Introduction to Energy-Efficient Train Operation

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Chapter 1
Introduction to Energy-Efficient Train Operation

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1.1 Background of Railway Energy Consumption

Energy and environmental sustainability in transportation have received increasing attention in recent decades. The Future of Rail—opportunities for energy and the environment, jointly published by The International Energy Agency (IEA) and the International Union of Railways (UIC) in 2019, underlined the global energy consumption data in the transport sector, particularly the railway [1]. On a global basis, the transport sector accounts for 29% of final energy use, and its energy demand has risen significantly in the past decade. The railway is one of the most energy-efficient modes of transport, which constituted 8% of passenger transport and 7% of freight movements globally in 2016 but only accounted for 2% of the energy used in the transport sector. Figure 1.1 shows the global final energy consumption in different sections [2].

From 1990 to 2015, even though the railway share of total transport activity kept above 8.5% (Fig. 1.2), the share of railway CO_2 emission was reduced to less than 3% (Fig. 1.3). Therefore, the railway plays an important role in reducing the environmental impact and improving energy efficiency. By offering efficient transport

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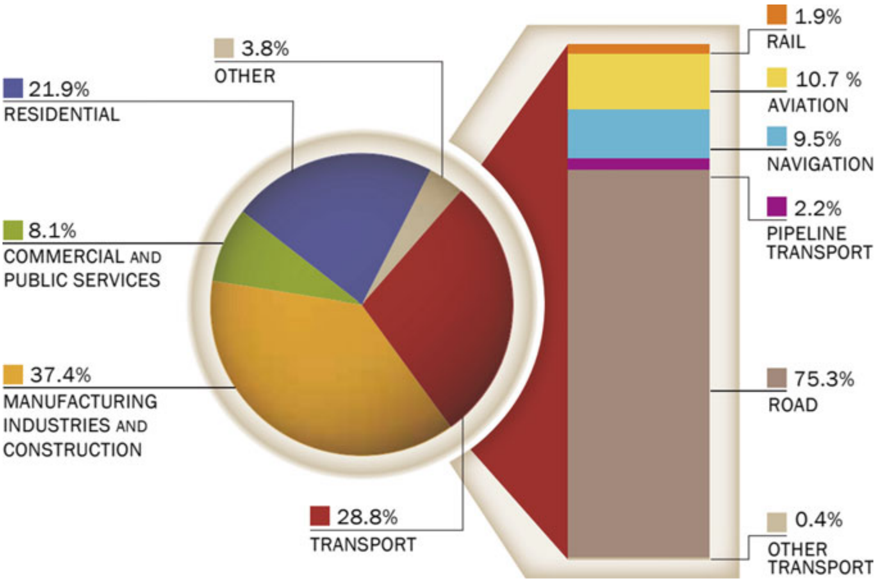


Fig. 1.1 Global energy consumption by sector [2]

with low environmental impacts, the railway helps create a more sustainable approach to transportation.

According to the various types of services, the railway can be classified into passenger and freight rail. The passenger rail includes urban rail, conventional rail, and high-speed rail. Urban rail transit generally refers to a railway system providing passenger services within metropolitan areas, which normally includes metro rail, light rail, and trams. Conventional rail normally serves medium- to long-distance train journeys with a maximum speed under 250 km/h and suburban train journeys connecting urban centres with surrounding areas. In terms of the rail infrastructure, conventional rail tracks refer to the tracks that can be used for passenger conventional rail and freight rail. High-speed rail is used for long-distance services which travel over 250 km/h. Figure 1.4 compares the track length for different rail types over the recent two decades. Conventional rail tracks account for 94% of all rail track-kilometres, but the length has grown slowly in recent decades. The high-speed rail track increases strongly in Europe and China. The Chinese high-speed rail expanded since 2005, and now accounts for nearly two-thirds of the world's high-speed rail lines. The urban rail lines increase gently in Europe and North America, but they expand significantly in Asia.

Hong Kong metro regularly transports 80,000 passengers per hour during peak time, which is four times higher than by bus [3]. In Tokyo, the share of public transport is 36%, while railway accounts for 91.7% of it in Fig. 1.5 [4]. Urban rail transit is also characterised by short headway and dwell time, and a high number of stations with short interstation distances. Urban rail systems can effectively satisfy

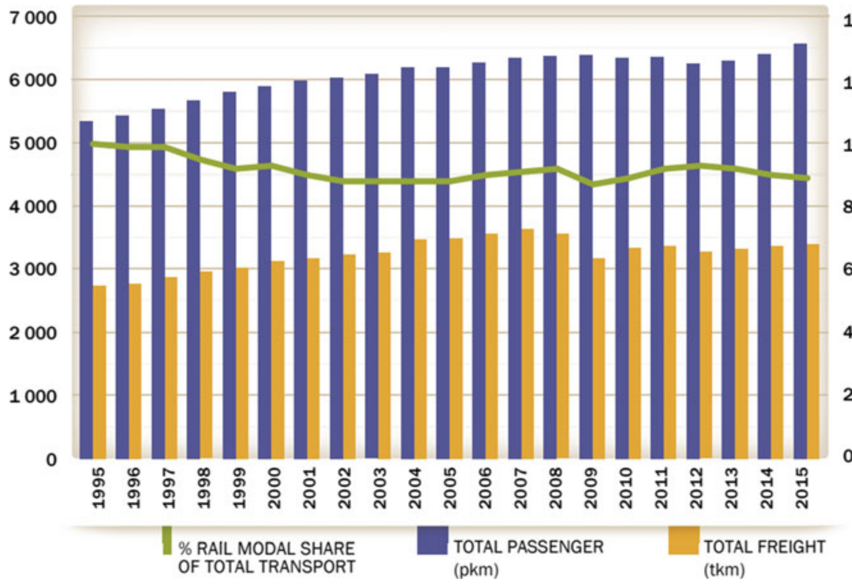


Fig. 1.2 Passenger and freight transport activity—all modes, 1995–2015 (billion pkm and tkm—left, share of rail over total—right) [2]

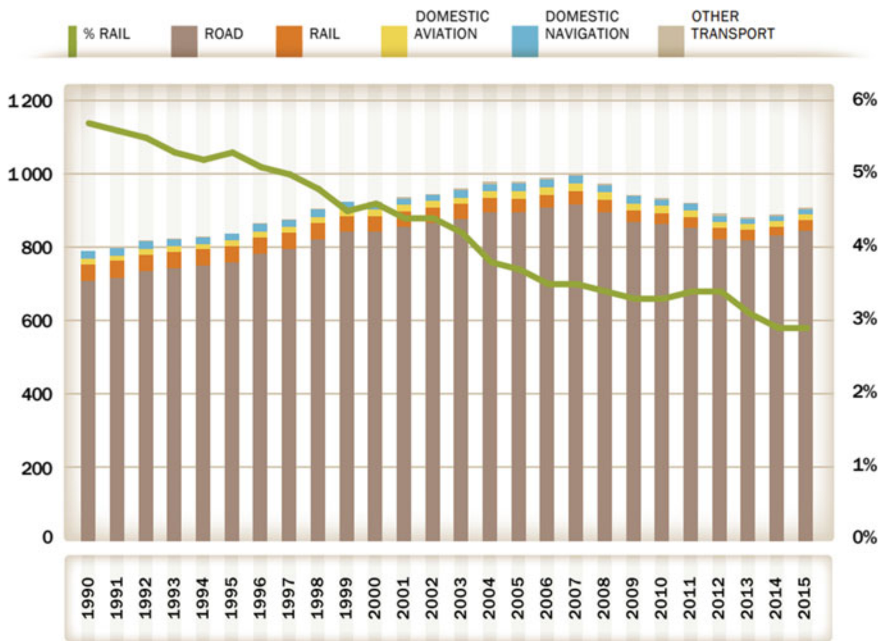


Fig. 1.3 Transport sector CO_2 emissions by mode, 1990–2015 (million t CO_2—left, rail share over total-right. Note: Electricity and heat production related emissions are reallocated to the end-use sectors.) [2]

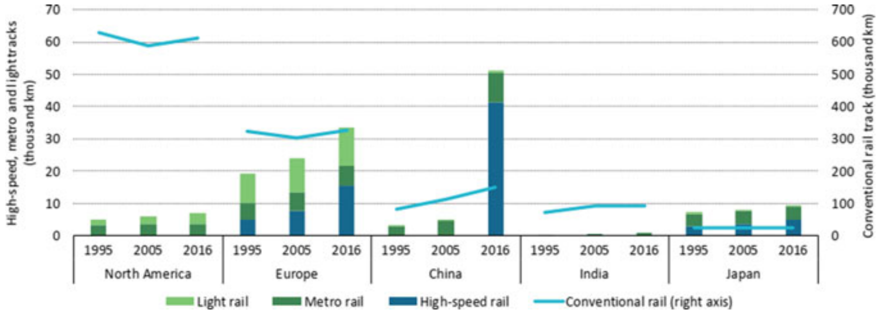
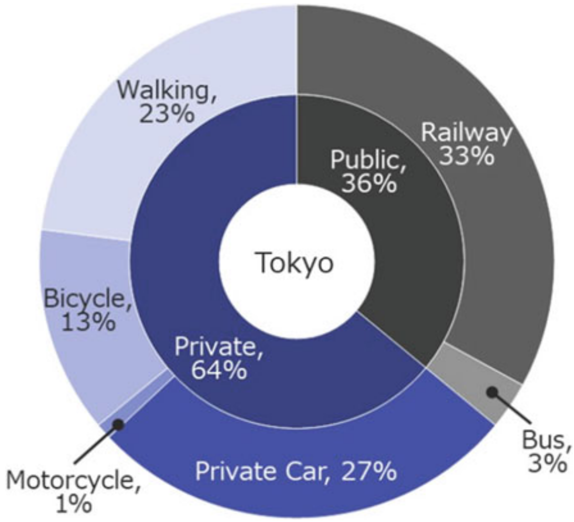


Fig. 1.4 Track length by region and network type, 1995–2016 (Note: Conventional rail includes infrastructure used both by conventional passenger and freight rail) [1]

high transportation demand and reduce air pollution in metropolitan areas. The total length of mainline railway, including passenger and freight, has also increased a lot in recent years. Significant investments have been made in high-speed rail in China, which has overtaken all other countries in terms of network length. Currently, about two-thirds of high-speed rail activity takes place in China [1]. The Chinese mainline is in charge of 22.9% of all passenger activity [5]. While in Australia, rail transport accounts for approximately 49% of total domestic freight, much higher than road freight, about 35%, and coastal sea freight 17% [6]. Additionally, freight rail offers the benefits of high throughput, low cost, and excellent safety while unaffected by the weather.

Fig. 1.5 Modal share in Tokyo



1.2 Projects in Railway Energy Efficiency

Although the railway system is arguably one of the most efficient forms of land-based transport, how to operate trains more efficiently is still of global importance. To improve sustainability, members of the International Union of Railways and the Community of European Railway and Infrastructure Companies proposed a unified approach to environmental and sustainability topics in the European rail sector in 2010 [7]. They addressed four targets for the rail sector to improve performance in terms of the environment, including climate protection, energy efficiency, exhaust emissions, and noise. European railway companies agreed to reduce specific average CO_2 emissions from train operation by 50% in 2030, compared to the emissions in 1990. In addition, it was agreed that by 2030 the energy consumption from train operation would be reduced by 30% compared to the consumption in 1990. There are a number of research and industry projects across the world studying energy efficiency in railways. This subsection provides an overview of the most relevant projects, including the national projects affiliated with the authors in this book.

1.2.1 European Projects

ON-TIME (Optimal Networks for Train Integration Management across Europe) was an EU project running during 2011–2014. The aim of the ON-TIME project was to develop new methods and processes to maximise the available capacity on the European railway network and to decrease overall delays in order to increase customer satisfaction and ensure that the railway network continues to provide a dependable, resilient, and green alternative to other modes of transport. ON-TIME proposed an integrated method to compute robust conflict-free train timetables including energy-efficient train trajectories, as a basis for efficient railway traffic management [8]. In addition, a real-time traffic management architecture was proposed in which traffic state monitoring and conflict detection and resolution modules were developed to maintain a Real-Time Traffic Plan (RTTP) consisting of conflict-free train paths and train orders over the railway network [9]. The RTTP is used both for automatic route setting and for calculating train path envelopes to feed Connected Driver Advisory Systems (C-DAS) to adopt an energy-efficient driving strategy. To allow the interoperable use of C-DAS throughout Europe, ON-TIME proposed a data format for communication of operational decisions (e.g., speed advice) between control centres and trains. Based on an extensive state-of-the-art analysis, three system architecture design alternatives and associated data formats were proposed to distribute the two key functions between trackside (control centre) and onboard components, i.e., (i) generating energy-efficient train speed profiles satisfying the targets and constraints of the train path envelope and (ii) presenting the corresponding advice to the driver [10–12]. The three DAS architecture alternatives and exchange data were further developed and standardized in the project SFERA (Smart communications for efficient rail activities) and are now part of the UIC code 90940 [13]. The train path envelope is here called the journey profile in analogy to the ATO-over-ETCS system requirement specification that is being developed for Automatic Train Operation running under the European Train Control System [14].

OPEUS (modelling and strategies for the assessment and OPtimisation of Energy USage aspects of rail innovation) is a project funded by Shift2Rail [15], which started in 2016 and ended in 2019. The aim of OPEUS was to develop a simulation methodology and an accompanying modelling tool to evaluate, improve and optimise the energy consumption of rail systems with a particular focus on in-vehicle innovation. The OPEUS concept was based on the need to understand and measure the energy being used by each of the relevant components of the rail system and, in particular, the vehicle, which includes the energy losses in the traction chain. New technologies were introduced to reduce these losses and optimise energy consumption. Specifically, the OPEUS approach had three components: (i) the energy simulation model, (ii) the energy use requirements (e.g., duty cycles), and (iii) the energy usage outlook and optimisation strategies recommendation. This project was built upon an extensive range of knowledge and outcomes generated by numerous key collaborative efforts. Significant complementary work from the academic community was used to enhance the activities of the project. With the help of simulation technology, this research created a programme that can calculate the energy consumption of various railway vehicles and their components. The energy KPI was also employed to quantify the relative savings of the technology demonstrator and summarise the overall savings per system platform demonstrator. Moreover, following the global trend, eco-labelling based on EN50591 was carried out to reinforce the attractiveness of railway transport.

In 2017, another Shift2Rail JU founded project, In2Stempo started [16]. This project focused on developing cost-efficient and reliable high-capacity infrastructure for the railway. The main components of this project included smart power supply, smart metering for Railway Distributed Energy Resource Management System, and future stations. The objectives of this project were to enhance the existing capacity fulfilling user demand for the European rail system, increase reliability by delivering better and consistent quality of service for the European rail system, and reduce the life cycle cost. These tasks were fulfilled in three steps: (i) develop a smart railway power grid in an interconnected and communicated system; (ii) achieve a fine mapping of energy flow within the entire railway system, forming the basis of later energy management strategy; (iii) improve the customer experience at Railway Stations. With the help of data analysis, process bus, digital twins, and machine learning, this project realised the smart power supply by developing a smart railway power grid in an interconnected and communicated system. Moreover, the fine mapping of energy flows and usage within the entire railway system was achieved by using smart metering. The outcomes of this project can help to build the future station by improving crowd management, station design, and accessibility to trains.

Apart from the research above, several other European projects have been carried out to improve the energy efficiency in railway systems. The Railenergy project, co-funded by the European Commission, started in 2006 to address the energy efficiency of the integrated railway system [17]. Recommendations included innovative traction technologies, components, and layouts for the development of rolling stock, operation, and infrastructure management strategies. The MERLIN project was conducted to investigate and demonstrate the viability of an integrated management system to achieve more sustainable and optimised energy usage in European electric mainline railway systems [18]. In 2012, 17 project partners collaborated on the OSIRIS project, including public transport operators, railway manufacturers, and research centres [19]. The OSIRIS project aimed to reduce energy consumption within European urban rail systems, focusing on developing and testing technological and operational solutions and tools.

1.2.2 Selected National Projects

In the UK, the Rail Safety and Standards Board (RSSB) is an independent safety, standards, and research body. They help to make an evolving railway safer, more efficient, and more sustainable. In 2017, RSSB launched a British rail research network, which focused on creating three centres of excellence, forming the heart of the British Railway Research and Innovation Network [20]. These centres include a digital system centre located at the University of Birmingham, a rolling stock centre led by the University of Huddersfield in collaboration with Newcastle and Loughborough universities, and an infrastructure centre led by the University of Southampton in collaboration with Sheffield, Loughborough, Nottingham, and Heriot-Watt universities. These centres aim at developing technology and products for trains, systems, and infrastructure in order to deliver a better, more reliable, and more efficient railway.

At the digital systems centre in the University of Birmingham, various railway decarbonisation research projects have been carried out. For instance, in 2018, the SmartDrive package was developed using software created by Birmingham Centre for Railway Research and Education researchers. This package helped minimise energy usage within a fixed total journey time by instructing drivers to apply energy-efficient driving techniques. Its effectiveness has been verified by real daily operations in the Edinburgh Tram Line [21, 22]. In the CaFiBo project [23], the world's first carbon fibre bogie was developed by the University of Huddersfield's Institute for Railway Research in collaboration with a British company. The new bogie is lighter than conventional bogies and optimises vertical and transverse stiffness, which will, in turn, reduce energy consumption and hence global warming footprint. The University of Southampton also received funding from UK's Department for Transport to research and developed new masts made from advanced composite materials that have negative embedded carbon. The new masts would be used to replace carbon-intensive steel production [24], which could significantly reduce the cost of railway electrification.

In the Netherlands, several projects were carried out at Delft University of Technology continuing and extending the work of the EU project ON-TIME, in collaboration with ProRail and the Netherlands Railways. A pseudospectral optimal control approach was developed to compute optimal train trajectories for generic single-train and multi-train trajectory optimisation problems [25]. The train path envelope was further developed and included in energy-efficient train trajectory optimisation algorithms for C-DAS/ATO [26], as well as energy-efficient train timetables [27, 28]. In addition, in collaboration with the Dutch regional railway undertaking Arriva, a project was carried out to identify and evaluate solutions for replacing diesel traction on non-electrified railways by alternative catenary-free propulsion systems and low/zero emission energy carriers to improve energy efficiency and reducing greenhouse gas emissions. The OPEUS simulation model was applied in a Well-to-Wheel analysis of various alternative systems including alternative Energy Storage Systems and hydrogen-powered propulsion systems [29, 30].

To get on track with Net Zero Emissions by 2060, the Chinese government carried out a "14th Five-Year Plan" Railway Science and Technology Innovation Plan, which scheduled a series of projects to reduce the energy consumption of railway. These projects include: building an energy-efficient system for the operation and control of multiple types of trains, developing energy supply and management technologies that match the layout of railway facilities, and exploring innovative traction power technologies such as energy storage devices and fuel cells [31].

In 2019, Beijing Jiaotong University started a project, Investigation into Intelligent Control of Heavy Haul Trains on Long and Steep Downhill Section, which was funded by the National Natural Science Foundation of China. This project focused on the core issues in the driving control of heavy haul trains, including the longitudinal impulse transmission mechanism, the driving control modelling, the decision-making of the cycle braking, and intelligent control approaches. The main research covered modelling of the heavy haul train operation, analysis of longitudinal impulse transmission mechanism, optimisation modelling, and intelligent control approaches. Through this project, a theoretical foundation and support were gained for implementing intelligent control of heavy-duty trains and enhancing the smooth, safe, and effective operation of heavy-duty railways [32].

From 2017 to 2019, the project, Integrate Train Energy Efficiency Optimisation Model Basing on On-Board Energy Storage Devices was carried out by the South China University of Technology. In this project, a Mixed Integer Linear Programming (MILP) technique was used to optimise an integrated energy-efficiency optimisation model for trains with onboard ESDs. This research mainly addressed two issues: first, the optimisation of charging and discharging strategies for ESDs under the constraints of train operations; second, the optimisation of train operations considering the train's traction system characteristics. By considering both the constraints of train traction systems and onboard ESDs, this project further improved the energy efficiency of train operations. The outcomes of this project would significantly contribute to the development of energy efficiency improvement technologies in urban rail transit systems [33].

Australian rail research centres and industry bodies are actively involved in developing products and technologies to enhance all aspects of rail transport [34]. The Energymiser System, developed by the University of South Australia, is an in-cabin Driver Advisory System (DAS), which provides real-time driver advice and web-based reports. The Centre for Railway Engineering (CRE), based at CQUniversity in Queensland, is applying a number of engineering disciplines to rail research. They are developing an Intelligent Train Monitor (ITM), an in-cabin device that provides the train driver with information about forces in the train. The ITM's software platform is able to display a variety of information in many different forms. It will also enable comments from train drivers and operators to be quickly incorporated into the system, which in turn saves energy consumption [35, 36]. In 2022, the technology company ABB also started a three-year project, which aims at capturing braking energy and returning it to the 1500 V DC wayside energy storage system (ESS) for the acceleration of other trains [37].

In Spain, the Comillas Pontifical University carried out a project to optimise the Automatic Train Operation (ATO) speed profiles on the metro line of Madrid, which is equipped with the Communications-based train control system (CBTC). The objectives of this project are to minimise energy consumption and generate the Pareto optimal curve [38]. This project considered the uncertainty of the train mass as a fuzzy number model. NSGA-II-F algorithm was applied to design the optimal speed profiles. This project has been realised on a real interstation in Metro de Madrid, showing that significant energy savings can be obtained by re-designing ATO speed profiles while taking advantage of the CBTC features (7–8%).

The Seoul Metro of South Korea joined the green approach by working together with the high-tech company EMERSON. EMERSON developed the SCADA software for Seoul Metro, to improve its energy efficiency. The SCADA software includes an entire management system and the station monitoring system, which can collect and monitor energy data from hundreds of stations, substations, and depots [39]. Its effectiveness in monitoring and analysing energy consumption has been shown. Moreover, Seoul Metro achieved a 4% reduction in total energy consumption with this software [40].

In 2009, a railway project supported by the Japan Science and Technology (JST) and Japanese Ministry of Land, Infrastructure was started. This project provides a detailed analysis of voltage drop and energy-saving effects when using the superconducting cable [41]. The main study focused on the energy analysis of superconducting power transmission on commercial railway lines. The results of this research showed that the energy-saving rate increases as the length of superconducting cable extends. While with a short cable, the voltage drop specific to railways could be reduced. This project provides a good solution to the problem of saving railway power and energy-related problems with superconducting feeder systems.

Even though numerous projects have been carried out to reduce railway energy consumption, which can be seen in Table 1.1, the study of innovative strategies and technologies is still attracting researchers across the world. In 2016, a comprehensive analysis of the railway was made by the UIC [42]. This report described the most recent research about the potential reduction of energy consumption, according to the technologies developed nowadays. Additionally, it also analysed practices carried out by railway undertakings that encouraged energy efficiency. The results show that the energy consumption in existing railway systems could be reduced by 10–30% with the application of smart energy management, 15% by reduction of the losses in the traction chain, and 7–15% by the inclusion of reversible substations. Therefore, research about the railway's power supply, traction, and regenerative braking system is still a promising way to improve its energy efficiency.

1.3 Energy Saving Methods in Railways

The energy consumption of a railway system is composed of many parts, which can be divided into traction energy consumption and non-traction energy consumption (see Fig. 1.6). The traction energy consumption represents the traction energy offered by substations for train operation, which includes the energy consumed by the onboard auxiliary systems, the traction energy used to overcome the motion resistance of rolling stock, the energy losses in the traction chain, etc. The non-traction energy consumption embraces all the energy utilised by different services ensuring the proper operation of urban rail systems. These typically comprise passenger stations, depots, and other infrastructure-related facilities such as signalling systems, tunnel ventilation fans, groundwater pumps, and tunnel lighting. Among the total energy consumption, traction energy consumption accounts for about 80% of the total energy consumption of the railway system, which is the focus of energy conservation research.

To reduce the traction and non-traction energy, Table 1.2 presents the main efficient measures proposed and implemented so far in the urban rail transit system, which can be divided into five categories: using regenerative braking, implementing eco-driving strategies, minimising traction losses, reducing the energy demand of comfort functions, and measuring and managing the energy flows efficiently. The first measure aims to recovering and reusing the vehicles' braking energy in the form of electricity. The synchronisation of train timetables, the usage of Energy Storage System (ESS), and the construction of reversible substations belong to this measure. Energy-efficient driving is the second energy-saving measure which refers to the group of techniques intended to operate rail vehicles as efficiently as possible while ensuring the safety and punctuality of services. Apart from energy consumption reduction, eco-driving strategies may also improve passenger comfort through smoother driving and reduce the wear of rolling components. Optimising the speed profiles, coasting and using the track gradients are the basic practices in eco-driving, supported by optimisation of timetables and railway traffic management. The energy-efficient traction systems can reduce the energy losses by optimising the parameters of the traction system. The fourth measure is reducing the energy demand of comfort functions, such as the optimal control of the fresh air supply. Measuring and managing the energy flows is the final measure including energy metering, local renewable power generation, and smart power management.

Table 1.1 Railway projects for energy-efficiency improvement

Project	Country/ region	Main contribution to improving energy efficiency	Duration
ON-TIME [10–12]	EU	Developed methods, system architectures and exchange data formats for train timetabling, traffic management and connected Driver Advisory Systems, integrating energy-efficient train trajectories throughout	2011–2014
OPEUS [15]	EU	1. Developed simulation methods and associated tools to evaluate and optimise energy consumption 2. Provided robust, stable, and readily available assessment methodology	2016–2019
In2Stempo [16]	EU	1. Developed a smart railway power grid 2. Constructed a fine mapping of energy flows	2017–2022
Railenergy [17]	EU	1. Addressed Energy Efficiency Issues for Integrated Rail Systems 2. Developed new verification standards for energy performance of railway products and services	2006–2010
MERLIN [18]	EU	Investigated and demonstrated the viability of an integrated management system to optimise energy usage in electric mainline railway systems	2012–2015
OSIRIS [19]	EU	1. Identified operational and technical innovations that reduce energy costs in running rail systems 2. Developed innovative methodology for simulating, evaluating, and optimising energy consumption in urban rail systems	2012–2015
SmartDrive [21, 22]	UK	Developed the SmartDrive package to achieve the application of an energy-efficient driving strategy	2019
CaFiBo [23]	UK	Developed the carbon fibre rail bogie, which can be used to reduce the mass of the rolling stock	2017–2019
Innovative composite mast for greener electrification [24]	UK	Developed new masts made from advanced composite materials to reduce the cost of electrification	2021
“14th five-year plan” railway science and technology innovation plan [31]	CN	Carry out a series of research plans to reduce the energy consumption of railway	2021–2026

(continued)

Table 1.1 (continued)

Project	Country/ region	Main contribution to improving energy efficiency	Duration
Investigation into intelligent control of heavy haul trains on long and steep downhill section [32]	CN	Obtained a theoretical basis and support for realizing intelligent control and improving the safe, smooth, and efficient operation of heavy-haul railway	2019–2021
Integrate train energy efficiency optimisation model basing on on-board energy storage devices [33]	CN	Developed an integrated energy-efficiency optimisation model for trains with onboard ESDs, and obtained the optimisation results with mixed integer linear programming (MILP)	2017–2019
ITM [35, 36]	AUS	Developed an in-cab system that can help with energy-efficient driving	1994–2008
Captures, stores and regenerates braking energy [37]	AUS	Aims to capture and store regenerative braking energy in the wayside energy storage system	2022–2025
Optimal design of energy-efficient ATO CBTC driving for metro lines [38]	ESP	1. Re-designed the ATO speed profiles and achieved energy saving 2. Provided a well-distributed pseudo-Pareto front	2014
Seoul metro and Emerson's cooperative project [39, 40]	KOR	1. Monitor and analysis of energy consumption 2. Reduction of the total energy consumption	2019
Energy analysis of superconducting power transmission installed on the commercial railway line [41]	JP	Achieved energy saving and suppression of voltage drop on city rail line model	2020

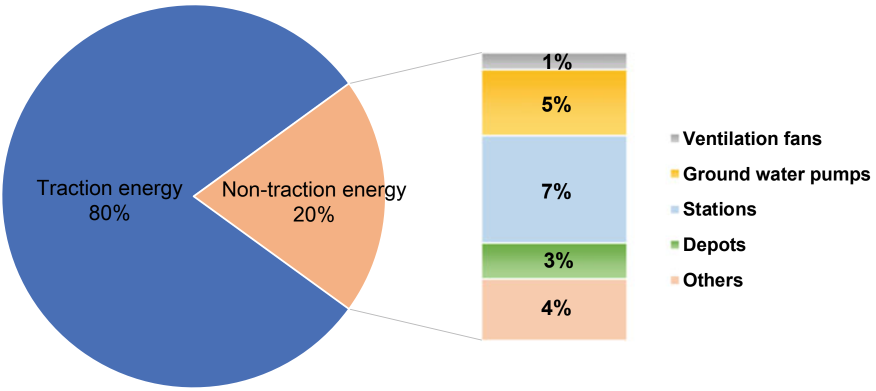


Fig. 1.6 Distribution of non-traction energy in railway systems [43]

Table 1.2 Main actions to save energy in urban rail [43]

Measures	Applied range	Type of measures	Objectives of measures
Timetable optimisation	Whole system	Operational measure	Regenerative braking
Renewable energy generation	Whole system	Technological measure	Measurement and management
Smart energy management	Whole system	Operational and technological measure	Measurement and management
Optimised traffic management	Whole system	Operational and technological measure	Energy-efficient driving
Energy metering	Whole system	Technological measure	Measurement and management
Passenger management in stations	Infrastructure	Operational and technological measure	Passenger management in stations
Reversable substations	Infrastructure	Technological measure	Regenerative braking
Reduced power supply losses	Infrastructure	Operational and technological measure	Traction efficiency
Low-energy tunnel cooling	Infrastructure	Technological measure	Passenger management in stations
Lighting and HVAC in stations	Infrastructure	Operational and technological measure	Passenger management in stations
Wayside ESS	Infrastructure	Technological measure	Regenerative braking
Optimised traction software	Rolling stock	Operational measure	Traction efficiency
Timetable optimisation	Rolling stock	Operational and technological measure	Passenger management in stations
Mass reduction	Rolling stock	Technological measure	Traction efficiency
ATO	Rolling stock	Technological measure	Energy-efficient driving
Thermal insulation	Rolling stock	Technological measure	Passenger management in stations
Eco-driving techniques	Rolling stock	Operational measure	Energy-efficient driving
PMSM	Rolling stock	Technological measure	Traction efficiency
On-board ESS	Rolling stock	Technological measure	Regenerative braking
Lighting and HVAC in Service	Rolling stock	Operational and technological measure	Passenger management in stations
DAS	Rolling stock	Technological measure	Energy-efficient driving

The relationship among the first four measures is shown in Fig. 1.7, while the general evaluation of each energy efficiency measure is shown in Table 1.3. According to the energy saving potential index, most methods of the regenerative braking measure and energy-efficient driving measure have an energy-saving potential of more than 5%, while only two methods of traction efficiency and comfort function measure may achieve an energy saving potential of more than 5%. Therefore, the optimisation measures on train operation need to be focused on to increase

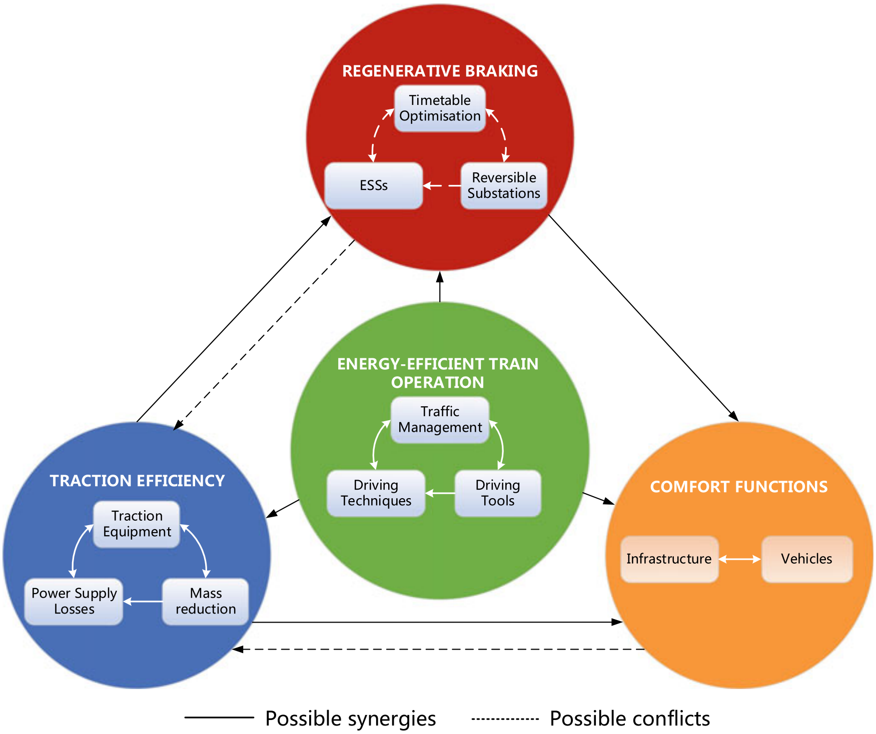


Fig. 1.7 Interdependences between energy efficiency measures [43]

the energy-saving effect by improving the utilization rate of regenerative energy and reducing the traction energy consumption.

1.4 Book Chapter Structure

Due to the significance of rail energy and the high potential to reduce the energy consumption in railway systems, this book further illustrates the energy-efficient train operation solutions for railway systems. This book is closely related to the energy conservation problem of the rail transit system by focusing on reducing the energy consumption for train operation. In this book, the whole systems processes of train operation with optimisation solutions are analysed and illustrated. The remainder of this book is structured as follows.

Chapter 2 introduces the relationship between train operation and energy consumption under different energy-efficient strategies. This relationship will serve as the basis for the energy-efficient optimisation methods in the subsequent chapters. Specifically, in the train-based energy-saving strategy that aims to minimise the net

Table 1.3 General evaluation of energy efficiency measures in urban rail systems [43]

Measures			Energy saving potential (%)	Suitability for existing systems	Investment cost
Cluster	Category	Solution			
Regenerative braking	Timetable optimisation		1–10	High	Low
	ESS	On-board	5–25	Medium	High
		Stationary	5–25	High	High
	Reversible substations		5–20	High	High
Energy-efficient driving	Eco-driving techniques	Coasting, optimised speed profile, use of track gradients	5–10	High	Low
	Eco-driving tools	DAS	5–15	High	Medium
		ATO	5–15	Medium	High
Traction efficiency	Power supply network	Higher line voltage	1–5	Low	High
		Lower resistance conductors	1–5	Low	High
	Traction equipment	PMSM	5–10	High	High
		Software optimisation	1–5	High	Low
	Mass reduction	Materials substitution	1–10	High	Medium
Comfort functions	Vehicles	Thermal insulation	1–5	High	Medium
		Heap pump	1–5	Medium	Medium
		LEDs	1–5	High	Medium
		HVAC and lighting control in service	1–5	High	Low
		HVAC and lighting control in parked mode	1–5	High	Low
	Infrastructure	Low-energy tunnel cooling	1–5	Low	High
		Geothermal heat pumps	1–5	Medium	Medium
		Control of HVAC, lighting and passenger conveyor systems	1–5	High	Low
		LEDs	1–5	High	Medium

energy consumption, four methods are introduced, including energy-efficient train control, energy-efficient train timetabling, integrated optimisation for regenerative braking, and energy-efficient driving considering energy storage systems. Then, the substation-based energy-saving strategy whose goal is to reduce the electric energy offered by substations, is briefly presented.

Chapter 3 formulates an optimisation model for energy-efficient train operation. The motion of the train is described by a pair of differential equations, with parameters including the tractive and braking effort curves, resistance forces, track gradient forces, and track curvature forces. Speed limits and timing requirements are imposed as constraints on the motion. By solving the optimisation model with the Pontryagin's maximum principle, five optimal driving modes including power, hold, coast, regen, and brake are achieved. Furthermore, these necessary conditions for optimal control are used to determine the optimal sequence of control modes for a journey, and when the control should be switched between modes.

Chapter 4 applies train trajectory optimisation to compute the minimum-time and energy-efficient train trajectories between two and more stops, as well as the optimal running time supplements in timetables over corridors with multiple stops. Also the trade-off is considered between energy-efficient train trajectories and the infrastructure occupation of multiple trains on heterogeneous train traffic corridors. The results are compared to other train-driving strategies used in practice. Realistic conditions are considered, including varying gradients and speed restrictions, and heterogeneous mainline railway traffic.

Chapter 5 focuses on the integrated driving strategy and train timetable synchronization method. Firstly, the mathematical models are formulated to calculate the amount of traction energy and reused regenerative braking energy (RBE). Then, two integrated timetabling approaches are introduced. In the first approach, the arrival time and departure time of trains are synchronized with consideration of the driving strategy to efficiently reuse the produced RBE. The second approach matches traction/braking regimes during the inter-station train operation, to get a better energy-saving effect. Both integrated timetabling approaches are verified by metro line examples based on real-world data.

Chapter 6 discusses the main technologies, the modelling, and control methods of energy storage systems. A case study is presented where different scenarios of energy storage and receptivity to regenerated energy are analysed based on the characteristics of a real line of the Madrid Underground. The influence of energy storage devices in energy consumption reduction and the optimal design of ATO speed profiles is evaluated.

Chapter 7 presents the development of energy evaluation simulation of electric railway systems. The train movement model and railway power network model are integrated into the simulator. Based on the power network model, this chapter also analyses the energy consumption of railway systems with regenerating trains, including the energy supplied by substations, used in power transmission networks, consumed by monitoring trains, and regenerated by braking trains. Finally, a case study of the Beijing Yizhuang Subway Line is conducted, which indicates that the available regenerative braking energy and total substation energy consumption vary with timetables.

Chapter 8 gives the basic conclusions about energy-efficient train operation covering energy-efficient train driving, energy-efficient train timetabling, regenerative braking, energy storage systems and power supply networks. This chapter also provides recommendations for further research, which includes the interaction of connected driver advisory systems (C-DAS) and automatic train operation (ATO) with railway traffic management systems, cooperative train control in platoons of virtually coupled trains, digital twin technology and particularly its application to power supply systems, and the interaction between the railway network with the electrical power grid and renewable energy generation.

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