. The Berlin-based company Join-and-Share was commissioned by the UIC to realize the technical implementation of the website.

Apart from a well-structured technology database the website will provide other useful information such as a database of energy efficiency related projects and studies made in railways or industry as well as an in-depth introduction to energy efficiency in railways.

The purpose of the Website goes far beyond just issuing the results of the EVENT project. The site is intended to become an actively used information and communication platform for energy efficiency issues in railways. Discussion forums and the possibility to add new entries to the technology and project databases make the website an interactive platform. This way EVENT provides a broad data basis and technical input to the UIC’s considerations with respect to further R&D activities and establishes an appropriate framework for the promotion of energy efficiency technologies.
4 Theoretical background

4.1 Energy consumption of trains

The energy demand of a train stems from four areas:

- **Train motion**
  Mechanical power at the wheels is needed to overcome the different types of resistance confronted by the train (running resistance on the one hand and inertia and grade resistance on the other hand).

- **Losses in traction equipment**
  This mechanical power is provided by traction equipment at the expense of a certain amount of heat losses. This includes auxiliaries such as motor ventilation.

- **Passenger comfort**
  In the case of passenger service, an appreciable share of the overall energy consumption is needed for passenger comfort (heating, lighting, toilets etc.)

- **Supply line losses**
  In the case of electric traction part of the energy never reaches the train, but is lost on the way from the substation to the pantograph.

Figure 2 shows the energy flow into and out of trains for the case of a passenger operation without regenerative braking. All the energy used to overcome inertia and grade resistance is eventually converted into heat in the brakes. In Figure 3 the situation is shown for a train with regenerative braking. The arrow "Inertia and grade resistance" is split into three arrows, one for the energy returned to the grid, one for the heat losses in the inverse traction chain and one for the share of the energy which for technical or operational reasons could not be recuperated.
Figure 2: Energy flow diagram for a passenger train without regenerative braking

Energy fed into the system at electric substation

- Net intake (100%)

Train

- Mechanical energy at the wheels (train motion)
- Inertia and grade resistance
- Air resistance and friction
- Comfort functions
- Losses in traction system

Eventually dissipated in brakes

Catenary losses

Source: IZT

Figure 3: Energy flow diagram for a passenger train with regenerative braking

Energy fed into the system at electric substation

- Net intake (100%)

Train

- Mechanical energy at the wheels (train motion)
- Inertia and grade resistance
- Air resistance and friction
- Comfort functions
- Losses in traction system

Regenerative braking

Energy returned to catenary

Catenary losses

Source: IZT
4.1.1 Resistances to be overcome by train motion

A moving train is confronted with various types of resistance.

*Inertia and grade resistance (non-dissipative)*

To start with it has to overcome inertia during acceleration. When climbing a slope a force has to be applied against gravity, this is commonly denoted as grade resistance. These effects will in most cases be treated as one, for two reasons:

- They are both proportional to train mass: As a consequence the corresponding saving strategies are mainly concerned with mass reduction.
- They are both non-dissipative: The energy invested into acceleration and uphill driving is not dissipated into heat but rather stored as kinetic and potential energy and can therefore be recovered to a large degree by regenerative braking (as far as electric or diesel-electric traction is concerned).

The relative share of total energy demand taken by inertia and grade effects is largely determined by train mass, track topography and the number of stops. The more mountains a train has to climb, the more energy has to be invested into overcoming grade resistance. The more often a train has to accelerate after stops, the more energy goes into overcoming inertia. As a consequence, such non-dissipative effects are dominant for local and regional lines (frequent stops and low velocity) or mountainous topographies.

*Running resistance (dissipative)*

Apart from mass proportional effects there is running resistance. This includes a number of dissipative effects: different frictional forces of the wheel-track system as well as air drag. The energy needed to overcome friction and air drag is dissipated, e.i. converted into heat, and is therefore lost for further use.

Running resistance shows a strong dependence on speed. It is usually given as a sum of three terms, one independent of speed, one proportional to speed and one proportional to the square of the speed:

\[ F_R = A + Bv + Cv^2 \]

The speed independent term \( A \) mainly derives from mechanical resistance (friction), \( Bv \) and \( Cv^2 \) from air drag. \( A \), \( B \) and \( C \) are not general constants but depend on train (mass, length etc.) and track characteristics (wheel-track friction etc.).

The quadratic term is dominant in most cases. Its coefficient \( C \) can be expressed as:\(^1\)

\[ C = \frac{1}{2} \rho A_J C_D \]

where \( A_J C_D \) is denoted as *air drag area*. It can be divided into two parts. One part is independent of train length and depends mainly on the shape and size of the front and rear ends of the train. The other part increases approximately linearly with train length.

\(^1\) Lukaszewicz (2001)
Example:
The Swedish KTH has conducted measurements on the Swedish X2 high speed passenger train yielding\(^2\):

\[
F_r = 80 \cdot (4 + n_{ax}) + (22 + 0.13 \cdot L_T) \cdot v + (2.5 + 3.24 \cdot 10^{-2} \cdot L_T) \cdot v^2 \quad \text{(N)}
\]

- \(n_{ax}\) = Number of axles of the cars in the train (i.e. excluding the power unit)
- \(L_T\) = Total train length (m)
- \(v\) = Train speed (m/s)

For an X2 consisting of one power unit and 6 cars (including the driving trailer) running at 200 km/h, the three terms respectively become:

\[
F_r = A + Bv + Cv^2 = 2240N + 2416N + 24267N
\]

This shows the strong dominance of the third (quadratic) term for high speeds.

The relative importance of running resistance for the energy demand of train operation is heavily dependent on the speed pattern of the service. In high speed operation, where average speeds are high and typical distances between stations are long, running resistance is the dominant quantity. This is almost exclusively owed to air drag. Track friction is generally small. It mainly depends on train weight and to a certain degree on the curving radii of the track. In heavy freight trains, wheel-track friction plays an important role for energy consumption.

### 4.1.2 Losses in traction system

The mechanical energy required at the wheels is provided by the traction motors. These are fed with electricity from the catenary or with diesel fuel. The involved conversion chains from the catenary or fuel tank to the wheel give rise to an additional energy consumption in the form of heat loss in the involved components and in auxiliaries such as ventilation equipment. In order to understand the losses in the locomotives or MUs, electric and diesel traction have to be treated separately.

#### Electric traction

In the case of electric traction the energy is taken from the catenary to feed a complicated conversion chain eventually supplying traction motors which convert electric into mechanical energy. Each of the involved components of the power train converts one form of energy into another, a process which can never be 100% efficient, but rather involves a certain amount of heat losses. In order to prevent the equipment from overheating, auxiliary cooling devices are needed. These themselves consume energy.

Modern electric rail vehicles are driven by AC induction motors which are supplied with 3-phase power of variable frequency and voltage by traction inverters. The

\(^2\) Fors (2001)
different supply systems differ in the way the DC current feeding these inverters is produced. This is represented in Figure 4. Inverters are supplied by the catenary in the case of DC systems, by a transformer and a rectifier in the case of AC power supply and by a combustion engine with a generator in the case of diesel-electric traction. The diesel-electric system was included to show the parallels to electrically supplied systems.

The efficiency of the traction chain of rail vehicles also differs between DC and AC supplied systems. State-of-the-art AC locomotives in 16,7 Hz 15 kV systems typically have an overall efficiency of around 85% at maximum load. In 50 Hz and in DC systems the value is somewhat higher. The traction efficiency from catenary to wheel and the efficiency of the inverse chain during braking are roughly the same.

Figure 4: Different traction systems with electric traction motors

Diesel traction

The energy source for diesel traction is obviously the fuel in the tank. The chemical energy of the fuel is converted into mechanical energy by the combustion engine. This process has typically an efficiency around 40% (ratio between the mechanical output and the energy content of the fuel input). Additionally there are conversion losses in the power transmission from motor to wheel, which can be realized by electric, hydromechanical (or "hydraulic") and mechanical transmission. Furthermore some of the energy produced is needed for traction auxiliaries (e.g. compressor of the diesel cooling system).

Power efficiency versus energy efficiency
The efficiency of a traction system (locomotive or MU) is usually given as power efficiency for a particular load. For example, "85% efficiency" means: At this particular load 85% of the power intake from catenary is converted into mechanical power at the wheels. Such an information is only of limited value when it comes to calculating energy consumption, since the load situation may vary considerably during a typical train service and efficiency generally depends on load. Energy is the time integral of power, so in order to determine energy consumption one needs to know the load cycle. The power efficiency of traction is usually much lower for low load. This is partly due to constant parts of the losses (from auxiliaries and other) gaining appreciable importance for small load. As a result "energy efficiency" (defined as energy output over energy intake for a certain period of time) is lower than power efficiency. If part of the energy taken from the catenary is recovered by electric braking, the occurring conversion losses in the inverse power train increase the absolute losses even more while reducing the net consumption. As a consequence the energy efficiency expressed as output divided by input becomes even worse, even though energy is saved3.

This can best be illustrated by an example. Figure 5 shows the situation for the Re 465 locomotive of SBB in a typical application context in Switzerland. In this (admittedly somewhat extreme) example the locomotive efficiency at maximum power is 85%, but the actual useful energy at the wheels in typical operation is only about 51%! Furthermore it is interesting to see that whereas at maximum power the transformer accounts for the biggest share of losses, it plays a minor role when it comes to energy consumption.

Figure 5: Comparison of power distribution at maximum power (P\text{max}) and energy losses in real operation for a Swiss Re 465.

It is especially important to look at the load dependence of power losses when it comes to optimising the efficiency of traction technologies. This may be demonstrated by means of the (hypothetical) example given in Figure 6. The load

---

3 For more details on this somewhat contra-intuitive effect see Meyer, Aeberhard 1997a.
dependence of losses are given for conventional technology as well as for two more efficient alternatives. Looking at the improved efficiency (i.e. reduced losses) at maximum load only, both alternatives show the same loss reduction compared to conventional technology. However, comparing the alternative A and B for a realistic load cycle with high relative share of low load operation, technology B is clearly more energy efficient. This example shows the importance of considering the real application scenario rather than maximum load only. Experts hold that railways are often not sufficiently aware of this difference when analysing technological options.

Figure 6: Load-specific losses for two alternative technologies as opposed to conventional technology

Source: IZT & Conversation with Mr Markus Meyer, Bombardier Transportation

4.1.3 Comfort functions

Freight trains only consume energy for traction and auxiliaries. In our terminology this includes the auxiliary energy needed for ventilation of traction motors etc. but also for the operation of the brakes along the train. In passenger trains there is an additional energy demand for ensuring passenger comfort, such as heating, lighting and coach ventilation. This energy, which typically accounts for about 20 % of the total energy consumption of a train, is supplied by the primary energy source used for traction (catenary or diesel) and transmitted along the train by the train bus supply. An additional energy demand arises for parked trains. They have to be heated and lighted for cleaning purposes and in order to have a comfortable temperature when service starts.

4.1.4 Losses in the supply system

Since railways sell transportation services, their energy consumption necessarily takes place across a wide area. This implies that energy has to be carried over big
distances, which always involves losses of some kind or the other. These losses shall be briefly discussed here. The losses occurring outside the railway supply system, such as conversion losses in power plants and losses in power lines of national grid\(^4\), are not addressed here, since they are not railway specific.

Losses in the electric supply system include conversion losses in substations as well as losses in the supply lines and catenary. The situation highly depends on the characteristics of the individual supply system. Generally, losses decrease with higher voltage. DC systems with their rather low voltages have the biggest losses in the catenary. Table 1 gives an overview of the voltages and frequencies used in different European countries.

**Table 1: Railway system voltages for some European countries**

<table>
<thead>
<tr>
<th>Country</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>3 kV DC</td>
</tr>
<tr>
<td></td>
<td>2x25 kV AC, 50 Hz (High speed lines &amp; 1 freight line)</td>
</tr>
<tr>
<td></td>
<td>25 kV AC, 50 Hz (1 freight line)</td>
</tr>
<tr>
<td>Denmark</td>
<td>25 kV AC, 50 Hz (main lines)</td>
</tr>
<tr>
<td></td>
<td>1,5 kV DC (metropolitan area Copenhagen)</td>
</tr>
<tr>
<td>France</td>
<td>25 kV AC, 50 Hz (TGV and main lines)</td>
</tr>
<tr>
<td></td>
<td>1,5 kV DC (others)</td>
</tr>
<tr>
<td>Germany</td>
<td>15 kV AC, 16 2/3 Hz</td>
</tr>
<tr>
<td>Italy</td>
<td>3 kV DC</td>
</tr>
<tr>
<td></td>
<td>25 kV AC, 50 Hz (high-speed lines)</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1,5 kV DC</td>
</tr>
<tr>
<td>Spain</td>
<td>3 kV DC (1,5 kV DC in some areas)</td>
</tr>
<tr>
<td></td>
<td>25 kV AC, 50 Hz (high-speed lines)</td>
</tr>
<tr>
<td>Sweden</td>
<td>15 kV AC, 16 2/3 Hz</td>
</tr>
<tr>
<td>Switzerland</td>
<td>15 kV AC, 16 2/3 Hz</td>
</tr>
</tbody>
</table>

Source: IZT

In the case of diesel traction losses in the supply system are not obvious. However, the energy needed for transporting the fuel to the locomotives fuel tanks could be considered as such. The same is true for the share of the diesel needed to transport the additional train mass represented by the filled fuel tank.

\(^4\) This includes the case of railway companies producing their own electricity.
4.2 Some quantitative aspects of energy consumption

4.2.1 A simple formula for energy consumption

In the following we will derive a general formula for the net energy intake for traction. If we consider a train which has an efficiency\(^5\) of \(\chi\) in its energy conversion chain from catenary to wheel and uses the regenerative brake with a share\(^6\) of \(\beta\) when braking, then we get the following situation. If for a given journey an energy \(E_{\text{kin+pot}} + E_{\text{run}}\) is required at the wheels in order to overcome inertia and grade resistance (kin+pot) and running resistance (run) respectively and \(E_{\text{comfort}}\) for comfort functions, \(1/\chi \ (E_{\text{kin+pot}} + E_{\text{run}} + E_{\text{comfort}})\) has to be taken from the catenary because of losses in the electric equipment\(^7\). As mentioned earlier the non-dissipative part (kin+pot) of this intake can be recovered by regenerative braking. Since the “upwards” efficiency of the conversion chain is assumed to be \(\chi\) as well, and the dynamic brake is only partly applied (\(\beta < 1\)), we get a recovered energy of \(\chi \ \beta \ E_{\text{kin+pot}}\). The net energy intake during a given journey is therefore

\[
E_{\text{net}} = \frac{1}{\chi} \left( E_{\text{kin + pot}} + E_{\text{run}} + E_{\text{comfort}} \right) - \chi \ \beta \ E_{\text{kin + pot}}.
\]

\(E_{\text{net}}\) = net energy intake

\(\chi\) = "energy efficiency", for a definition cf. Section 4.1.2 (Caution: \(\chi\) is not identical with power efficiency \(\eta\) !)

\(E_{\text{kin+pot}}\) = the sum of energy required at the wheels to accelerate the train or climb a slope

\(E_{\text{run}}\) = the energy required at the wheels to overcome running resistance (mechanical friction + air drag)

\(E_{\text{comfort}}\) = the energy needed for passenger comfort functions

\(\beta\) = the share of regenerative braking

Obviously, this is the formula for energy consumption in electric passenger trains. But it can easily be generalised to other cases: The case of diesel traction is obtained by simply leaving off the recovery term \(\chi \ \beta \ E_{\text{kin+pot}}\). Energy consumption of freight trains is given by the above expression if one leaves off the term \(E_{\text{comfort}}\).

---

\(^5\) The energetic efficiency \(\chi\) is defined as \(E_{\text{wheel}} / E_{\text{catenary}}\), that is the percentage of the energy taken from the catenary actually converted into mechanical energy at the wheels.

\(^6\) If for example the dynamic (=regenerative) brake comes up for 60 % of the braking power and the rest is filled in by the mechanical or other dissipative brakes, then \(\beta = 0.6\).

\(^7\) This is based on the assumption that the efficiency of the conversion chain for comfort energy is the same as for traction. This is only approximately true, since the train bus supply is taken from the DC link and so the DC/AC inverter and motor losses do not occur.
From the above formula the principal strategies for saving energy can be derived. Each of the five quantities on the right-hand side can be influenced in order to reduce energy consumption.

- Reducing the train’s mass reduces $E_{\text{kin+pot}}$.
- Optimising the train’s aerodynamics and track friction reduces $E_{\text{run}}$.
- Reducing conversion losses in the locomotive or MU increases its energetic efficiency $\chi$.
- Improving its capacity to use regenerative braking increases $\beta$.
- Making comfort functions in passenger service more efficient reduces $E_{\text{comfort}}$.

These are the basic efficiency strategies to be discussed in Chapter 5.

4.2.2 Basic elasticities

The formula derived above shows how energy consumption depends on its key determinants. It may be used to calculate the basic elasticities of energy consumption. Elasticity is a convenient measure to show the dependence of one quantity on another. To put an example: For energy consumption an elasticity of 0.5 with respect to train mass means that reducing train mass by 4%, cuts energy consumption by $0.5 \times 4\% = 2\%$. Generally, high elasticities indicate strong dependence on this particular parameter, or in other words: changing the respective parameter has a strong effect on the target quantity (energy consumption in our example).

Obviously these elasticities heavily depend on the individual train and operation context. However, a number of typical operation contexts can be given which yield good estimates for a wide range of real train runs. Within in the EVENT project 13 train/operation types were chosen as sufficiently representative. These generic types are systematically represented in Figure 7.

Figure 7: Generic train/operation types for the calculation of elasticities

<table>
<thead>
<tr>
<th>Type</th>
<th>Engine</th>
<th>Braking</th>
</tr>
</thead>
<tbody>
<tr>
<td>High speed operation</td>
<td>electric</td>
<td>no regenerative braking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>regenerative braking</td>
</tr>
<tr>
<td>Intercity operation</td>
<td>electric</td>
<td>no regenerative braking</td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td>regenerative braking</td>
</tr>
<tr>
<td>Regional operation</td>
<td>electric</td>
<td>no regenerative braking</td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td>regenerative braking</td>
</tr>
<tr>
<td>Suburban operation</td>
<td>electric</td>
<td>no regenerative braking</td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td>regenerative braking</td>
</tr>
<tr>
<td>Freight operation</td>
<td>electric</td>
<td>no regenerative braking</td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td>regenerative braking</td>
</tr>
</tbody>
</table>

Source: IZT
The following diagram shows the typical composition of energy demand for these train/operation types.

**Figure 8: Typical composition of energy demand for different operation/traction classes**

For these 13 types the elasticities of total energy consumption with respect to mass, running resistance and efficiency of the power train were calculated. The results are given in Table 2.

---

8 The figures underlying this diagram have been derived from a number of publications (Pittius 2000, Ilgmann 1998, Klose, Unger-Weber 2000 and others), as well as basic assumptions such as an average 20% energy demand for comfort functions (with a slight relative increase if recuperation is applied) and 50% use of recuperation brakes. It is evident that these assumptions and the values drawn from several publications only give an average picture and do not accurately describe all conceivable train runs.

9 The basic assumptions and the detailed derivation are presented in Section 0 (Appendix B).
### Table 2: Elasticities for generic situations

<table>
<thead>
<tr>
<th></th>
<th>Traction</th>
<th>Recuperation</th>
<th>Elasticities with regard to</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>traction</td>
<td>mass</td>
<td>running</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>efficiency</td>
<td></td>
<td>resistance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High speed train</td>
<td>electric</td>
<td>no</td>
<td>1,00</td>
<td>0,17</td>
<td>0,63</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electric</td>
<td>yes</td>
<td>1,11</td>
<td>0,12</td>
<td>0,66</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td></td>
<td>1,00</td>
<td>0,19</td>
<td>0,61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercity train</td>
<td>electric</td>
<td>no</td>
<td>1,00</td>
<td>0,12</td>
<td>0,66</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electric</td>
<td>yes</td>
<td>1,12</td>
<td>0,14</td>
<td>0,65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td></td>
<td>1,00</td>
<td>0,19</td>
<td>0,61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional train</td>
<td>electric</td>
<td>no</td>
<td>1,00</td>
<td>0,52</td>
<td>0,27</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electric</td>
<td>yes</td>
<td>1,33</td>
<td>0,44</td>
<td>0,31</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td></td>
<td>1,00</td>
<td>0,52</td>
<td>0,27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suburban train</td>
<td>electric</td>
<td>no</td>
<td>1,00</td>
<td>0,64</td>
<td>0,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electric</td>
<td>yes</td>
<td>1,42</td>
<td>0,57</td>
<td>0,18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td></td>
<td>1,00</td>
<td>0,64</td>
<td>0,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freight</td>
<td>electric</td>
<td>no</td>
<td>1,00</td>
<td>0,29</td>
<td>0,71</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td></td>
<td>1,00</td>
<td>0,29</td>
<td>0,71</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: IZT

Elasticities allow to calculate the effect, a specific measure or technology has on total energy consumption of a train. This provides a sound quantitative basis for technology evaluation. The general procedure may be illustrated for the case of medium frequency transformers:

**Example: Medium frequency transformer**

Efficiency of medium frequency transformers: > 94%

Efficiency of conventional transformers: ~ 92%

This corresponds to an increase of efficiency of the transformer of 2 – 3%. This efficiency gain directly translates into an equal gain in the overall efficiency of the power train (since it is the product of the efficiencies of the individual components). This yields the following table specifying in the last column the effect on the total energy consumption for the individual train classes.

<table>
<thead>
<tr>
<th></th>
<th>Traction</th>
<th>Brake energy recovery</th>
<th>Effect on efficiency of power train</th>
<th>Elasticity with regard to efficiency of power train</th>
<th>Effect on total energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>High speed train</td>
<td>Electric</td>
<td>no</td>
<td>2 – 3 %</td>
<td>1,00</td>
<td>2 – 3 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td>1,14</td>
<td>2 – 3 %</td>
<td></td>
</tr>
<tr>
<td>Intercity train</td>
<td>Electric</td>
<td>no</td>
<td>2 – 3 %</td>
<td>1,00</td>
<td>2 – 3 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td>1,15</td>
<td>2 – 3 %</td>
<td></td>
</tr>
<tr>
<td>Regional train</td>
<td>Electric</td>
<td>no</td>
<td>2 – 3 %</td>
<td>1,00</td>
<td>2 – 3 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td>1,43</td>
<td>3 – 4 %</td>
<td></td>
</tr>
<tr>
<td>Suburban train</td>
<td>Electric</td>
<td>no</td>
<td>2 – 3 %</td>
<td>1,00</td>
<td>2 – 3 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td>1,55</td>
<td>3 – 5 %</td>
<td></td>
</tr>
<tr>
<td>Freight</td>
<td>Electric</td>
<td>no</td>
<td>2 – 3 %</td>
<td>1,00</td>
<td>2 – 3 %</td>
</tr>
</tbody>
</table>

Range: 2 – 5%

Source: IZT
5 Energy efficiency strategies

5.1 Mass reduction

Typical passenger trains have specific weights between 400 and 800 kg per seat\(^{10}\), 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\(^{11}\).

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 9 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.

---

\(^{10}\) 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.

\(^{11}\) It has to be pointed out that mass per seat is also owed to space utilisation, an issue addressed in section 5.3.
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\(^\text{12}\)). 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\(^\text{13}\). 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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\(^{12}\) Dompke, Brunnecker 1998

\(^{13}\) Schenk 2000
independently rotating wheels instead of a common axle and directly-steered wheel-pairs.

### Mass reduction

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium car-body</td>
<td><em>New generation of urban trains Copenhagen</em>¹⁴</td>
</tr>
<tr>
<td>Articulated trains (Jakob-type bogies)</td>
<td>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.</td>
</tr>
</tbody>
</table>
| Fibre reinforced polymers               | 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  
| Light coach interior equipment          | 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 %**. |
| Mechatronic innovations for future running gear |                                                                 |
| Sandwich structures                     | 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. |
| Single-axle bogies                      |                                                                 |

### 5.2 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 %.

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 10 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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¹⁴ Source: DSB  
¹⁵ 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)\textsuperscript{16}.

**Figure 10: Percentage share of the aerodynamic drag by the different parts of a typical high speed train with 14 coaches**

![Pie chart showing percentage shares of aerodynamic drag](image)


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.

\textsuperscript{16} 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.

<table>
<thead>
<tr>
<th>Aerodynamics and friction</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technologies/strategies</strong></td>
<td><strong>Fairing of bogies</strong>¹⁷</td>
</tr>
<tr>
<td>Aerodynamic optimisation of pantographs</td>
<td>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.</td>
</tr>
<tr>
<td>Aerodynamic ordering of freight cars</td>
<td>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 <strong>bogie covers cut running resistance by 10%</strong>. Given that running resistance accounts for 60-70% of the energy demand for high speed service (including passenger comfort), <strong>the saving potential of bogie covers is 6-7%</strong>.</td>
</tr>
<tr>
<td>Bogie fairings</td>
<td></td>
</tr>
<tr>
<td>Covers for open freight cars</td>
<td></td>
</tr>
<tr>
<td>Lubrication of wheels and tracks</td>
<td></td>
</tr>
<tr>
<td>Streamlining of head and tail</td>
<td></td>
</tr>
<tr>
<td>Streamlining of train sides and underfloor areas</td>
<td></td>
</tr>
<tr>
<td>Virtually coupled trains</td>
<td></td>
</tr>
</tbody>
</table>

5.3 _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)

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

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 11. 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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elimination of dining car</td>
<td><em>TGV Duplex</em>&lt;sup&gt;18&lt;/sup&gt;</td>
</tr>
<tr>
<td>Double-decked stock</td>
<td>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.</td>
</tr>
<tr>
<td>Wide-body stock</td>
<td>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, <strong>mass per seat is reduced by 36% and energy consumption per seat-km by almost 30%!</strong></td>
</tr>
<tr>
<td>Multiple units (MUs) vs. loco-hauled trains</td>
<td>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%).</td>
</tr>
</tbody>
</table>

### 5.4 Reducing conversion losses

#### 5.4.1 The electric case

Figure 12 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.<sup>19</sup>

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.<sup>20</sup>

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<sup>18</sup> Source: SNCF  
<sup>19</sup> Kunz, et al. 1999  
<sup>20</sup> [http://www.bahntechnik.de/berlin/antriebstechnisc.html](http://www.bahntechnik.de/berlin/antriebstechnisc.html) and Matsuoka (1997)
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\textsuperscript{21}. This offers some efficiency potential by introducing demand-operated solutions\textsuperscript{22}.

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.\textsuperscript{23} A modification of the corresponding traction software is often a cost- and energy-efficient option.

### Reducing conversion losses in electric traction

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transversal flux motor</td>
<td>Optimisation of traction software\textsuperscript{24}</td>
</tr>
<tr>
<td>Optimisation of traction software</td>
<td>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</td>
</tr>
<tr>
<td>Medium-frequency transformer</td>
<td></td>
</tr>
<tr>
<td>HTSC transformer</td>
<td></td>
</tr>
<tr>
<td>IGBT</td>
<td></td>
</tr>
<tr>
<td>Wheel-mounted permanent magnet synchronous motor</td>
<td></td>
</tr>
<tr>
<td>Switch-off of traction group</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{21} Slattenscheck 1997
\textsuperscript{22} Bänziger et al. 1995
\textsuperscript{23} Meyer, Aeberhard 1997a
\textsuperscript{24} 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.

5.4.2 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\(^\text{25}\) ("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 (cf. Figure 4)

\(^{25}\) Natural gas is also discussed as an alternative fuel. Since it needs modified engines it will be discussed separately in section 5.6.
• 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 3. 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 5.5.

Table 3: Comparison of transmission systems in diesel traction

<table>
<thead>
<tr>
<th></th>
<th>Diesel–mechanic</th>
<th>Diesel-electric</th>
<th>Diesel-hydraulic (Voith gear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine efficiency</td>
<td>equal</td>
<td>equal</td>
<td>equal</td>
</tr>
<tr>
<td>Transmission efficiency</td>
<td>~95%</td>
<td>~85%</td>
<td>~85%</td>
</tr>
<tr>
<td>Possibility for optimum engine load</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Potential for recuperation</td>
<td>low 26</td>
<td>high</td>
<td>?</td>
</tr>
</tbody>
</table>

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.

26 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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-engining of diesel stock</td>
<td>Upgrading of existing engines[^27]</td>
</tr>
<tr>
<td>(replacement of engine)</td>
<td>Due to the long useful life of railway vehicles</td>
</tr>
<tr>
<td>Diesel-mechanic transmission</td>
<td>there are a lot of old diesel locomotives around</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>with a fuel economy far from optimised. They can</td>
</tr>
<tr>
<td>Fuel or oil additives</td>
<td>be upgraded in order to improve injection and</td>
</tr>
<tr>
<td>for diesel traction</td>
<td>compression characteristics.</td>
</tr>
<tr>
<td>Upgrading of engines</td>
<td>Starting 1995 German DB AG has refitted a</td>
</tr>
<tr>
<td>Future developments in diesel</td>
<td>series of older locomotives. Apart from</td>
</tr>
<tr>
<td>technology</td>
<td>substantially reduced emission, fuel economy</td>
</tr>
<tr>
<td>Common Rail</td>
<td>was improved by 6%. The measure is estimated</td>
</tr>
<tr>
<td></td>
<td>to pay off in 4 to 5 years.</td>
</tr>
</tbody>
</table>

[^27]: Source: Schmidt 1996

### 5.5 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.

It is clear from Figure 8 that 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.

[^27]: 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).\(^28\)
- 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 \textit{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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel-electric vehicles with energy storage</td>
<td>\textit{Stationary energy storage in Cologne light rail network}</td>
</tr>
<tr>
<td>Regenerative braking in 16,7 Hz, 15 kV systems</td>
<td>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.</td>
</tr>
<tr>
<td>Radio-controlled double traction in freight trains</td>
<td>Comprehensive tests demonstrate that energy storage \textit{saves about 24 % of the total energy consumption}. Additional cost effects can be</td>
</tr>
<tr>
<td>Regenerative braking in freight trains</td>
<td></td>
</tr>
<tr>
<td>On-board use of braking energy in diesel-electric stock</td>
<td></td>
</tr>
<tr>
<td>Revision of limit value for longitudinal forces in the train</td>
<td></td>
</tr>
<tr>
<td>Inverter unit for DC substations</td>
<td></td>
</tr>
<tr>
<td>On-board energy storage in DC systems</td>
<td></td>
</tr>
</tbody>
</table>

\(^{28}\) Moninger, Gunsellmann 1998
5.6 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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29 Godbersen, Gunselmann 2001, calculations by IZT
New traction concepts and energy sources

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM fuel cell</td>
<td>CNG railcar at SNCF(^{30})</td>
</tr>
<tr>
<td>Natural gas</td>
<td>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.</td>
</tr>
<tr>
<td>Hydrogen engine</td>
<td>Natural gas is seen by SNCF as today's best short-to-medium-term option for replacing diesel traction. Main benefits are seen in</td>
</tr>
</tbody>
</table>
| Gas turbine             | ➢ less emission  
➢ less noise  
➢ less smell and smoke |

5.7 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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic levitation technology (maglev)</td>
<td>Swissmetro(^{31})</td>
</tr>
<tr>
<td>Swissmetro</td>
<td>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 landscape could be substantially lower.</td>
</tr>
</tbody>
</table>

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\(^{30}\) Chabas et al. 2001
5.8 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 13 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.32

Figure 13: Energy demand of comfort functions for extreme outside temperatures (- 20 °C or + 40 °C)

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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31 Ernst et al. 2000
32 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 m³ of fresh air are typically added to a passenger coach per seat and hour. For a coach with 80 seats, this means 1600 m³ 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 CO₂-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.

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coach insulation</td>
<td><strong>CO₂-operated ventilation</strong></td>
</tr>
<tr>
<td>Modification of target temperature in passenger coaches</td>
<td>In order to ensure air quality passenger coaches are ventilated with 20 m³ of outside air per hour and seat. This system is not very efficient since for low occupancy the ventilation is excessive. CO₂-concentration in the air is a good indicator for the number of passengers actually present. Installation of CO₂-sensors and a control circuit for ventilation therefore allows a demand-oriented and energy efficient ventilation of passenger coaches.</td>
</tr>
<tr>
<td>Smart windows</td>
<td>A pilot project realized in NS Reizigers showed that <strong>climatisation energy may be reduced by 20%</strong>. Correspondingly, <strong>total energy consumption is reduced by 3-4 %</strong>.</td>
</tr>
<tr>
<td>Improved operation control for air-conditioning</td>
<td>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.</td>
</tr>
<tr>
<td>ORC technology to use waste heat in MUs</td>
<td>Technological challenges lie in:</td>
</tr>
<tr>
<td>Heat exchangers to use waste heat in MUs</td>
<td>- sensor stability: state-of-the-art CO₂-sensors suffer from strong drift and have to be calibrated regularly</td>
</tr>
<tr>
<td>CO₂-based demand control for coach ventilation</td>
<td>- additional bad air sensor: CO₂ 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.</td>
</tr>
<tr>
<td>Excess ventilation</td>
<td></td>
</tr>
</tbody>
</table>

**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.33

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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control of comfort functions in parked trains</td>
<td><em>Automatic control of comfort functions in parked trains</em></td>
</tr>
<tr>
<td>Coupling of parked trains for common energy supply</td>
<td>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 <strong>saving potential</strong> of the measure is expected to lie <strong>between 3 and 5% per vehicle</strong> (with respect to total energy consumption).34</td>
</tr>
</tbody>
</table>

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33 This energy is not included in most considerations and does not appear in Figure 2, since usually the train is looked at during service.

34 Source: SJ, calculations by IZT
5.9 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*.

5.9.1 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.

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
</table>
| 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.
5.9.2 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.

<table>
<thead>
<tr>
<th>Reduced standing times in stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technologies/strategies</td>
</tr>
<tr>
<td>Systematic train delays</td>
</tr>
<tr>
<td>Passenger information to reduce boarding time at stations</td>
</tr>
</tbody>
</table>

5.9.3 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.

[^35]: 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.

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficient driving strategies</td>
<td>German driving advice system ESF</td>
</tr>
<tr>
<td>Energy efficient driving by low-tech measures</td>
<td>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.</td>
</tr>
<tr>
<td>Driving advice systems in suburban operation</td>
<td>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.(^{36})</td>
</tr>
<tr>
<td>Driving advice systems in main line operation</td>
<td>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.</td>
</tr>
<tr>
<td>Driving advice systems in freight operation</td>
<td></td>
</tr>
</tbody>
</table>

5.9.4 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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\(^{36}\) Sanftleben et al. 2001
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 14. 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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimisation of train operation by control center</td>
<td><em>Impact of traffic situation on energy consumption</em></td>
</tr>
<tr>
<td>Moving block</td>
<td>A study(^\text{37}) made by ETH Zürich, Adtranz and SBB in 2000 revealed a considerable influence of traffic situation on energy consumption.</td>
</tr>
<tr>
<td>Automatic train control</td>
<td>Measurements realized on IC-2000 tilting trains running between Luzern and Zurich demonstrated that those trips affected by unexpected stops at signals showed an <em>energy consumption 10 – 15 % higher</em> than unimpeded trips. This indicates the big saving potential offered by traffic fluidity measures.</td>
</tr>
<tr>
<td>Demixing of railway infrastructure</td>
<td></td>
</tr>
<tr>
<td>Speed harmonisation</td>
<td></td>
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</tbody>
</table>

5.10 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.

\(^{37}\) 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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-propelled freight cars</td>
<td>Growing modularity in German ICE generations</td>
</tr>
<tr>
<td>Modular train sets for passenger operation</td>
<td></td>
</tr>
</tbody>
</table>

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.

### 5.11 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

<table>
<thead>
<tr>
<th>Technologies/strategies</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy meters (electric)</td>
<td><em>The TEMA project</em>38</td>
</tr>
<tr>
<td>Diesel flow meters</td>
<td>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.</td>
</tr>
<tr>
<td>Database of traction</td>
<td>Energy metering is seen as an essential prerequisite for determining the influencing factors of energy consumption and monitoring the success of energy saving measures.</td>
</tr>
<tr>
<td>consumption</td>
<td>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.</td>
</tr>
</tbody>
</table>

### 5.12 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 occurring in a real application context. A representative and verifiable reference cycle

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38 For details cf. Treige, Olde 2000
(like the F-cycle for diesel vehicles) has to be defined in order to allow railways to compare the energy efficiency of different products.

<table>
<thead>
<tr>
<th>Procurement strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technologies/strategies</td>
</tr>
<tr>
<td>LCC-driven procurement</td>
</tr>
<tr>
<td>Reference cycle for energy efficiency</td>
</tr>
<tr>
<td>Bonus/penalty rules</td>
</tr>
</tbody>
</table>

### 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.

<table>
<thead>
<tr>
<th>Awareness of personnel and incentives</th>
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</thead>
<tbody>
<tr>
<td>Technologies/strategies</td>
</tr>
<tr>
<td>Incentives for drivers</td>
</tr>
<tr>
<td>Training programs to raise awareness of personnel</td>
</tr>
</tbody>
</table>

\(^{39}\) Dongen, Fiechter 2000

\(^{40}\) Source: Deutsche Bahn AG
6 Implementation factors

The introduction and diffusion of energy efficiency technologies and concepts in railways takes place within a complicated framework of interdependent implementation factors. Figure 15 only gives an overview of some of the more important interactions.

Figure 15: Implementation factors and their interdependence

Some of these implementation factors (like the motivation of personnel) can be influenced by railways, others are completely external (like the developments in mass markets). In the following the more relevant factors are described in some detail.

6.1 Economic factors

The main cost segments of a rail vehicle during its lifetime are:

- Initial costs
- Energy costs
- Maintenance costs (including repairs and downtimes)

If not stated otherwise, all vehicle-related costs refer to the relevant unit, e.g. when comparing different train concepts for passenger operation, all costs are to be understood per seat.

The impact of energy efficiency technologies on the individual cost segments is analysed in the following.
Initial costs

Investment costs often constitute the decisive factor in purchasing decisions. It is therefore worth taking a closer look at initial costs of energy efficiency technologies. In this context, one has to distinguish between technologies that are additional compared to conventional traction (e.g. energy storage systems) and others that rather replace conventional components (e.g. medium-frequency transformers replacing conventional low frequency transformers). The latter class of technologies is clearly more relevant for this study.

Whereas additional technologies necessarily create additional purchasing costs, higher costs for technologies replacing conventional components are usually due to technological innovation and have a transitory character.

Price decline of new technologies may be expected usually from two developments:

- **Technological improvements**: e.g. development of cheaper materials or construction principles having the same or better performance
- **Scale effects**: As production figures of new technologies start to take off, industry can usually exploit economies of scale and reduce prices.

A key factor for both points is the existence of mass markets to be followed. The market for railway vehicles and equipment is a niche market compared to the automotive market and the railway industry cannot afford extensive R&D departments to develop innovative technologies (such as fuel cell, gas propulsion, gas turbine etc.). Their future strongly depends on success in mass markets (mainly automotive).

Energy costs

Energy supply and price vary considerably between railways. Some operators like German DB AG take a large share of the power demand from their own power plants, other operators completely depend on external electricity suppliers. The supply contracts negotiated between railways and external suppliers define the energy prices for different load situations. Usually a base load is defined which is supplied at a negotiated price. For load peaks exceeding this level a considerably higher price has to be paid.

As a consequence, there is not always a proportional relation between saved energy and saved energy costs. Measures tending to level out the energy demand are especially profitable for railway operators since they cut energy costs by more than the share of energy saved. This is mainly the case for recuperation and energy storage technologies, because they aim at reducing acceleration peaks.

In AC networks and some DC networks recovered energy can be returned in principle to the supply grid. However, supply contracts usually do not foresee a monetary compensation of this energy. Suppliers are generally reluctant to bill for the net rather than the gross energy intake of railways. Returned energy would have to be measured separately and there are concerns that the returned power is "electrically polluted" (with admixtures of other frequencies). The case of the Cologne light rail network shows that special contracts with suppliers on the compensation of returned energy can be achieved.
**Maintenance costs**

Maintenance costs are understood in a broad sense covering

- regular maintenance and overhaul
- repairs
- downtimes

The effect of energy efficiency technologies on maintenance costs cannot be given in general terms but are highly specific in each case.

Most innovative technologies tend to increase maintenance costs due to a lack of maturity of the technology as well as a lack of experience on the part of the operator. This is one of the main reasons for railway managers to be hesitant about new traction and other technologies. On the other hand, there is a number of energy efficiency technologies which reduce wear on mechanical parts. For example, regenerative braking is wear-free and therefore very favourable for maintenance.

**Life-cycle-costs of rail vehicles**

In order to assess the overall cost effect of a specific technological measure, all these cost segments have to be collected along the whole lifetime of the technology and have to be accumulated into one cost indicator. This is the approach of life-cycle costing (LCC). Life cycle costs include capital costs (depreciation + interest) and operation costs (energy, maintenance etc.). There is no canonical and standardized LCC concept for rail vehicles. Some LCC calculations include costs for operation personnel, costs of downtimes and costs for disposal, whereas others only consider initial, maintenance and energy costs.

The following table gives an idea of the relevance of energy costs in LCC (Costs for personnel are excluded, since some of the sources specify them while others don't).

**Table 4: LCC for rail vehicles**

<table>
<thead>
<tr>
<th>Locomotive for passenger service*</th>
<th>Locomotive for freight service*</th>
<th>High-speed train (ICE 3)**</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment</strong></td>
<td>22,7 %</td>
<td>11,7 %</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>46,2 %</td>
<td>73,8 %</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>31,0 %</td>
<td>14,4 %</td>
</tr>
</tbody>
</table>

Source: * Trümpi 1998   ** Ernst 2001

The figures presented in Table 4 have to be treated with caution. They are taken from different sources and are therefore based on somewhat different assumptions (interest rates, energy costs etc.). Moreover, the great differences between locomotives and ICE stems firstly from the fact that LCC of ICE refer to an entire train, whereas the locomotive LCC exclude LCC from coaches/freight wagons, and secondly from the assumption that locomotives have a lifetime of 25 years, ICE 3 of only 15 years.

While theoretically being the most complete cost indicator, LCC is difficult to handle and cannot be given in a general and straightforward manner. The reason is its
strong dependence on operational conditions, which vary between operators and may not be predictable for the future.

*Payback time*

If a measure or technology reduces LCC, it pays off during its lifetime. However, the lifetime of rail vehicles is very long and the management expects a good return on investment for energy saving measures in a reasonable time. A payback time of more than five years is usually seen as unacceptable. Of course there are exceptions, especially if the technology or feature is seen as strategically important.

### 6.2 Environmental issues

#### 6.2.1 Environmental competition

The environmental competition between different transport modes is not just a question of marketing to gain customers. It is also a competition for the patronage of public regulation and funding which is expected to gain more importance in the future. Table 5 illustrates the environmental leadership of railways. These figures have to be treated however with caution because they only reflect the German situation in long distance travel and give values averaged over a variety of travel aims.

**Table 5: Environmental comparison between different transport modes (the German case)**

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>Railways (main lines)</th>
<th>Airplane</th>
<th>Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary energy per 100 passenger kms in petrol equivalents</td>
<td>2,3</td>
<td>5,8</td>
<td>7,0</td>
</tr>
</tbody>
</table>

Source: Ostermayer, Halder 2000

There is reason to believe that the environmental advantage of railways could be at stake in a long-term perspective. The environmental performance of private and commercial road transport has improved tremendously over the last decade, especially as far as emission control is concerned. This has been mainly due to the joint effect of the high innovation dynamics typical of mass markets and the strong pressure from both legislation and public awareness.

#### 6.2.2 Environmental framework and legislation

Environmental issues put strong constraints on any kind of business activities. This does not only apply to direct environmental legislation but to a complex texture of policies ranging from EU energy policy to self-committed environmental targets of
companies or sectors. In the following three main areas of environmental issues are addressed focusing on their interdependence with energy efficiency matters.

Energy policies

The development of energy markets and policies has a crucial impact on the diffusion of energy efficiency technologies in railways. The energy price determines the payback of energy efficiency investments and the future availability of oil largely decides on railways' efforts to pull out of diesel traction and find convenient substitutes at an early stage.

On the EU level three key aims for energy policy are followed presently and are adopted by national governments:

- Supply energy at low prices for both private households and enterprises. The strategies of market liberalisation and deregulation point in this direction.
- Enhance efficiency of both energy generation and use. This includes the spreading of decentralised energy generation with combined heat-power production.
- Promote renewables.

This sets the framework for energy policies in Europe. As far as energy taxation is concerned, there is general agreement that taxes should reflect the external costs of energy production, namely the environmental costs caused by the generation of energy. This is however not always easy to realize. Railways are for example systematically discriminated with regard to air transport, since the latter does not pay any energy taxes. A taxation of fuel for air transport is difficult due to the international, non-territorial character of travelling by air. In mid-term perspective there is however a growing tendency for taxation to reflect external costs.

The energy price is difficult to predict due to a number of imponderabilities:

- The liberalisation of energy markets will potentially reduce energy prices. However, the first experiences in European countries show a heterogeneous picture, but companies could often benefit from lower prices.
- Strong concentration processes in energy markets and the formation of global players with quasi-monopolistic market power could have negative price effects in mid-term perspective.
- Unpredictable external factors (such as wars in the Middle East).

Pollutants

Any energy production from fossil sources (or biomass) is accompanied by the emission of pollutants such as noxious gases and particulates. In the case of electric traction, atmospheric pollution occurs at the power plant rather than at the vehicle.

In the case of diesel traction the situation is more complicated. Emission regulations for combustion engines exist for different vehicle classes such as trucks, marine vessels and mobile machinery. They have become stricter over the last years and
will continue to do so in mid-term perspective. This can best be exemplified by means of the EURO limits, which are mandatory for commercial road trucks. Table 6 gives an overview.

Table 6: EURO emission limits for heavy duty trucks

<table>
<thead>
<tr>
<th>Date</th>
<th>NOx in g/kWh</th>
<th>HC in g/kWh</th>
<th>NOx + NMHC</th>
<th>CO</th>
<th>Particulates</th>
<th>Test Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO II</td>
<td>1 Oct 1995</td>
<td>7.0</td>
<td>1.1</td>
<td>4.0</td>
<td>0.15</td>
<td>ECE R49</td>
</tr>
<tr>
<td>EURO III</td>
<td>1 Oct 2000</td>
<td>5.0</td>
<td>0.66</td>
<td>2.1</td>
<td>0.10</td>
<td>ESC</td>
</tr>
<tr>
<td>EURO IV</td>
<td>1 Oct 2005</td>
<td>3.5</td>
<td>0.46</td>
<td>1.5</td>
<td>0.02</td>
<td>ESC</td>
</tr>
<tr>
<td></td>
<td>1 Oct 2008</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Schreiner et al. 2000

Although railway transport emits much less pollutants than road or air transport (if calculated per transported good or passenger), there have been efforts by the UIC for many years to define emission limits for diesel locomotives and railcars. At present there are two UIC leaflets addressing diesel emissions: Leaflet 623-2 and 624. Their recommendations are summarised in Table 7. On the part of European legislation there are currently no limit values for diesel emissions from rail vehicles.

Table 7: Emission regulations given by UIC leaflets 623-2 and 624

<table>
<thead>
<tr>
<th>Engine power</th>
<th>Time horizon</th>
<th>CO in g/kWh</th>
<th>HC in g/kWh</th>
<th>NOx in g/kWh</th>
<th>Opacity in Bosch</th>
<th>PM in g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 560 kW</td>
<td>until 31.12.02</td>
<td>3</td>
<td>0.8</td>
<td>12</td>
<td>1.6 – 2.5</td>
<td>0.25 (0.6)</td>
</tr>
<tr>
<td></td>
<td>since 01.01.03</td>
<td>2.5</td>
<td>0.6</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 560 kW</td>
<td>until 31.12.02</td>
<td>3</td>
<td>0.8</td>
<td>12</td>
<td>1.6 – 2.5</td>
<td>0.25 (0.6)</td>
</tr>
<tr>
<td></td>
<td>since 01.01.03</td>
<td>3</td>
<td>0.8</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: UIC PROSPER Workshop

Any emission regulation for combustion engines has to address two issues:

- A test cycle with load conditions (e.g. 50% idling, 25% full load, 25% intermediate load) has to be specified
- On the basis of the chosen test cycle, limit values for the different emissions must be set

The first step is highly non-trivial since it implies a target conflict between the need for a cycle tailored to the specific railway situation and the need of engine manufacturers for standardised requirements in order to exploit economies of scale. Emissions are highly dependent on the cycle realized in regular operation and an engine optimised for one particular cycle is usually not optimised for another load situation. Therefore it would be desirable to individually optimise all engines to their respective application context. However, emission control requires costly R&D efforts.
which eventually increases engine prices. Therefore a homogeneous playing field for manufacturers is essential to ensure further advances in emission control.

There are strong differences in the load profile of main-line locomotives, shunting locomotives and railcars which are due to different operation contexts as well as different types of transmission (diesel-electric, diesel-hydraulic, diesel-mechanic). Nevertheless, the UIC recommendations on diesel emissions are based on a single cycle, the ISO 8178 F-cycle (60% idling, 15% intermediate, 25% full load) which has been agreed upon several years ago as the best fitted average load profile in railway operation.

Emission control was outlined here in some detail because it is relevant for energy efficiency matters in two regards:

- For many pollutants there is a target conflict between fuel economy and emission control. For example, reducing the fuel consumption of a diesel engine strongly increases its NOx emissions. Therefore additional R&D efforts on the part of engine manufacturers is required to meet stricter emission regulations without compromising on fuel economy.

- The on-going discussion in railways and industry on the appropriate test cycle is very instructive when it comes to defining a test cycle for the energy efficiency of traction units. For diesel traction the one possible choice would be to adopt the ISO F-cycle for energy purposes as well. However, experts stress that this cycle is not appropriate for diesel-mechanic transmission. The discussion for electric traction will be technically different. However just as in the diesel case a compromise has to be found between the adequacy of the cycle for a specific application context and the need for harmonised requirements in order to exploit economies of scale.

LCA of different materials

The use of new materials especially for lightweight design of rail vehicles cannot be viewed from an energy perspective alone. In a life cycle perspective other aspects such as toxic waste during production as well as recyclability have to be taken into consideration.

For example, fibre-reinforced polymers and other composite materials can lead to substantial lightweight effects in many fields of rail vehicle design but imply at the same time negative environmental impacts during production and end of life. The manufacturing of these materials is energy intensive and recycling is usually not possible or not economic. Estimates made by the German Aerospace Center (DLR) for automotive applications indicate that the energy net effect of fibre-reinforced polymers along the entire life cycle (compared to conventional materials) may be close to zero.\(^{41}\)

It has to be stressed that LCA studies from automotive applications are hardly transferable to railways. Rail vehicles have a much longer product life (in km) than private cars. For this reason positive effects occurring during the use phase have a much stronger impact on total LCA than they do in automotive applications. In other

\(^{41}\) Pehnt 2001
words, for railway applications the increased energy efficiency during use will in many cases outweigh negative effects during production or end of life. Target conflicts between energy efficiency during use and environmental impacts during production and end of life are therefore limited.

6.3 Policy framework

6.3.1 Role of railway deregulation

Historically many railway operators in Europe have been state-owned. In order to make railway operation more efficient and competitive, legislators (both on a national and a European level) have made efforts in recent years to deregulate the market. This has led to a reorganisation of the railway sector in many countries within the last two decades. This concerns the following issues

- **Privatisation**: While some railways (e.g. in Great Britain) have been completely privatised, in most countries this process was only partial. For example, in Germany the former Deutsche Bundesbahn was converted into the DB AG, a public limited company with the federal government being the only shareholder ("formal privatisation").

- **Vertical disintegration**: Whereas in state-owned railway companies all functional parts of the railway system (infrastructure, passenger operation, freight operation etc.) are in one hand, deregulation efforts have led to a separation of these functions in most countries. Just as in the case of privatisation, this so-called vertical disintegration has taken many forms: While in Great Britain or Sweden infrastructure and trains are run by separate companies, in German DB AG this functional separation has a purely organizational character. Vertical disintegration is seen as an important prerequisite for market liberalisation since cross subsidizing is eliminated and market entry for private operators is facilitated.

- **Intramodal competition**: Compared to other network sectors such as telecommunication or energy, the railway sector lags behind as far as competition is concerned. This has partly to do with the fact that railway operation requires high investments into long-lasting capital goods (mainly rolling stock), which creates high barriers for market entry. However, in some countries such as Denmark or Germany the former monopolist companies are meeting growing intramodal competition in "their" networks. In other countries such as France, monopolies persist.

Although there are no direct impacts of deregulation on energy efficiency, various indirect effects are to be expected:

- **Vertical disintegration** leads to a functional separation of formerly integrated carriers. The creation of several companies (or sub-companies) leads to a segmentation of LCC responsibility, e.g. energy is provided by the infrastructure manager, while other operation costs are taken by the operating company. The newly created financial interfaces (e.g. energy billing between operator and infrastructure manager) often do not reflect the “economic truth”
which destroys incentives to reduce LCC. In the long run, it will be in the economic interest of the companies to create economically transparent interfaces.

- **Privatisation** is expected to have only a minor impact on energy efficiency targets but could improve the collaboration between railways and industry by giving operators a free hand to co-operate with one manufacturer. State-owned railways tend to be somewhat constricted in their R&D co-operation projects with industry since once a R&D project is finished they cannot buy the resulting vehicles from the respective manufacturer since the law demands an open call for tender.

- **Intramodal competition** will increase the pressure on railway operators to maximise cost effectiveness. This may prove beneficial for energy efficiency. Although energy costs are not the main cost item in railway operation, they could turn out to be easier to reduce than other costs. On the other hand, growing levels of competition in railway markets could prove a strong barrier for knowledge transfer between railway companies. To put an example: Whereas SNCF and DB used to operate in markets separated by national frontiers, nowadays one company may see the others as competitors on their own infrastructure. As operators increasingly see energy efficiency as an issue of competitive relevance, the free exchange of experience and knowledge becomes more difficult. In this sense, competition in within railways also poses a challenge for the EVENT project itself having knowledge transfer as one of its key aims.

### 6.3.2 The UIC leaflets

UIC leaflets give technical specifications for rolling stock operated in international rail traffic. They address and regulate issues such as interoperability, infrastructure, signalling, catenary and operational regulations as well as principles for commercial practice. Some leaflets have a mandatory character (e.g. for braking systems, wheelsets and buffers), whereas others only serve as recommendations (e.g. emission regulations for diesel traction).

Whereas only a small number of UIC leaflets (such as Nr. 553) explicitly address energy issues, there is a considerable number of leaflets having an indirect impact on energy efficiency. This issue has not been systematically studied in the EVENT project. The following table gives only some hints on the links between UIC leaflets and energy efficiency. A more exhaustive critical revision of the UIC leaflets is necessary in order to assess their (positive or negative) role for energy efficiency in railways (cf. Chapter 7.3, Recommendation 15).

<table>
<thead>
<tr>
<th>Section</th>
<th>Issues treated</th>
<th>Relevance for energy efficiency issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger and baggage traffic</td>
<td>Tariffs, reservations, catering etc.</td>
<td>-</td>
</tr>
<tr>
<td>Freight Traffic</td>
<td>Tariffs, relations with other transport modes, quality</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8: Overview of UIC leaflets (by sections used by UIC) and relevance for energy efficiency
6.4 Procurement

Purchasing projects for new stock usually start out with a call for tender containing the relevant specifications to be met by the offered product. After a decision has been taken for one of the tenderers, a contract is set up containing guarantees for relevant parameters of the operation phase such as energy efficiency, maintenance, downtimes or more generally life cycle costs. Penalty payments are agreed between the contracting partners for the case of non-compliance to these guarantees.

Specifications in calls for tender

The specifications in railway procurement projects cover a wide range of issues. Among those relevant for energy efficiency are

- Efficiency of traction equipment
- Mass per seat
- k-values of passenger coaches
- lay-out of comfort functions
- control of comfort functions during standstill
- life cycle costs

It has been a long discussion in railways whether calls for tender should contain functional specifications (e.g. energy efficiency of traction equipment) or demand specific design solutions (e.g. use of medium frequency transformer). Manufacturers argue that with specifications being too design-oriented railways end up “designing” the product while they should leave this task to the manufacturer. The advantage of functional specifications is to leave the freedom to manufacturers to find the most innovative or practicable solution in order to achieve a certain performance.

Reference cycles for traction efficiency

It was set out in Section 4.1.4 that the efficiency of traction equipment at a certain load point does not tell much about the energy efficiency of the vehicle in real operation. The reason is that for any real operation scheme there is a characteristic distribution of load points and for each of these load points traction efficiency is different. This is more than an academic problem since it has a considerable effect on energy consumption. As a consequence, it is not always (although often it will be) the most energy efficient choice to buy the train or locomotive having the best efficiency at payload. Depending on the application context, another vehicle having a better efficiency at lower load may consume less energy in operation.

Most railway operators and manufacturers are aware of this problem. Even so, they are usually not able to make a more rational choice, since there is no straight-forward way to compare the efficiency-load behaviour of different vehicles. This is arguably a major barrier for the diffusion of energy efficient stock.

In principle, there are two strategies to tackle this problem:

- Including the speed and load pattern of the specific service (which the vehicle is planned for) in the call for tender and asking tenderers to design the vehicle for an energy efficient operation on this particular line.
- Defining an international set of standardised reference cycles for energy efficiency

These approaches will be discussed in the following in more detail.

If manufacturers are required to specify the energy consumption of their product for the given operation profile, the railway operator can easily choose the most energy efficient solution for the intended application context. This method is already common practice especially for suburban and regional operation. However, it makes only sense in cases where the planned field of application of ordered stock is very narrow or even restricted to one single line. For "general-purpose" stock (e.g. locomotives used for both freight and passenger operation according to demand), such an approach is obviously not of much use.

A standardised set of reference cycles for energy efficiency generalises this approach by defining several load profiles ("reference cycles") which represent typical cases of railway operation, e.g. one for regional operation, one for high-speed, one for intercity operation etc. Such a set of reference cycles does not exist yet. It would provide a standardised basis for comparing the energy efficiency of vehicles
irrespective of the specific application context. In a purchasing project, the load cycle best fitted to the eventual application context of the vehicles could be chosen as a reference point for both manufacturers and railways. This way, manufacturers could optimise vehicles to this particular cycle and railway operators would have an easy way of comparing the tendered products. Although a standardised reference cycle will never be 100% identical with a real load situation, this approach has a number of advantages:

- It is much closer to reality than just giving the efficiency at payload and in idling
- Compared to operation profiles for one purchasing project only, standardised reference cycles will improve the planning reliability of manufacturers and their suppliers by providing them with a clear guideline for traction optimisation.
- A reference cycle would enable operators to easily compare the energy efficiency of different vehicles not only in a particular purchasing project but in general.

Therefore both manufacturers and railway companies stress the need for such a set of reference cycles.

Role of LCC in procurement

While most environmental efforts such as emission control or waste separation tend to increase costs, energy efficiency creates a win-win situation for profitability and the environment. Since reduced energy costs during the operation phase are often paid for by higher initial investment for rolling stock, the LCC concept (cf. Section 6.1) provides a good instrument to look at the overall cost effectiveness of an investment. Although purchasing contracts between operators and manufacturers usually contain LCC guarantees and foresee penalty clauses for the case of non-compliance, initial investment rather than life cycle costs plays the decisive role in most railway purchasing decisions.

This has several reasons:

- **Definition and verification of LCC:** While theoretically being the most complete cost indicator, LCC is difficult to handle and cannot be given in a general and straightforward manner. There is no standardized LCC model accepted by all manufacturers and by railways. Therefore LCC guarantees given by different company often lack comparability. There is a number of problems making LCC difficult to define and verify. For example, individual cost items occurring in operation cannot be clearly attributed to one vehicle making the definition of system borders difficult. Furthermore, LCC are difficult to handle due to their strong dependence on operational conditions, which vary between operators and may not be predictable for the future. As a consequence, LCC guarantees are difficult to enforce since operators will have a hard time proving non-compliance. Any penalty claim by railways can be rejected by the manufacturer alleging inefficient operation schemes etc.

- **Budget segmentation:** The concept of LCC collects all costs caused by an investment into one single cost indicator. However, today's railway companies have a high degree of functional segmentation. This concerns both the internal structure and the vertical disintegration into separate companies (or sub-
companies) in the context of deregulation. As a consequence the life-cycle costs of a rail vehicle are not paid by one department but are split up among several budgets. The train operator usually bears the purchasing and maintenance costs. As far as energy and track wear etc. are concerned, the operator only pays a fee to the infrastructure manager which doesn't always reflect the real costs. Energy debiting is presently based on estimates or calculations on the energy demand of individual trains. In most cases these calculations are rather general and do not take into account the specific features of the train let alone the driving style of the driver (regenerative braking rate, coasting etc.). A similar budget separation occurs between the procurement division and the operative division of the carrier, the first accounting for initial investment the latter for operation costs. Due to this financial segmentation, railway companies often have no incentive to purchase stock with favourable LCC.

- **Short-sighted management and controlling:** Although railway vehicles have an economic lifetime of 20 – 40 years, a payback time of 5 years is seen by many managers as far too long and hardly justifiable. The pressure for cost efficiency and budget balance is high and often keeps decision makers from choosing the option which is cheapest in mid-term or long-term perspective.
7 General recommendations

As was laid out in the previous chapter, there exists a number of key implementation factors for energy efficiency measures in railways. The diffusion of innovative technologies is not only decided by the pace of technological development but rather needs a favourable environment within and outside railway companies.

The following recommendations do not refer to specific technological developments or energy saving measures but rather to the creation of favourable conditions for energy efficiency in railways in general. The emphasis is put on such measures, which can be realized by railway companies as key agents. This includes procurement policy, the optimisation of financial interfaces between and within railway companies and possible action to be taken by the UIC.

Detailed recommendations relating to individual technology fields are given in Chapter 8.

7.1 Energy efficiency in railway procurement

Energy efficiency is largely decided already at the design stage of a rail vehicle. As long as energy efficiency is not a competitive issue and no incentives are given, manufacturing companies have no interest of their own to improve the energy efficiency, especially if this increases the costs. In order to improve the situation, the following strategies or steps are recommended.

Define standards for specifying and measuring energy efficiency

Reference cycles are needed to increase comparability and thus transparency of manufacturers' specifications. They would enhance competition in this field.

1. It is strongly recommended to initiate a consultation process on an international level to develop a set of reference cycles for energy efficiency of rolling stock. This requires a task force with members of UNIFE and UIC setting up appropriate load cycles. The composition of such a committee should be chosen very carefully in order to satisfy two key requirements:
   - adequately represent all involved interest groups
   - ensure the operativeness and efficiency of such a group to avoid stagnation caused by endless discussions on the adequateness of the individual load cycles.

2. A standard simulation programme agreed upon by manufacturers and railway operators would enable railway operators to use the product specifications of manufacturers to calculate the energy consumption in different application contexts. Standards for the simulation of energy efficiency should however be seen as an option, which is complementary and not alternative to reference cycles.

Strengthen LCC-orientation in procurement

Even if LCC are squarely in favour of energy efficient rolling stock, procurement decisions often prefer less efficient products due to lower initial investment. A
stronger LCC orientation in procurement decisions is therefore a key factor for energy efficiency in railways.

3. Invitations for tender should contain strong LCC requirements. However, this can serve as a useful guideline for manufacturers only if the operator specifies the way LCC are calculated. Furthermore LCC requirements have to be compatible with other specifications included in the call for tender. For every call an LCC check should be made by assessing the LCC implications of all specifications.

Create incentives for manufacturers

Railways have two principal ways to influence manufacturers towards energy efficiency: make energy efficiency a competitive issue by paying more attention to energy efficiency when making a procurement decision and provide a monetary incentive by returning a certain share of the saved energy costs to the manufacturer. This can be realized by bonus/penalty agreements.

4. Consultations with manufacturers should be initiated to assess feasibility and acceptance of bonus/penalty rules. In a pilot project the system could be tested for a parameter like "mass per seat" where first experiences already exist.

The segmentation of budgets and responsibilities within railways is one of the main barriers for such a system. Possible lanes of improving the situation are sketched in next section.

7.2 Creating financial interfaces between railway departments

Life cycle costs can only have a decisive influence on railway procurement if there is one department having the budget responsibility for the costs along the whole life cycle. This however is usually not the case in railway companies (cf. section 6.4). In the following some recommendations are given to create financial internal interfaces within railways reflecting the economic truth.

Interface procurement / operation

5. The introduction of virtual budgets would create an incentive to reduce LCC without the need for a complete redesign of budgeting practice in railways. A virtual budget collects all life cycle costs of a vehicle across the company. This way positive LCC effects of a procurement or other decision become visible even if it has negative effects on individual budgets.

Operation/infrastructure (energy)

6. In order to create an incentive to use energy efficient stock and to train drivers to apply an energy efficient driving style, billing should be based on energy measurements (cf. Section 8.5).
Emission trading

The European Union has just decided to establish a trade with CO₂ emission titles. Emission trading has also proven a viable and effective internal instrument for companies to increase corporate energy efficiency. Large oil companies like Shell and BP have successfully introduced internal emission trading in recent years.

7. It is recommended to make a feasibility study on an emission trading system between different departments of railway operating companies.

7.3 The role of the UIC

The UIC has recognized the growing importance of energy efficiency for its members both as a cost and a strategic issue. This is reflected in the formation of a dedicated organisational unit, the Subcommission Energy Efficiency (SCEE).

As the international association of railway companies, the UIC can promote and support the energy efficiency efforts of its members in a number of ways. In the following activities aiming in this direction are proposed. Some of these fields are already covered to some extent by UIC, others aren't.

8. UIC should develop visions for the "Railways of the future" or the "Train of the future" which integrate the changing market conditions as well as the vision of sustainability. These visions could serve as a reference point for national railways and trigger fruitful discussions on future strategic issues.

9. The European Commission and other organisations offer funding for R&D and pilot projects concerned with the use of innovative technologies. However, the spectrum of corresponding programmes and funding conditions is highly complex. UIC could offer dedicated advisory services to its members in order to help them to exploit the existing possibilities.

10. Along with the different standardisation and harmonisation efforts concerned with current technological issues, the UIC should intensify its efforts to set technical and functional requirements for emerging technologies (e.g. fuel cells and HTSC transformers) at an early stage in order to facilitate the R&D activities of both railways and industry. These specifications should provide a minimum of general requirements to enhance planning processes. Standardisation should only be sought in those fields where the advantages of international harmonisation clearly outweigh the drawback of a time-consuming standardisation process. In some cases, national solutions contribute better to energy efficiency than standardised European solutions.

11. Energy efficiency is an issue, which is highly inter-related with a number of issues treated at UIC, such as rolling stock, interoperability, telematics etc. It is therefore crucial to anchor energy issues as a cross-sectional issue to be considered in all decision-making processes of the organisation. This could be achieved e.g. by means of a manual giving information on interdependences between energy efficiency and other railway issues.
12. It is recommended that UIC offers a platform for the exchange of know-how and implementation experiences with energy efficiency technologies. This includes an implementation network linking different R&D and pilot activities of national railways in order to enhance synergies and avoid double work. The EVENT project is a first step in this direction and lays the basis for further activities.

13. A central database of energy consumption data from national railways should be set up. This would not only serve statistical purposes but would promote a competitive philosophy in energy matters between individual national railway companies.

14. On the basis of this data a European or world-wide benchmarking process between railway operators should be initiated leading to mid- or long-term energy targets. Although the UIC cannot itself commit energy targets for its members, it can support them in doing so by delivering relevant data and share experiences from other countries.

15. A thorough analysis of the positive and negative effects of railway specific standards (e.g. TSI, UIC leaflets, CENELEC) on energy efficiency is recommended to identify areas of improvement. The improvement potential could be especially high for regulations concerning the use of comfort functions. Some possible links between the body of UIC regulations and energy efficiency are indicated in Section 6.3.2.
8 Lanes of action for most relevant technology fields

Whereas the action recommended in the previous chapter aims at creating a favourable framework for the dissemination of energy efficiency measures, the following sections give recommendations for all relevant technology fields. For every area detailed recommendation are given as numbered items grouped according to the time horizon for realization (short, mid and long term). These recommendations are ranked by priority according to the following colour key:

| "Priority 1" recommendations |
| "Priority 2" recommendations |
| "Priority 3" recommendations |

At the end of each section there is a diagram giving an overview over the lane of action in this particular technology field.

8.1 Efficiency potential of electric traction

The power train of modern electric stock consists of the following components:

- AC asynchronous traction motors powered by frequency-variable 3-phase current supplied by
- traction inverters based on IGBT power electronics fed by DC current.
- In AC supply systems there are additionally a transformer and a rectifier feeding the DC link.

This can be considered today's state of the art in electric traction and is the product of decades of technological progress, especially in the field of power electronics. Due to these achievements, the single components are very mature and offer little potential for further optimisation. However, substantial short-term improvements can be realized by optimising the control of these components and their interaction. In long-term perspective, quantum leaps in energy efficiency can be achieved by the next generation of traction components.

Short to mid term: Implement intelligent management of power train

The operation and mutual interaction of all traction components usually offers considerable optimisation potential to be exploited with no or only minor changes in the train's hardware:

1. Software optimisation of the power train: For each large vehicle series a team of experts from the manufacturing company and/or the operator should assess cost and saving potential of such a measure as well as possible implications on vehicle performance. Those vehicle series offering a good cost-benefit ratio can be modified in short term. In the procurement of new stock this point should be looked at and discussed with manufacturers.
2. Traction group switch-off: Potential implications on safety braking capacity, adhesion and motor lifetime have to be clarified by a feasibility study. As far as no principal barriers are identified, a widespread introduction seems feasible in 2 - 5 years.

3. Ventilation control: For larger vehicle series, the operation control of traction ventilation should be evaluated. This knowledge exists in technical departments of railway operators and/or manufacturers and has to be located and collected "only". In a second step, for all those vehicle series not equipped with demand-operated ventilation, retrofit options have to be elaborated and economically assessed. For large vehicle series offering good conditions for a retrofit, corresponding measures can be realized in short or mid term. Despite slightly increased initial costs due to additional auxiliary inverter equipment, demand-operated ventilation reduces LCC and should be part of specifications for new stock (both locomotives and MU).

**Mid to long term: Introduce innovative traction components**

Modern asynchronous traction motors are a very mature and highly optimised technology, which has proven today’s best option for electric rail vehicles. However, they do not produce enough torque density in order to allow for a wheel-mounted operation. The two most promising candidates for a direct drive are permanent magnet synchronous motors and transversal flux motors. Both concepts seem to have potential. Whereas permanent magnet synchronous motors are a mature technology, the transversal flux principle still has to prove feasible for railway applications.

IGBT technology is expected to remain the undisputed state-of-the-art choice for inverters in the near future. The speed of diffusion of IGBTs into the fleet is essentially limited to stock renewal since refurbishment is usually not cost-effective.

In AC supply systems, additional conversion losses come from traction transformers. Two innovative transformer concepts exist which could yield a quantum leap in overall energy efficiency, especially in 16,7 Hz systems where transformer losses play a more dominant role than in 50 Hz systems. Medium frequency transformers and HTSC transformers both exist as prototypes for railway applications but some technological and operational uncertainties remain.

Main R&D impulses to bring these technologies to market stage have to come from manufacturers, but railway companies can enhance and speed up this process:

4. Manufacturers are often hesitant to invest into technological innovations since railways' long-term purchasing strategies are uncertain or not well communicated. It is recommendable that railways and manufacturers agree upon roadmaps for long-term technological options to improve the planning basis of industry.

5. Although most railways consider R&D efforts to develop new technologies as an industry's task, a closer co-operation in some areas could be beneficial. For example, establishing standard requirements for new traction technologies at an early stage between European railway operators could help to improve planning reliability of manufacturers and create a more homogeneous market for these technologies. At a later stage of development, the supplying of test carriers to industry is another key success factor for new traction technologies.
8.2 The future of diesel traction

Even though there has been the tendency to reduce diesel fleets in some railways over the last decades, diesel traction will continue to play a role in future railways. Especially on unelectrified lines and for shunting operation diesel stock will remain indispensable for a long time.

In the automotive sector, diesel technology has considerably improved over the last years both in performance and environmental compatibility. However, the diffusion of innovative diesel technologies into the railway sector has been slow. European diesel fleets have a high average age and many vehicles stemming from the first post-war locomotive generation are still in service. There are therefore three main strategies to improve the energy efficiency of diesel stock:

- Refurbishment programmes for current stock
- Procurement of state-of-the-art diesel vehicles within the framework of stock renewal
- Generate alternative options for a substitution of diesel traction in long term
Short term: Re-engine and upgrade existing stock

The average age of European diesel fleets is high. The technological potential for refurbishment is therefore substantial. However, the exploitation of this potential is restricted due to the fact that measures do not pay off if residual lives of locomotives are too short.

6. If no systematic re-engining/upgrading programme for the diesel fleet is in place, operators should set up such a programme by identifying the most effective and profitable solution being either upgrading or replacement for each fleet segment.

7. Since little or no knowledge is available about the optimisation potential of auxiliaries in diesel traction, more R&D efforts are recommended in this field.

Mid term: Reassess diesel strategy and refine calls for tender

In future diesel procurement, the following points should be given special attention:

8. Major advances in diesel injection technologies are achieved in the segment of private cars. It then takes several years for the technological state of the art to reach the high power segment needed for railways. Although the possibilities of railways to speed up this process are obviously limited, it is recommended that railways specifically demand modern direct injection technology such as common rail in purchasing projects.

9. A big share of today's DMUs have an electric or hydro-mechanic (Voith) power transmission. Modern diesel-mechanic transmission is state-of-the-art technology and represents a cost- and energy-efficient alternative. Diesel-mechanic stock should be seriously considered when purchasing diesel railcars.

Mid to long term: Improved diesel technology and options for diesel substitution

With continuously improving emission standards, the local pollution of diesel vehicles is becoming increasingly irrelevant. At the same time, future developments in diesel technology, especially in electronic injection control, are expected to yield further improvements in fuel economy. If these advances are rapidly transferred to railways, diesel traction will remain environmentally competitive.

However, limited oil reserves with corresponding price effects in the long-term future may force railways to pull out of fossil diesel traction. In order to be prepared for this far-reaching technological transition, alternative concepts have to be developed and evaluated in a proactive manner. Since electrification is often not an option, alternative autonomous traction technologies have to be found. Biodiesel is not an appropriate substitute because its production is environmentally ambivalent and the production figures will hardly meet the present or future fuel demand. Natural gas seems to be a viable option but environmental advantages over diesel are comparably small and resource availability is higher but nevertheless limited. Gas turbines lag behind internal combustion engines as far as energy efficiency is concerned. Although fuel cells technologically still have a long way to go and
environmental performance is highly dependent on primary sources used, they are seen as the most promising technology to replace diesel traction in long term. The success or failure of fuel cells will be decided in mass markets namely the automotive sector.

<table>
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<tr>
<th>Lane of action for diesel traction</th>
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<td><img src="Image" alt="Diagram of lane of action for diesel traction" /></td>
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10. Despite the limited influence of railway operators on the future development of future technologies, railway companies can prepare for a potential introduction of fuel cells by defining technical requirements for a railway application at an early stage. This should be done on an international level to ensure a more homogeneous playing field for manufacturers' R&D.

8.3 Energy recovery

Modern rail vehicles with three-phase induction motors allow for the recovery of energy while braking. The actual recuperation rates are however strongly influenced by the supply system and traffic density.
8.3.1 AC main line networks

AC supply systems have a high catenary voltage (15 kV or 25 kV), which facilitates a transmission of recovered energy from one train to another over relatively long distances\(^{42}\). This potential is only partly exploited in today’s railway operation. Reasons range from limited braking power and safety considerations to the operation concepts of driver cabins.

**Short term: Assess status quo and enhance drivers’ skills**

11. It is recommended to elaborate a detailed study on the technological potential for brake energy recovery in the fleet. This includes analysing
   - the technical capacity of all electric vehicles to recuperate
   - the operation concept for the use of the recuperation brake in all electric vehicles (manual or automatic blending of brakes)
   - main barriers (if known)

12. In case a high share of the electric stock has manually operated recuperation brakes, training programmes should be set up to raise the awareness of drivers. A competition between drivers’ teams on selected lines could increase motivation and at the same time provide valuable information on the existing potential and the influence of drivers’ choice on recuperation rates.

13. Existing regulations on longitudinal forces in trains are a non-negligible barrier for regenerative braking in freight operation. The realization of a safety audit is recommended to assess the impact of a modification of these regulations. The Swiss regulations could serve as a guideline.

**Mid term: Optimise operation concept for driver cabins**

In most EMUs blending of mechanical and regenerative braking is governed by automatic control. As a consequence the driver has no influence on the use of regenerative braking. In many locomotives, the driver can choose however between both braking modi manually. In this case the arrangement of the handles strongly influences recuperation rates. For example, in many DB locomotives the brake handles are usually coupled for blended braking. For an exclusive use of electric braking an extra effort is required to decouple the handles.

14. A thorough assessment of current operation concepts of driver cabins is recommended to identify areas of improvement. The potential for automatic brake blending on locomotives should be evaluated.

\(^{42}\) However, in 50 Hz systems this transmission is limited due to phase differences between feeding sections.
The optimum solution for locomotives identified in 14 should become part of specification sheets for future purchasing of electric locomotives.

Lane of action for energy recovery on AC lines

**8.3.2 DC local lines**

In DC systems catenary voltage is low (1,5 or 3 kV). The resulting transmission losses strongly limit the feasible distances for an exchange of recovered energy between trains. Substantial recuperation rates on DC lines can therefore only be achieved in dense suburban networks.

There is however a number of technological options for enhancing recuperation in DC systems. Most of them have reached or are close to reaching market stage. This includes inverter units or stationary storage devices for substations as well as on-board storage systems. A variety of storage technologies has been discussed but there is general agreement that the most promising solutions are fly-wheels and double-layer capacitors. The main barrier for these technological options are high costs, complexity and lack of experience.

*Short term: Conduct comparative study*
A comparative study on the profitability and effectiveness of different technological upgrades of DC systems should be made including both vehicle-side and system-side solutions. Such a study was realized by NS Reizigers for their entire DC network and yielded rather negative results. However, the situation is expected to be much more favourable in local networks.

Mid to long term: Enhance recuperation in DC networks by technological upgrades

Pilot projects should be realized with the technological solution identified as most promising in 16. Experience from various projects in the Cologne light rail network and elsewhere should be exploited as far as transferable.

In the long run, train designers have to integrate energy recovery options into the concept development as an integral element of future traction rather than a mere add-on. Calls for tender ought to push manufacturers into this direction.

Whenever feedback into the supply grid appears as the most promising solution, the supply contracts should be revised in order to integrate a compensation for electric energy returned to the supplier. This can either involve metering devices to measure the power fed back into the grid or a flat rate agreed upon on the basis of estimated average recovery rates. The issue of the quality of the returned power has to be addressed.
Lane of action for energy recovery on DC lines

8.3.3 Diesel-electric traction

Whereas diesel-mechanic and diesel-hydraulic stock offer no or only very little potential for recovering brake energy, diesel vehicles with electric transmission can be technologically enhanced in order to facilitate the use of regenerated energy. If such technologies are in place, diesel-electric power transmission becomes a very energy efficient traction technology.

**Short term: Introduce brake energy recovery for comfort functions**

20. State-of-the-art diesel-electric technology allows for an on-board use of recovered braking energy at no additional investment cost. This feature is of high relevance for energy efficiency in passenger operation and its integration into future calls for tender is recommended.

**Mid to long term: Consider on-board storage**

21. As soon as the Alstom LIREX is operated in regular service with a fly-wheel storage, valuable experience with technical and economic feasibility of such a system will be produced. This should be taken as a starting point to consider a more widespread roll-out of on-board energy storage in diesel-electric vehicles operating on local and regional lines.
8.4 Comfort functions

The energy consumption of comfort functions represents a substantial part of the energy demand of passenger trains. There is reason to believe that the (relative) efficiency potential in this field is bigger than in traction since optimisation efforts have never been as systematic as for the power train.

The main fields of potential improvement are the following:

- A critical revision of target values for both temperature and fresh-air supply
- An intelligent control for ventilation and its interaction with air-conditioning
- Use of waste heat from traction components
- Intelligent control systems for parked trains

**Short term: Reassess standards and specifications**

22. The status quo of set values for temperature and ventilation should be evaluated taking both passenger comfort and energy efficiency parameters into account. A modification of target temperature in passenger coaches can in many cases lead to a win-win-situation for energy efficiency and...
passenger comfort. A stronger dependence of inside temperature targets on outside conditions should be considered. A detailed assessment of passenger satisfaction could remove acceptance barriers on the part of the decision makers. A measurement programme could create strong arguments for such measures.

23. Many quantities (such as k-values and target temperature) relevant for the energy consumption of comfort functions are regulated by UIC leaflets. An assessment of the adequacy of these regulations and possible impeding effects on energy efficiency is strongly recommended.

24. Some state-of-the-art features of air-conditioning should be integrated into the specification sheets for passenger stock. This includes demand-operated coach ventilation, a control tool for excess ventilation and the use of waste heat in diesel railcars.

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**Mid term: Spread state-of-the-art technology by refurbishment measures**

25. For the larger series of passenger coaches already in service a bundle of energetic refurbishment measures is to be elaborated. This should include an improved insulation of walls and windows as well as an intelligent ventilation control based on CO$_2$-concentration and allowing for excess operation.

26. A detailed assessment of the status quo in parked trains is highly recommended in order to identify the potential and the requirements for a control of comfort functions during stand-still periods. The assessment should focus on current operation practice for standstill as well as the different types of control mechanisms in existing passenger coaches.

27. Based on the results of the proposed assessment of the status quo, tailored solutions should be developed and implemented into the individual vehicles classes. Parallel efforts should be made to raise the motivation of cleaning personnel and to create incentives to collaborate in the saving measures.

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**Mid to long term: Develop new solutions**

28. R&D efforts are needed to develop innovative solutions for comfort functions. This covers areas such as an efficient generation of 220V supply in passenger coaches or a transfer of ORC technology to railways in order to optimise the exploitation of waste heat in both diesel and electric railcars.
Lane of action for comfort functions

- **R&D in innovative concepts for the use of waste heat**
  - ORC technology
  - using waste heat in EMUs

- **Develop new solutions**
  - for 220V-technology
  - for energy management

- **Integration of advanced features into calls for tender**
  - intelligent ventilation management and use of waste heat in diesel railcars

- **Refurbishment measures**
  - Bundle of energetic refit measures for larger vehicle series

- **Parked trains**
  - Assess status quo of parking trains (operational practice + existing control tools)
  - Develop tailored solutions based on the above assessment

- **Measurement programme**

- **Modification of target values**
  - Evaluate potential for modified target values for temperature and ventilation
  - Assess adequacy of UIC regulations

8.5 Energy meters

On-board energy meters for electric stock provide consumption data which are more reliable than those generated by simulation. An energy debiting system based on actual consumption creates an economic incentive for operators to save energy. But even in railways that are vertically integrated and do not have energy debiting processes, energy meters could turn out to be promising to improve the monitoring of energy saving measures. Experience from DB AG demonstrates that a quick roll-out is both technically and economically feasible.

**Short term: Realize standardisation and common R&D efforts**

29. The different power supply systems may require some interoperability efforts for the design of energy meters. Although a UIC standard is not a crucial prerequisite for introducing energy meters, standardisation on a European level could accelerate technological development, create scale effects and improve planning reliability of manufacturers. At the same time common development efforts may be beneficial especially for small operators.

Source: IZT
### Mid term: Roll-out of energy meters

30. Standard metering equipment should be a requirement for new stock. The already equipped part of the fleet can then be used to supply the data basis for improved energy calculations (for billing or other purposes). A step-by-step introduction of metering equipment in old stock has to be initiated and carried out.

31. Parallel to the roll-out, an efficient read-out process and intelligent algorithms for data processing should be developed in order to make the consumption data available in a structured way both for energy billing and for monitoring of energy efficiency measures.

32. As soon as a substantial part of the fleets is equipped with measurement devices, infrastructure management should offer meter-based energy billing as an option for operators. In long term on-board measurements are to become the only basis for energy debiting.

### Lane of action for energy meters

![Diagram showing the lane of action for energy meters](source: IZT)
8.6 Energy efficient driving and traffic fluidity

Energy efficient driving is arguably the most promising strategy to save energy in railway operation. It covers a wide range of single measures and approaches ranging from instructions and training programmes for an "unaided" energy efficient driving style to sophisticated driving advice and traffic management systems.

Short term: Carry out non-technological measures

33. A thorough assessment of energy consumption for selected parts of the network (based on simulation or data from actual train runs) could reveal "hidden" potential for coasting or the elimination of speed peaks. Especially in local networks where stopping frequency is high and punctuality at the next station is easy to predict, drivers can exploit a great part of this potential without the need for timetable changes or sophisticated electronic advice systems.

34. Dedicated training efforts are to be undertaken in order to enable drivers operating the respective lines (cf. previous item) to exploit the existing potential. Additional permanent assistance can be given in the form of extra timetables for internal use of drivers telling them when to coast and/or signs along the way indicating optimum points of coasting (provided the train is ahead of time).

35. Incentives should be considered to motivate drivers to adhere to the recommendations given. While monetary incentives are confronted with high barriers, non-monetary incentives such as drivers' contests for energy efficiency meet high acceptance and have proven an effective means to raise interest for such measures.

36. An energetic revision of timetables and speed limits is often feasible without increasing running time and can in some cases even improve punctuality. State-of-the-art simulation tools can be used to identify and exploit hidden potential. Special emphasis should be given to buffer times and the elimination of unnecessary low-speed sections.

Mid to long term: Introduce driving advice systems in suburban and main line operation

Advanced driving advice systems (DAS) exist and have proven to be operable in service by several tests in different countries. The achieved energy savings are lower than theoretically predicted but still high. Several operators are currently considering a system-wide introduction. The main technical barrier is the compilation of digital track data. In view of the fact that DAS is one of the most effective technological measures to reduce fleet-wide energy consumption in mid-term perspective, strong efforts should be made to overcome remaining barriers.

37. Pilot projects should be realised on some selected suburban lines with expected high potential (e.g. due to generous time-table buffers). Suburban networks are especially well suited for implementing first DAS applications since technical obstacles are generally smaller than in main line operation,
digital track data are more easily available and no international standardisation process has to be waited for.

38. If availability of digital track data is critical, it is recommended to introduce DAS on few selected lines (which can be "manually" digitised). This way the potential and high economic profitability of such systems can be proven to management without the need to overcome the obstacle of high initial investment.

39. Before implementing a system-wide roll-out of DAS, the technological interfaces have to be carefully designed. The driving recommendations should be integrated into the existing drivers' display in a clear and functional manner. The machine-machine interfaces should maximise synergy effects with existing hardware platforms as well as positioning and data supply systems in order to reduce costs and overall system complexity. It is essential to provide the option of a future interface to the control centres (cf. recommendation 39). International standardisation efforts in this field should be supported and followed in order to create scale effects for the development and introduction of such systems. Furthermore, synergy effects with other international systems such as ETCS should be envisaged at an early stage.

40. Since drivers’ acceptance is a very critical issue, a system-wide roll-out of DAS should be prepared for by an elaborated communication strategy focusing on the purely advisory character of DAS and its added value namely helping the driver to ensure punctuality at all times.

41. Although the obstacles for DAS in freight operation are higher than in passenger transport, R&D efforts should be undertaken to solve the specific technological challenges of freight DAS such as the highly variable mass of freight trains. The principal limitations posed by mixed infrastructures and high traffic density will only be solved in long term (cf. recommendation 43).

42. The potential for infrastructure measures should be assessed which aim at smoothening the speed profile of tracks and removing low speed sections where ever feasible at reasonable cost.

Long term: Introduce advanced telematic solutions for future management of traffic flows

Modern telematic equipment allows for the implementation of advanced traffic management systems optimising traffic flows on a systemic level. Given the immense benefits for service quality, infrastructure management and energy efficiency, the introduction of such systems will be a key success factor for the efficiency and quality of railway operation in dense infrastructures.

43. In long-term perspective a link between the traffic management of the control centres and the on-board DAS systems should be envisaged. The corresponding system lay-out and technological requirements for such a link should be fixed at an early stage. The cost effectiveness and speed of the introduction of traffic optimisation systems strongly depends on standardised interfaces ensuring maximum synergy effects with other telematic solutions.
44. Train control systems based on moving block are expected to show a better traffic fluidity than today’s fixed block systems do. However little is known on the corresponding energy saving potential. It is recommended to initiate a study on the energy effects of moving vs. fixed block train control based on simulations and energy consumption data.

Lane of action for energy efficient driving

8.7 Vehicle strategy

8.7.1 Passenger operation

Modern rolling stock for passenger operation has to fulfil a number of requirements such as low investment costs per seat, high reliability (low downtimes), interoperability and high standards for passenger comfort. From an energy efficiency point of view, the key requirements for modern vehicles are

- lightweight design
- optimised space utilisation (measured in seats per train length)
- modularity (adaptability to varying demands).
Even though energy efficiency is obviously not the most important criterion in purchasing, these three requirements already play an important role in vehicle strategy because they have a strong impact on other cost aspects as well:

- Light vehicles need less installed power for fixed acceleration rates and reduce axle load and thus wear on many components
- An improved space utilisation reduces most seat-specific costs (initial investment, maintenance etc.)
- Modular train concepts tend to raise load factors and thus increase profitability of train operation

As a consequence railways intend to optimise these issues whenever they purchase new stock. However, this is mostly done on the basis of conventional vehicle design. The introduction of new vehicle concepts is usually impeded since decision makers fear high transition costs.

**Short term: Assess potential for new train concepts**

45. An unbiased assessment of the operability of double-decked or wide-body stock on parts of the infrastructure should be made. If not exploited yet, there is usually major potential in local and regional operation. For insular solutions requiring the elimination of a small number of obstacles a cost-benefit analysis should be made to evaluate the profitability of such a transition.

46. Many railway operators only purchase stock with a high degree of applicability throughout their infrastructure. For example, DB AG wants a regional train used in Bavaria to be usable in other parts of the country as well. This obviously limits the potential for wide-body stock. A critical revision of this “regional interoperability” paradigm is needed to assess whether it is economically reasonable.

**Mid term: Introduce new train concepts**

47. Those operators not using double-decked high-speed trains yet should develop design solutions together with manufacturers meeting all comfort and operation requirements. The TGV Duplex successfully operated for many years could serve as a benchmark.

48. Articulated trains with Jakob-type bogies are considerably lighter than their conventional counterparts. Short units of articulated trains used in local and regional service usually meet no major barriers. Longer units needed in main line and high-speed service often require additional buildings for maintenance and repairs. Those operators not prepared for fixed train-sets should exploit the potential for shorter articulated trains in local and regional transport in a first step and reconsider vehicle strategy in long-term.

49. The development of modern curve-steered single-axle running gear (such as the Alstom KERFs) is a very promising alternative to heavy 2-axle bogies in local and regional transport. This technology should be seriously considered in future purchasing.
**Mid to long term: Realize or support R&D for active suspension technology**

50. Future developments point in the direction of active suspension technology with mechatronic control. R&D in this field is still rather academic, but should be followed and supported by railways. Acceptance barriers against actively controlled running gear could be reduced with a dedicated communication strategy focusing on the successful use of active controlled mechanical elements in other industries such as ABS braking in cars and fly-by-wire in planes.

**Lane of action for passenger trains**

- **Assess potential for wide-body and double-decked stock**
  - reconsider paradigm of "regional interoperability"
- **Develop double-decked high-speed trains**
  - if not realized yet
- **R&D in active suspension technology with mechatronic control**
- **Consider introduction of articulated trains**
  - Jakob bogies
  - Curve-steered single axle running gear (KERFs)

**8.7.2 Freight operation**

In the freight sector, existing rolling stock offers substantial energy efficiency potential. This mainly refers to an aerodynamic optimisation of freight cars and train configurations. In mid- and long-term perspective, the changing structure of cargo and logistic markets pose new requirements for railway transport. The classic freight train configuration carrying heavy low-value mass goods from point A to point B is not well fitted to this challenge. In order to successfully compete with road transport in the growing market of small high-value goods, freight trains have to become more truck-like, i.e. long loco-hauled trains have to be replaced by smaller units with a high degree of modularity and flexibility.
**Short to mid term: Optimise aerodynamics of freight train configurations**

51. Given present train formation processes, imposing aerodynamic constraints on car order is expected to meet huge organisational obstacles. Nevertheless, the potential for optimising the aerodynamic order of freight trains ought to be assessed on the basis of current operational practice.

52. The big theoretical saving potential of imposing an aerodynamic car order justifies a close look at chances to overcome the barriers. R&D is recommendable to examine the possibility of integrating aerodynamic constraints into existing or future logistic planning and fleet management systems.

**Mid to long term: Develop new systemic approaches**

53. The self-propelled freight car and other innovative freight train concepts should be further developed and tested in pilot projects. This does not only concern the vehicles themselves but also the development of new systemic approaches to coupling and train formation processes such as the concept of virtually coupled trains, advanced logistic planning systems and driverless operation.

**Lane of action for freight trains**

- **Assess potential for aerodynamic ordering of freight cars**
- **Develop advanced telematic solution**
  - intelligent fleet and logistic planning systems to facilitate aerodynamic ordering of freight cars
- **R&D in technologies for future freight operation**
  - Modular, self-propelled freight cars
  - Driverless operation
  - Virtually coupled trains
- **Pilot projects for modular self-propelled freight cars**

Source: IZT
9 Conclusions

The study has identified considerable potential to reduce the energy consumption of train operation. It has become clear that the energy efficiency of train operation is a very complex issue and cannot be fully understood from a mere technological and single-train perspective. The study has therefore taken a very broad and comprehensive view and has identified a number of promising approaches that go beyond technological modifications on rolling stock itself. In addition, favourable framework conditions and obstacles for technology implementation have been analysed in some detail. Recommendations have been derived covering both technological and implementation issues. In the following the most important conclusions are summarised.

9.1 Energy efficiency strategies

The potential of individual technologies or measures is mainly determined by the possible energy savings to be achieved and the chances for implementation. While the first issue is of technological or operational nature, the second one depends on a broad range of success factors and obstacles. These conditions eventually decide on the time horizon for and the success of implementation.

Whereas technological improvements to rail vehicles will be rather incremental and require a long time for diffusion there are many short- and medium-term saving measures aiming at an optimised control and use of present technologies or operational improvements. Many of them require only minor investments in new technologies and often rely on "soft" factors such as training programmes. In long-term perspective the introduction of innovative traction technologies, the integration of energy efficiency targets into vehicle strategies and the focus on more systemic approaches such as telematics-based traffic management will yield considerable further steps towards an energy efficient (and cost-effective) railway operation.

Energy efficient driving strategies are the most promising single approach to save energy in train operation. They offer a huge saving potential which can be exploited partly in short term and partly in medium and long term.

A saving potential of similar order lies in improved traffic fluidity and systemic optimisation. For example, a future traffic management system linked to the onboard driving advice units in the trains could help to avoid a good share of unnecessary stops at signals in long-term perspective.

Double-decked and wide-body rail vehicles are another very promising approach for reducing seat-specific energy consumption. However, conflicts with the infrastructure gauge limit the fleet-wide potential.

Regenerative braking has been used in electric traction for many years. Nevertheless the remaining potential is still huge making recuperation a promising field of action for energy efficiency. In AC systems considerable improvements are to be expected from drivers’ sensitisation and training programmes. In DC systems, the theoretical potential is even higher but can only be exploited by high investments in storage and/or inverter technology, which are only profitable in contexts with an especially high saving potential.
The traction system of modern state-of-the-art rail vehicles shows a high degree of energetic optimisation already both for electric and diesel propulsion. There is some minor potential for further technological advances based on current technologies but the main efficiency gains lie in the diffusion of the state of the art into railway fleets. Refit options for the electric power train are limited but there is some improvement potential in the control software of locomotives and railcars. Diesel stock can be re-engined in order to speed up the diffusion of state-of-the-art technology. Highly innovative transformer and motor technology could bring a quantum leap in energy efficiency of electric stock. However, the market stage of most of these developments will only come in the next decade.

Comfort functions take a smaller share in total energy consumption than traction equipment but arguably offer more technological optimisation potential. Especially the optimisation of comfort functions in parked trains is very promising particularly in cold climate zones.

9.2 Favourable implementation frameworks

Implementation and diffusion of energy efficiency technologies depend on a number of factors inside and outside railways. Among the factors which are completely beyond the influence of railway companies are the energy price and the development in mass markets (especially automotive). Other relevant framework conditions come from policy makers and can only be influenced to a very limited extent by railways. This includes the deregulation of railway markets as well as environmental legislation and taxation.

Apart from these strictly external factors, a number of conditions inside railway companies can be identified which favour a rapid diffusion of energy efficiency technologies and strategies. A key area is represented by procurement strategies. Apart from the need for a set of standardised and verifiable environmental requirements in calls for tender, economic incentives should be given to manufacturers to implement cutting edge technology to reduce the energy demand of their products. Well-defined financial interfaces between operating and infrastructure companies as well as between functional divisions within companies will create additional incentives to disseminate energy efficient technology in railways.

Given the complexity of the subject, the transfer of knowledge on energy efficiency is a critical issue. The exchange of information and know-how has to be actively sought both between railway companies and between departments within railways. At the same time an adequate communication of energy efficiency measures towards the management level on the one hand and the personnel involved in the implementation process on the other hand is a key success factor for energy efficiency. The EVENT ComTool containing the technology and project databases offers a platform for communication and knowledge transfer on energy efficiency technologies.

Furthermore the challenge of energy efficiency has to be put into the context of other challenges faced by railways in the future. On the one hand, there are radical changes occurring in railway markets due to liberalisation and privatisation processes. On the other hand, railways have to adapt their supply structure to a changing demand structure. This is especially true in freight transport, where competition with road transport becomes more and more difficult in view of small high-value goods gaining importance over heavy low-value mass goods.
A very broad view has been taken in this study ranging from traction technologies to system optimisation and management approaches. However, the energy consumption of infrastructure and stationary installations were excluded. This limitation could be overcome by a comprehensive study looking at railways as a system.

The findings of this study will have to be broken down to specific national conditions to derive energy efficiency strategies for individual railway companies. In addition to specific technical conditions (such as the electric supply system), there are pronounced national differences in the degree of dissemination of innovative technologies. This translates into different points of departure for energy efficiency strategies between countries. Other decisive factors are the structure and nature of the involved companies related to the national degree of railway deregulation and/or privatisation. Although the derivation of national energy efficiency strategies would be far beyond the scope of this study, the EVENT technology and project databases provide a wide range of relevant data to facilitate the elaboration of tailored national strategies and action plans.
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11 Appendix A: The Evaluation Tool

11.1 Description of criteria and values

The following table gives an introduction into the Evaluation tool. All evaluation criteria are explained and the evaluation procedure is made as transparent as possible.

<table>
<thead>
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<th>Criterion</th>
<th>Explanation</th>
<th>Possible values</th>
<th>Explanation of the values</th>
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<tbody>
<tr>
<td>Technology field / underlying saving strategy</td>
<td>The technology field (e.g. traction technologies) to which the described technology belongs or the corresponding saving strategy is specified.</td>
<td>Mass reduction, Aerodynamics and friction, Space utilisation, Traction technologies, Regenerative braking and energy storage, Innovative traction concepts and energy sources, Non-conventional trains (Maglev etc.), Comfort functions, Energy efficient driving, Load factor and flexible trains, Energy measurement and documentation, Management and organisation</td>
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<tr>
<td>Description</td>
<td>The technology or measure is described in detail. This includes (as far as applicable) • underlying principle</td>
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</tbody>
</table>
In case the technology is not railway specific, the description covers both the technology in a general context and its application in railways.

### General criteria

<table>
<thead>
<tr>
<th>Status of development</th>
<th>Status of development of railway application. For the status of development of the corresponding technology outside railways cf. Application outside railways - Status of development</th>
<th>Concept</th>
<th>Research &amp; experiments</th>
<th>Prototype</th>
<th>Test series</th>
<th>In use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time horizon for broad application</td>
<td>Period of time, until technology is expected to reach broad application in railways (broad = approximately 10 % of fleet segment to be considered for application)</td>
<td>In &gt; 10 years</td>
<td>5 – 10 years</td>
<td>2 - 5 years</td>
<td>in &lt; 2 year</td>
<td>now</td>
</tr>
<tr>
<td>Expected technological development</td>
<td>The technological development potential of the railway application is specified along the following lines: Performance</td>
<td>Highly dynamic</td>
<td>Quantum leaps expected through new materials or new construction principles. At the same time high development dynamics often imply low maturity at present and high degrees of uncertainty.</td>
<td>Dynamic</td>
<td>Considerable optimisation expected mainly on the basis of present materials and construction principles</td>
<td></td>
</tr>
</tbody>
</table>
The main technological shortcomings and hot spots of the railway application are specified. For the development dynamics outside railways cf. *Application outside railways - Expected technological development*.

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Principal motivation for an introduction of the technology is given.</th>
<th>None</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits (other than environmental)</td>
<td>Benefits and positive side effects of the technology are specified such as:</td>
<td>None</td>
<td>There is virtually no benefit other than energy efficiency (or other environmental issues)</td>
</tr>
<tr>
<td></td>
<td>- Passenger comfort</td>
<td>Small</td>
<td>There are some minor non-environmental benefits, but main motivation for implementation lies in energy efficiency.</td>
</tr>
<tr>
<td></td>
<td>- Reduced wear</td>
<td>Medium</td>
<td>The technology offers some additional benefits besides energy efficiency.</td>
</tr>
<tr>
<td></td>
<td>- Cost savings other than energy costs</td>
<td>Big</td>
<td>The technology is mainly driven by strong benefits other than energy efficiency.</td>
</tr>
<tr>
<td></td>
<td>- Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental effects are described in detail in section <em>Environmental criteria</em> and are therefore excluded here.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barriers</td>
<td>Barriers impeding or slowing down technology implementation are identified, such as</td>
<td>None</td>
<td>There are virtually no barriers impeding the introduction of the described technology.</td>
</tr>
<tr>
<td></td>
<td>- Costs</td>
<td>Low</td>
<td>Existing barriers are small and can be overcome with low efforts.</td>
</tr>
</tbody>
</table>

- Energy efficiency
- Mass and volume
- Reliability (lifetime, liability to defect, complexity, maintenance)

Basic exploited

Only minor optimisation expected
<table>
<thead>
<tr>
<th>Success factors</th>
<th>Influence factors for a successful implementation are described. This may include a variety of internal and external issues such as</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Policy and economic framework (market deregulation, energy prices etc.)</td>
</tr>
<tr>
<td></td>
<td>• Developments in relevant mass markets</td>
</tr>
<tr>
<td></td>
<td>• R&amp;D efforts in industry and railways including feasibility studies</td>
</tr>
<tr>
<td></td>
<td>• Dependence on other technological or strategic decisions within railways or manufacturers</td>
</tr>
<tr>
<td></td>
<td>• Communication policy to improve acceptance</td>
</tr>
<tr>
<td>Applicability for railway segments</td>
<td>The railway segment is specified to which technology is applicable. Refit options are discussed if applicable.</td>
</tr>
<tr>
<td></td>
<td>The applicability of the technology is quantified by using a reference fleet (cf. Section 11.2)</td>
</tr>
<tr>
<td>Medium</td>
<td>Overcoming of barriers requires substantial financial, R&amp;D or communication efforts.</td>
</tr>
<tr>
<td>High</td>
<td>There are major barriers, which can be overcome only at very high costs often involving structural changes within the company or technological infrastructure.</td>
</tr>
<tr>
<td>Low</td>
<td>&lt;10% of typical fleet</td>
</tr>
<tr>
<td>Medium</td>
<td>10-20% of typical fleet</td>
</tr>
</tbody>
</table>
(cf. Section 11.2).

<table>
<thead>
<tr>
<th>Type of traction</th>
<th>Applicability to different traction systems is specified. Applicability to one traction type does not necessarily imply applicability to all vehicles of this traction type.</th>
<th>High</th>
<th>&gt; 20% of typical fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>electric - AC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electric – DC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>diesel</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of transportation</th>
<th>Applicability to passenger or freight operation is specified. Applicability to one operation field does not necessarily imply applicability to all vehicles in this field.</th>
<th>Suburban lines</th>
<th>Regional lines</th>
<th>Main lines</th>
<th>High speed</th>
<th>Freight</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Grade of diffusion into railway markets</th>
<th>Degree of market penetration is specified describing both the Diffusion into relevant segment of fleet and the Share of newly purchased stock equipped with the technology. The percentages given refer to the relevant railway segment only (cf. Applicability for railway segments).</th>
<th>Diffusion into relevant segment of fleet</th>
<th>Share of newly purchased stock</th>
<th>Market potential (railways)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 %</td>
<td>5 – 20 %</td>
<td>Market potential in the order of less than 2 % of the total market for rail vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 5 %</td>
<td>&gt; 20 %</td>
<td></td>
</tr>
</tbody>
</table>

<p>| Market potential (railways) | The market for the respective technology is evaluated. The market potential essentially results from the | None | Market potential in the order of less than 2 % of the total market for rail vehicles |
|-----------------------------|-------------------------------------------------------------------------------------------------|------|-----------------------|---------------------------|
|                             |                                                                                                                |      |                       |                           |
|                             |                                                                                                                |      |                       |                           |
|                             |                                                                                                                |      |                       |                           |</p>
<table>
<thead>
<tr>
<th>Potential</th>
<th>Market potential in the order of 2-10 % of the total market for rail vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Market potential in the order of 10-50 % of the total market for rail vehicles</td>
</tr>
<tr>
<td>Medium</td>
<td>Market potential in the order of more than 50 % of the total market for rail vehicles</td>
</tr>
<tr>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

**Example**

An example of implementation (at least on a prototype level) is specified. As far as available, details including user experience, success factors, achieved energy savings etc. are given.

**Environmental criteria**

<table>
<thead>
<tr>
<th>Energy efficiency potential for single vehicle</th>
<th>The energy saving effect for a single vehicle is specified. This is done considering the following points:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- In a first step the direct effect (e.g. mass reduction) of the technology or measure is quantified.</td>
</tr>
<tr>
<td></td>
<td>- In a second step, elasticities (if applicable) (cf. Section 4.2.2) are used to derive the effect on total energy consumption of the vehicle. The total energy consumption includes the energy required for both traction and comfort functions.</td>
</tr>
<tr>
<td></td>
<td>- Owing to different application contexts, the total energy efficiency potential is usually given as a range of possible values from best to worst case.</td>
</tr>
<tr>
<td></td>
<td>&lt; 2 %</td>
</tr>
<tr>
<td></td>
<td>2 – 5 %</td>
</tr>
<tr>
<td></td>
<td>5 – 10 %</td>
</tr>
<tr>
<td></td>
<td>&gt; 10 %</td>
</tr>
</tbody>
</table>

| Example | - | - |

---

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- As far as possible, this saving potential is differentiated according to traction and transportation type or application context. The most important factors of influence such as vehicle type, timetable or topography are discussed.

### Energy efficiency potential throughout fleet

The system-wide energy saving potential is identified. Assuming a 100% diffusion into the relevant fleet segment, the fleet-wide saving potential for the reference fleet (Section 11.2) is derived. This value describes what can be achieved by introducing a specific technology but does not tell anything about the probability or speed of a fleet-wide implementation.

<table>
<thead>
<tr>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 %</td>
<td>Negative effect</td>
</tr>
<tr>
<td>1 – 2 %</td>
<td>Neutral effect</td>
</tr>
<tr>
<td>2 – 5 %</td>
<td>Positive effect</td>
</tr>
<tr>
<td>&gt; 5 %</td>
<td>Positive effect</td>
</tr>
</tbody>
</table>

### Other environmental impacts

Environmental effects other than energy efficiency are discussed. This includes:
- pollution
- hazardous substances
- waste
- passenger and personnel health
- noise
- long-term availability of energy

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative</td>
<td>The balance of environmental effects (other than energy efficiency) add up to a negative effect.</td>
</tr>
<tr>
<td>Neutral</td>
<td>The balance of environmental effects (other than energy efficiency) add up to a neutral effect.</td>
</tr>
<tr>
<td>Positive</td>
<td>The balance of environmental effects (other than energy efficiency) add up to a positive effect.</td>
</tr>
</tbody>
</table>
From these effects, an overall evaluation of environmental impacts (apart from energy efficiency) is derived. The outcome of the balance of environmental effects (other than energy efficiency) is highly dependent on the framework conditions (recycling rates, production processes etc.)

<table>
<thead>
<tr>
<th>Economic criteria</th>
<th>None</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle - fix costs</td>
<td>No vehicle fix costs.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt; 1 % of initial investment of the vehicle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - 5% of initial investment of the vehicle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 5% of initial investment of the vehicle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle - running costs</td>
<td>Significant reduction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strong cost reductions through energy savings (= energy efficiency per vehicle &gt; 2%) and or major additional reductions in running costs (e.g. maintenance)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure - fix costs</td>
<td>No infrastructure investment needed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Only minor adjustments in existing infrastructure required</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Considerable investment in additional infrastructure components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Major investment for area-wide roll-out of new infrastructure components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure - running costs</td>
<td>Reduced</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unchanged</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increased</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale effects</td>
<td>Scale effects refer to price decreases due to mass production. In most cases it proves impossible to quantify these effects. Main qualitative indicators are the chances to follow external mass markets or reach critical mass within railway markets</td>
<td>None</td>
<td>No mass markets to be followed and no critical mass to be reached within railway markets</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>------</td>
<td>---------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Low</td>
<td>No mass markets to be followed and only minor scale effects for large vehicle series</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>Medium</td>
<td>No mass markets to be followed, but critical mass may be reached within railway markets</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>high</td>
<td>Mass markets to be followed</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amortisation</th>
<th>Period of time to pay back initial investment through reduced running costs</th>
<th>&lt; 1 year</th>
<th>1 – 2 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 – 5 years</td>
<td>&gt; 5 years</td>
</tr>
</tbody>
</table>

**Application outside railways**

<table>
<thead>
<tr>
<th>Status of development outside railway sector</th>
<th>Status of development of the technology outside the railway context.</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Research &amp; experiments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prototype</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test series</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In use</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time horizon for broad application outside railway sector</th>
<th>Period of time, until technology will reach broad application in at least one of the application fields (broad = approx. 10 % of the market segment to be considered for application)</th>
<th>In &gt; 10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In 5 – 10 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In 2 – 5 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In &lt; 2 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Now</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expected technological development</th>
<th>The technological development potential outside the railway sector is specified along the following lines:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Performance</td>
</tr>
<tr>
<td>Expected technological development</td>
<td>Very dynamic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expected technological development</th>
<th>Quantum leaps expected through new materials or new construction principles. At the same time high development dynamics often imply low maturity at present and high degrees of uncertainty.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected technological development</td>
<td>Dynamic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expected technological development</th>
<th>Considerable optimisation expected mainly on the basis of present materials and construction principles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected technological development</td>
<td></td>
</tr>
</tbody>
</table>
The main technological shortcomings and hot spots are specified.

<table>
<thead>
<tr>
<th>Market potentials outside railway sector</th>
<th>The general market potential of the technology outside railways is estimated.</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>No market</td>
</tr>
<tr>
<td>Small</td>
<td>Product meets a niche market (in the order of &lt; 1 % of truck market)</td>
</tr>
<tr>
<td>Medium</td>
<td>Product meets a big but no mass market (in the order of 1 - 10 % of truck market)</td>
</tr>
<tr>
<td>High</td>
<td>Product meets a mass market (in the order of &gt; 10 % of truck market)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential</td>
</tr>
<tr>
<td>The different criteria of the above technology evaluation are condensed into an overall potential. This is done according to a key taking into consideration the following criteria:</td>
</tr>
<tr>
<td>General criteria:</td>
</tr>
<tr>
<td>• Benefits</td>
</tr>
<tr>
<td>• Barriers</td>
</tr>
<tr>
<td>Environmental criteria:</td>
</tr>
<tr>
<td>Very promising</td>
</tr>
<tr>
<td>Promising</td>
</tr>
<tr>
<td>Interesting</td>
</tr>
<tr>
<td>For details cf. Section 11.3</td>
</tr>
</tbody>
</table>
- Energy efficiency potential throughout fleet

Economic criteria:
- Vehicle - fix costs
- Vehicle - running costs
- Infrastructure - fix costs

The other criteria are taken as a qualitative background in order to modify the result of the above quantitative approach if needed.

The details of the procedure are laid out in Section 11.3.

<table>
<thead>
<tr>
<th>Time horizon</th>
<th>The time horizon for technology implementation is specified. This refers to the time horizon for the railway use of the technology. This criterion is therefore not identical with the Time horizon for broad application.</th>
</tr>
</thead>
<tbody>
<tr>
<td>short-term</td>
<td>&lt; 2 years</td>
</tr>
<tr>
<td>mid-term</td>
<td>2 - 10 years</td>
</tr>
<tr>
<td>long-term</td>
<td>&gt; 10 years</td>
</tr>
</tbody>
</table>

Not promising
11.2 The reference fleet

For some of the evaluation criteria, fleet-wide effects are estimated. This of course requires the definition of a "typical" railway fleet (concerning diesel vs. electric traction and passenger vs. freight operation), which serves as a reference frame for calculations. The following reference fleet was defined:

<table>
<thead>
<tr>
<th></th>
<th>Electric</th>
<th>Diesel</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger operation</td>
<td>55%</td>
<td>10%</td>
<td>65%</td>
</tr>
<tr>
<td></td>
<td>(regional/main line: 45%/20%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freight operation</td>
<td>30%</td>
<td>5%</td>
<td>35%</td>
</tr>
<tr>
<td>Sum</td>
<td>85%</td>
<td>15%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Source: IZT

Weighting issues

The most natural approach to defining a reference fleet would be a vehicle count. However, it is hardly reasonable to count one locomotive or one passenger coach with the same weight as one high-speed train or DMU. Since the target quantity of the EVENT project is energy efficiency and fleet-wide effects eventually refer to this quantity, it was decided to take energy consumption as the weighting criterion for the individual fleet segments. When counting diesel and electric traction an additional weighting issue arises: how to compare diesel and electric power consumption. Two approaches seem reasonable:

1. take costs as a weighting factor
2. take primary energy as a weighting factor

The first option is closer to the economic reality of railway operators, the second one is more relevant in an environmental perspective. Since energy prices (both diesel and electric power) vary extremely between railway companies, the cost approach is hardly feasible. Therefore a primary energy perspective was adopted by this study.

The concept of primary energy refers to the total energy consumed along the entire energy chain. In the case of diesel traction this includes the whole process of exploiting and refining and producing of diesel from crude oil as well as the transport of diesel fuel to the locomotive tank. In the case of electric traction, the efficiencies of power plants and the pre-chains of all the involved fossil energy sources based on the national energy mix are taken into account when calculating the primary energy.

Derivation of an "average" fleet

Naturally, there are pronounced national differences in the composition of railway fleets. Taking primary energy as a reference parameter introduces differences in national energy mixes as an additional factor. However, a closer look at some of the major European railways shows that for the purposes of the EVENT project, a reference fleet can be defined which is sufficiently accurate for most European railway companies in order to give rough estimates on system-wide effects. The
reference fleet was derived by comparing those railway companies for which primary energy figures are available (complete figures from SBB, Trenitalia, Deutsche Bahn and DSB, partial figures from SNCF). Given the similarities between the big railway companies in Italy, France and Germany, average values were derived from their fleets (expressed in terms of primary energy consumption). This procedure has the drawback of not taking into account the specific national situation in countries such as Denmark (dominant role of diesel traction) or Switzerland (no diesel traction). However, it is argued that it is preferable to have a reference fleet which properly reflects the situation in many countries than to have one that is the average taken across all countries but does not correctly represent the situation in any country. Nevertheless it is important to keep in mind the limitations of the reference fleet given above. This means that those evaluation criteria, which are calculated on the basis of a reference fleet (e.g. energy efficiency potential throughout fleet) have to be treated with great care since some railways do differ considerably from the reference fleet defined for this evaluation tool. Despite these limitations, we believe that the definition of a reference fleet helps to give a reasonably accurate estimate on fleet-wide effects.

11.3 The overall rating

In order to set up a quantitative procedure for evaluating the Overall potential of a technology, three main implementation factors (with corresponding criteria) have to be considered:

- Energy efficiency performance (Criterion: Energy efficiency potential throughout fleet)
- Benefits and constraints (Criteria: Benefits (other than environmental), Barriers)
- Economic factors (Criteria: Vehicle - fix costs, Vehicle - running costs, Infrastructure - fix costs)

This selection does not cover the whole range of criteria used in the evaluation tool. However the criteria were chosen in such a way that a comprehensive view of the technology is guaranteed:

- The main key factors are included.
- Some of the criteria considered have in itself an accumulative character such as Benefits or Barriers and therefore cover a variety of issues.

For a given technology an overall potential is derived from these criteria as follows:

Step 1: Values assigned to each criterion

The possible values of the individual criteria are represented by numbers from 1 to 4 according to the following key:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Numbers assigned to the individual values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits (other than None)</td>
<td>1</td>
</tr>
<tr>
<td>None</td>
<td>1</td>
</tr>
</tbody>
</table>
### Step 2: Point score

For each technology the total number of points is calculated by adding up the points of the individual criteria (Energy efficiency is accounted for with a weighting factor of 2):

\[
\text{Total score} = \text{Benefits} + \text{Barriers} + 2 \times \text{Energy efficiency potential} + \text{Vehicle fix costs} + \text{Vehicle running costs} + \text{Infrastructure fix costs}
\]

### Step 3: Overall potential

Step 2 yields a number between 8 and 28. From this total score an overall potential is derived according to the following key:

- < 14 → Not promising
- 14 - 16 → Interesting
- 17 - 19 → Promising
- > 19 → Very promising
Step 4: Plausibility check

The result is checked for plausibility using the criteria not considered in the algorithm as a qualitative background. In a limited number of cases, this step will lead to a modification of the result from Step 3.

Note:

The technology database contains a number of energy efficiency strategies that are concepts rather than technologies (e.g. LCC-oriented procurement). It is evident that for these database entries the above quantitative procedure involving such criteria as Vehicle fix costs is not applicable. In these cases the overall potential is evaluated in a more heuristic way.
12 Appendix B: Derivation of elasticities of energy consumption

Elasticity is a concept describing the sensitivity of a function to relative changes of one of its variables. If increasing the variable by 10% changes the function by 5%, elasticity is 0.5.

In mathematical terms this means that for a function \( y = f(x_1, x_2, \ldots) \) elasticity is defined as:

\[
Elasticity = \frac{\Delta y}{\Delta x_1} \frac{y}{x_1}
\]

Infinitesimally this becomes:

\[
Elasticity = \frac{x_1}{y} \frac{\partial y}{\partial x_1}
\]

For the case of energy efficiency, we look at the function derived in Section 4.2.1

\[
E_{net} = \frac{1}{\chi} (E_{kin/pot} + E_{run} + E_{comfort}) - \chi \beta E_{kin/pot}
\]

Its elasticity with respect to \( \chi \) for example is calculated as follows:

Given that

\[
\frac{\partial E_{net}}{\partial \chi} = - \frac{1}{\chi^2} (E_{kin/pot} + E_{run} + E_{comfort}) - \beta E_{kin/pot}
\]

we get for the elasticity:

\[
Elasticity (\chi) = \frac{\chi}{1 \left( E_{kin/pot} + E_{run} + E_{comfort} \right)} \left( - \frac{1}{\chi^2} (E_{kin/pot} + E_{run} + E_{comfort}) - \beta E_{kin/pot} \right)
\]

This is the general formula for \( \chi \)-elasticity. For a specific situation, it can be evaluated by taking the respective values for the variables. For example, for the case of an electric train without regenerative braking in regional operation\(^4\)\(^3\) \((E_{comfort} : E_{kin/pot} : E_{run} = 20 : 53 : 27, \chi = 0.67, \beta = 0)\), one gets

\[
Elasticity (\chi) = 1
\]

\(^4\) Cf. Section 4.2.2
All the other elasticities are calculated in a similar manner.