

A systems approach to reduce urban rail energy consumption



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ABSTRACT

There is increasing interest in the potential of urban rail to reduce the impact of metropolitan transportation due to its high capacity, reliability and absence of local emissions. However, in a context characterised by increasing capacity demands and rising energy costs, and where other transport modes are considerably improving their environmental performance, urban rail must minimise its energy use without affecting its service quality. Urban rail energy consumption is defined by a wide range of interdependent factors; therefore, a system wide perspective is required, rather than focusing on energy savings at subsystem level. This paper contributes to the current literature by proposing an holistic approach to reduce the overall energy consumption of urban rail. Firstly, a general description of this transport mode is given, which includes an assessment of its typical energy breakdown. Secondly, a comprehensive appraisal of the main practices, strategies and technologies currently available to minimise its energy use is provided. These comprise: regenerative braking, energy-efficient driving, traction losses reduction, comfort functions optimisation, energy metering, smart power management and renewable energy micro-generation. Finally, a clear, logical methodology is described to optimally define and implement energy saving schemes in urban rail systems. This includes general guidelines for a qualitative assessment and comparison of measures alongside a discussion on the principal interdependences between them. As a hypothetical example of application, the paper concludes that the energy consumption in existing urban rail systems could be reduced by approximately 25–35% through the implementation of energy-optimised timetables, energy-efficient driving strategies, improved control of comfort functions in vehicles and wayside energy storage devices.

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1. Introduction

Transport is currently one of the most energy-consuming and polluting sectors in both developing and developed countries. In the European Union (EU), for instance, it causes approximately 31% of total greenhouse gas (GHG) emissions [1]. Within this sector, metropolitan transportation is responsible for about 25% of the total CO₂ emissions [2]. Additionally, high levels of air pollution and congestion are major issues related to transport in urban areas. Therefore, in a worldwide context of growing urbanisation, the implementation of efficient, reliable and environmentally friendly transport systems becomes imperative not only to meet the international agreements on GHG emissions reduction [3,4], but to guarantee liveable conditions in urban areas. In this vein, the EU aims at halve the use of oil-fuelled vehicles in urban transport by 2030 and eventually phase them out in urban centres by 2050, [2]. Instead, cleaner metropolitan public transport systems are being strongly promoted.

Urban rail is regarded as an ideal solution to reduce the impact of urban mobility because of its great capacity, safety, reliability and excellent environmental performance [5]. This is so much so that urban rail systems have been gaining increasing appeal as effective and sustainable methods of mass-transport for the last decade in the EU, as shown in Fig. 1 [6]. Nevertheless, in a very competitive context where other transportation modes are considerably improving their environmental performance – in particular the automotive sector [7] – and the energy costs are steadily increasing, it is crucial that urban rail reduces its energy use while maintaining or enhancing its service quality and capacity [8]. Otherwise, urban rail may risk losing its competitive position at the forefront of economic and sustainable solutions for mobility in metropolitan areas [9].

A few research projects and studies discussing different technologies and operation strategies to increase the energy efficiency of railway systems and reduce their GHG emissions have been performed in recent years [10–14]. Although some of the energy efficiency measures generally proposed for the rail sector may also work in urban rail, the singular characteristics of these systems seem to call for more dedicated studies. Furthermore, urban rail

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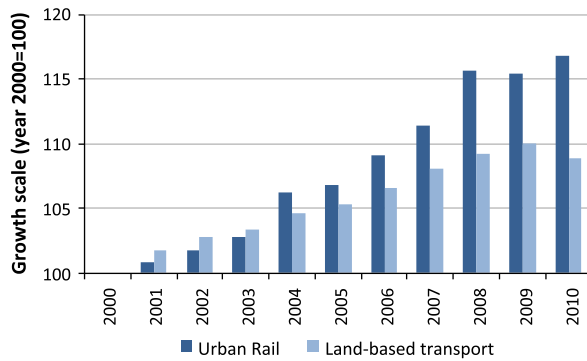


Fig. 1. Evolution of urban rail transport demand in the EU: comparison with total land-based passenger transport.

systems are complex environments where energy consumption is defined by a wide range of interdependent factors. Therefore, what is needed is a global perspective ensuring that the introduction of new measures reduces the energy consumption at system-level, rather than concentrating on individual energy efficiency solutions that may compromise other aspects of the system performance.

With the intention of covering a lack found in the literature, this paper presents a systems approach to reduce the energy consumption of urban rail. Firstly, the paper presents a general characterisation of urban rail systems as singular, complex transit systems, providing insights in the energy consumption of their different subsystems. Secondly, the most effective practices, strategies and technologies to reduce their energy consumption are identified and analysed. This includes a list of the most relevant examples of application and the latest research studies on this topic. The paper concludes by describing a methodology to evaluate and optimally implement energy efficiency measures in urban rail systems. The final objective of this paper is to provide useful guidance for the stakeholders involved in improving the competitiveness of urban rail by reducing its energy consumption.

2. Urban rail systems: characterisation and energy flow

In order to establish a clear context for the identification and evaluation of energy saving measures in urban rail, this section describes the main characteristics of urban rail systems and discusses how energy is utilised within them.

2.1. General characterisation

The term “urban rail transport” generally refers to railway systems providing public transport services within metropolitan areas. Therefore, the short distance between stations is one of their main characteristics. Urban rail comprises four basic modes: tramway, light rail transport, rail rapid transport (more commonly known as metro) and regional or commuter rail transport [5]. Among them, metro systems have the greatest level of service, operating approximately 3.5 million passenger-kilometres annually within the European Union [15].

With the exception of some regional rail systems utilising diesel traction (which are out of the scope of this work), all urban rail systems are electrically powered. Consequently, urban rail is characterised by presenting a high performance of operation, low levels of noise and absence of local air pollution. Other distinguishing features that make urban rail a very appealing option to improve passengers’ mobility in urban areas are: relatively low surface space requirements, high capacity and frequency of services, possibility of automation, elevated degree of safety and punctuality, strong image and identity attracting passengers. On the negative side,

urban rail systems typically require higher investment costs than non-rail modes.

2.2. Energy use in urban rail systems

Energy use in urban rail systems may be typically classified into two categories: traction and non-traction consumption. Traction consumption comprises not only the propulsion of the vehicle itself, but also its auxiliary systems in service mode; in other words, “traction” accounts for the power required to operate the rolling stock across the system. The term “non-traction”, in turn, refers to the energy utilised at stations, depots and other facilities in the system such as tunnel ventilation fans, signalling, groundwater pumps, etc.

2.2.1. Traction energy consumption

2.2.1.1. Description of the traction system. Unlike diesel traction, where the energy required for train operation is generated within the vehicle itself, electric traction requires an external power supply system. In general, these kinds of electric systems can either work with direct current (DC) or alternating current (AC). Notwithstanding, most urban rail systems worldwide are DC-powered, either at 600/750 V, 1500 V or 3000 V. Regardless of the type of electrification, railway power supply networks essentially consist of the following subsystems, see Fig. 2:

- Substations: Allocated at predetermined places along the track, they include step-down transformers to condition the power from the distribution network, which can be the public grid or a distribution network within the system itself. In the case of DC electrification, substations are additionally equipped with a rectifier assembly to convert AC into DC.
- Traction power distribution system: It conveys the electric power from the substations to the rail vehicles. It typically consists of an overhead line (catenary), though a conductor rail (third rail) can be also found in some metro systems with heavy traffic loads and/or reduced space inside tunnels.
- Traction power return system: It returns the electric power to the substations, typically through the running rails or an extra (fourth) conductor rail.

Rail vehicles are directly fed from the power distribution system by means of pantographs or current collector shoes, depending on whether the electricity is supplied through overhead lines or conductor rails, respectively. Within the rolling stock itself, electricity is used to drive both the traction equipment and the auxiliary systems. The auxiliaries consist of all the equipment assuring the operation of the vehicle such as traction cooling systems, compressors, etc. Moreover, in the context of this work, auxiliaries include the passengers’ comfort functions, i.e. heating, ventilation and air-conditioning (HVAC), lighting and information systems. In turn, the propulsion system comprises the electric traction drive, including its associated equipment (converter and control system) and the torque transmission system. As for the type of traction motors, DC machines have traditionally been the most widely used in urban rail. However, as a result of the outstanding advances experienced by power electronics in the last decades, AC (usually asynchronous induction) motors have been widely introduced, as they typically require less maintenance work, offer lighter weight per output torque and present higher efficiency [16].

2.2.1.2. Traction energy flow. Fig. 3 shows a typical traction energy flow chart for urban rail, a result of the amalgamation of measured and estimated consumption data for different urban rail systems within Europe, [14,17–24]. This diagram should therefore be considered as illustrative rather than as a representative example of

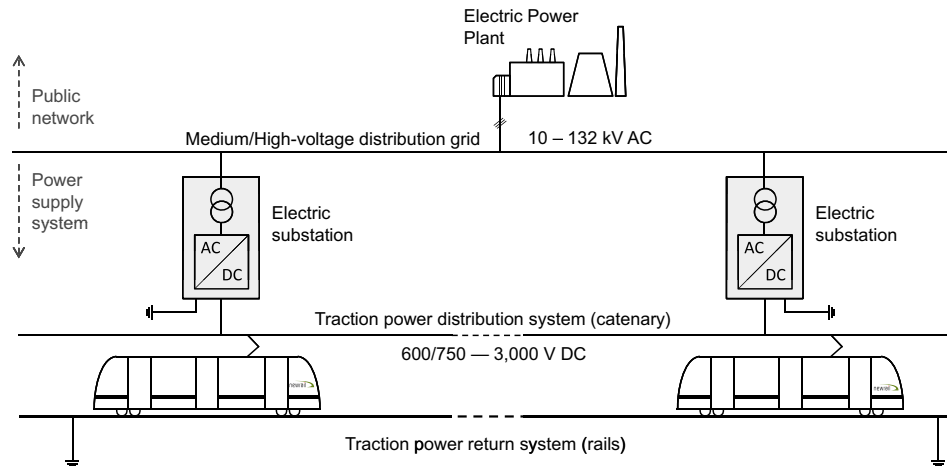


Fig. 2. Diagram of a typical DC power supply network for urban rail systems.

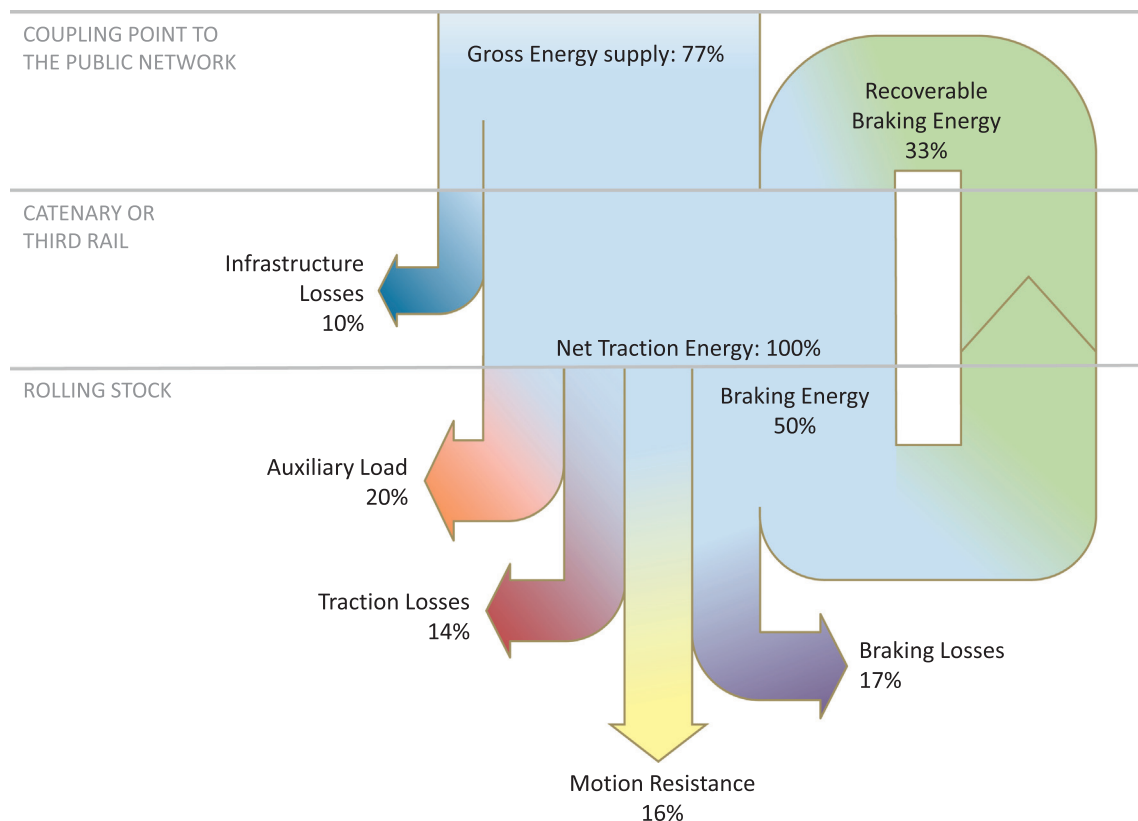


Fig. 3. Typical traction energy flow in urban rail systems.

the proportion of energy consumed by different traction subsystems in urban rail, as there is significant variation between different systems.

In Fig. 3, infrastructure losses refer to the electric losses occurring from the point of common coupling to the pantograph (or collector shoes); that is, the electric losses in the substations and the distribution network, the latter being significantly higher [12]. Infrastructure losses principally depend on the voltage level of the rail system and its traffic load, being more important for low-voltage networks with heavy traffic. Additionally, in “coupled through” systems, where several electric sections of the line are connected to favour the regenerative energy transfer between

vehicles, the electric losses are also higher. Typical values for infrastructure energy losses can be as high as 22%, 18%, 10% and 6% for 600 V, 750 V, 1500 V and 3000 V-DC networks, respectively [25,26].

As seen in Fig. 3, auxiliary systems consume an important share of the total energy entering the rolling stock. HVAC equipment is generally responsible for the most significant part of this consumption, which is strongly influenced by the climate conditions [27]. For instance, it has been reported that heating systems account for 28% of the total traction energy in Metro Oslo [21], whereas all auxiliary systems represent about 10% of the total vehicle consumption in London Underground [22].

Another major share of the traction energy is dedicated to overcoming the motion resistance of the rolling stock. This comprises both aerodynamic opposition to the vehicle advance and mechanical friction between wheels and rails. Aerodynamic drag increases with the square of velocity, therefore its influence is more noticeable in commuter trains than in tramways, for instance. In turn, mechanical resistance plays a more decisive role in low-speed services, the mass of the rolling stock being the main parameter to take into account for reducing its effect. It can be concluded from the available literature that, on average, motion resistance is responsible for approximately 16% of the traction energy use in urban rail services [14,17,21,22], as illustrated by Fig. 3.

Energy losses in the traction chain itself mainly consist of inefficiencies in the converters, the electric motors and the transmission system. The efficiency of these components may significantly vary across the speed and power ranges, and so the overall values will depend on the duty cycle. A recent report on railway energy performance assesses that the efficiency of converters (primarily GTO and IGBT) are about 98.5–99.5% [17]. Likewise, they estimate that the efficiencies of DC and induction motors are about 90–94% and 93–95%, respectively. In turn, the losses in the gear system are evaluated to be around 2–4%.

The greatest portion of traction energy is wasted in braking processes, see Fig. 3. The amount of energy dissipated in braking strongly depends on the kind of urban rail system, but generally speaking it accounts for half of the energy entering the rolling stock. This rate clearly increases with the frequency of stops, being higher in tramways and metros than in commuter rail, for instance. Provided that electric motors can act also as generators while braking, it is possible to recover and reuse a significant proportion of the braking energy [28]. In contrast, about one third of the braking energy is irreversibly lost because of the use of friction brakes and the losses occurring in motors, converters and transmission system during dynamic braking.

2.2.2. Non-traction energy consumption

The term 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. Even though the vast majority of non-traction services are electricity-powered, it is also possible to find some diesel- or gas-fired heating systems in stations and depots [29,30].

Stations, and particularly underground stations, are complex systems that integrate both mobility and commercial services and where human and comfort aspects are of great importance [31–35]. The main energy-demanding facilities typically include HVAC, lighting, escalators, moving walkways, lifts and information/advertising screens [36]. In subway stations, the HVAC equipment is generally responsible for the greatest energy consumption, especially in summer, when the energy demand of air conditioning and ventilation may represent up to two thirds of the total consumption [37]. The thermal loads in stations are due to passengers, heat transfer from the ground, electrical equipment and train operation in tunnels (braking heat, electrical losses, etc.) [38,39].

In depots, energy consumption is mainly due to inspection, maintenance and cleaning of rolling stock [40]. These processes not only require energy to run the depot facilities themselves, but they also imply energy consumption in some auxiliary systems of the vehicle such as lighting or HVAC. Additionally, vehicles' comfort systems consume a non-negligible amount of energy during stabling of rolling stock; this includes both hibernation periods and pre-heating or pre-cooling operations [41].

The non-traction energy share in urban rail systems strongly depends on whether the system is underground or surface

operated, and also on the climate conditions. Thus, the non-traction energy consumption in tramway system is minor, whereas it accounts for approximately one third of total energy use in metro systems on average [29]. The lack of published data on the energy consumed by non-traction subsystems makes it difficult to provide generalised figures for urban rail. However, to give an idea of the order of magnitude of these consumptions, Fig. 4 shows the specific case of London Underground [30]. Here, stations consume about 37% of the total energy destined for non-traction purposes, while operations in depots account for 12.5% and tunnel ventilation fans for 6%. Especially noteworthy is the high energy consumption of ground water pumps, about 23% of the non-traction energy demand.

3. Overview of energy efficiency measures for urban rail

This section identifies and appraises the most promising practices, strategies and technologies available to minimise urban rail energy consumption in the available body of research.

3.1. Literature search methodology

An academic literature search – which represents the core of this section – was primarily conducted using international, online databases such as Scopus (<http://www.scopus.com>) and the Newcastle University Library Search Tool, which is linked to the major electronic resources worldwide. The main keywords used in this literature search are shown in Table 1. Furthermore, relevant unpublished information from personal communications with urban rail operators, dedicated conferences, seminars and workshops was examined. In addition, as the topic is not only of academic interest, the literature search also included international databases of research and industrial projects, such as the Transport Research Portal (<http://www.transport-research-portal.net>) and Spark (<http://www.sparkrail.org>). In general, the literature search was focused on last 15 years, although older resources were also consulted. In total, over 200 documents and websites were reviewed for the purpose of this section.

3.2. Operational and technological measures

Fig. 5 presents a non-exclusive list of the main initiatives proposed and implemented so far to minimise energy consumption in urban rail. As seen, these energy efficiency actions are classified into operational and technological measures. Operational measures aim at using both existing rolling stock and infrastructure more efficiently, which can be achieved with minor changes to the facilities. In contrast, the introduction of new technologies requires higher investment costs and implies major modifications in the system equipment. Additionally, Fig. 5 tabulates the measures according to their level of application; that is, the rolling stock, the infrastructure or the whole system.

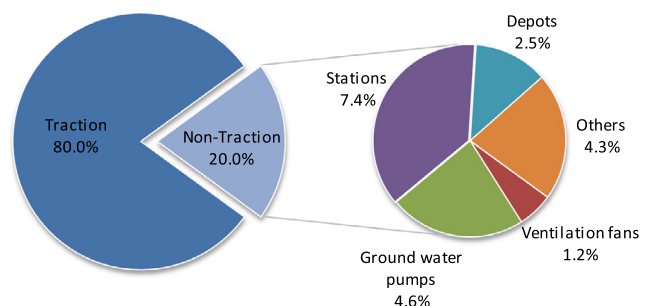


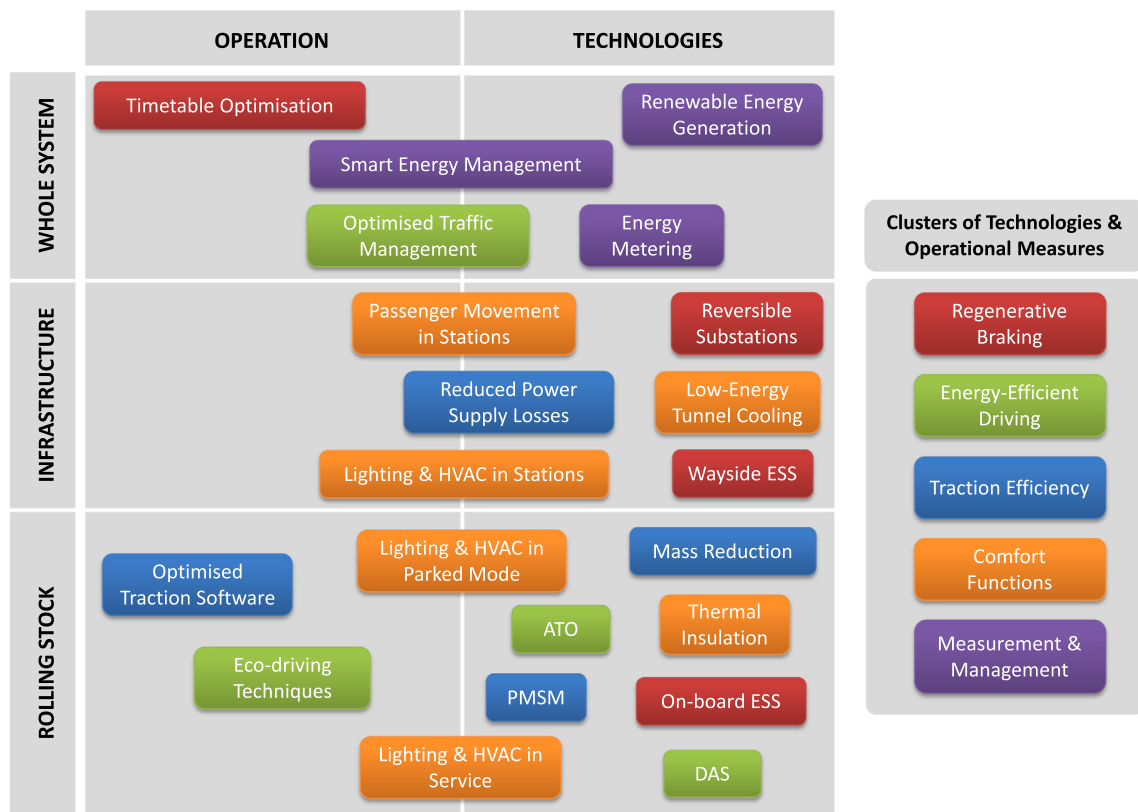
Fig. 4. Distribution of non-traction energy in London Underground.

Table 1

Main keywords used in the literature search.

Energy efficiency measures in general	Keywords*
Energy efficiency measures in general	Energy consum*, efficiency, reduc*, saving*; rail*; urban rail; metro; tram; light rail; technolog*; strateg*; operation*
Regenerative braking	Regenerative braking; energy recovery; timetable optimisation; energy storage; on-board, stationary, wayside, trackside system*; reversible, inverting, bidirectional substation*; supercapacitor*; ultracapacitor*; flywheel*; batter*
Energy-efficient driving	Energy efficient driving; eco-driving; speed profile*; coasting; Driving Advice System*; Automatic Train Regulation, Operation; traffic management optimisation
Energy-efficient traction system	Power supply line, network, grid; electrical loss*; traction; electrical motor*; permanent magnet; vehicle mass reduction; lightweight material*
Comfort functions	Temperature control; demand-controlled ventilation; heating; air-conditioning; thermal demand; lighting; optimal regulation, control; waste heat recovery; underground, subway station*, escalator*
Energy measurement and smart management	Energy metering, measurement, management; renewable power; smart grid*

* The use of asterisks at the end of keywords means that different suffixes are included in the search.

**Fig. 5.** Main actions to save energy in urban rail.

Five clusters of actions have been considered, namely: using regenerative braking, implementing eco-driving strategies, minimising traction losses, reducing the energy demand of comfort functions, measuring and managing the energy flows efficiently. Details of each group of measures will be given below.

3.3. Regenerative braking

Regenerative braking consists in recovering and reusing the vehicles' braking energy in the form of electricity. This technology may offer a great potential to reduce energy consumption in urban rail systems as they are typically characterised by numerous and frequent stops. The regenerated energy primarily feeds the vehicle's auxiliary functions, and the excess energy is usually returned into the supply line to power other vehicles accelerating in the

same electric section. However, since the consumption of auxiliaries is relatively minor and the simultaneous acceleration and deceleration of different vehicles is unlikely to happen, a considerable amount of braking energy is still wasted into braking resistors. The following options are currently available to maximise the utilisation of the regenerated braking energy in urban rail [28]: optimising the service timetables to increase the energy transfer between vehicles; using trackside and/or on-board energy storage systems (ESSs); and sending the regenerated energy back to the upstream AC network.

3.3.1. Energy-optimised timetables

Synchronising accelerating and braking vehicles by means of timetable optimisation is a straightforward action to maximise the use of regenerated braking energy in urban rail. A few

examples available in the literature show that significant energy savings of up to 14% can be achieved with this measure [42–45]. Additionally, timetable optimisation may limit peaks of power consumption, which represents an important issue in urban rail systems [46,47]. The optimum implementation of this operational measure will require a real time control system recalculating the schedule in case of unforeseen events or delays, and advising drivers on best departure times and driving strategies. Its investment cost may be relatively low though, especially if compared to other technologies such as energy storage or reversible substations. Therefore, timetable optimisation should be considered as a primary option to increase the benefits of regenerative braking in urban rail.

3.3.2. Energy storage systems

The outstanding advances in both power electronics and energy storage technologies have enabled ESSs to become an excellent option for reusing regenerated braking energy in urban rail. ESSs can be installed either on board vehicles or at specific points along the track. On-board ESSs permit rail vehicles to temporarily store their own braking energy and reutilise it in the next acceleration phases. In turn, trackside ESSs collect energy from any braking train in the near area and release it when demanded by other accelerating vehicles.

If properly dimensioned, both on-board and wayside ESSs may lead to considerable traction energy savings in urban rail (typically between 15% and 30%); moreover, they may contribute to stabilise the network voltage and to shave the power consumption peaks [19,20,23,48–59]. Additionally, on-board systems may provide a certain degree of autonomy for catenary-free services (e.g. lines going through historical city centres) [60]. In general, on-board ESSs operate with higher efficiency than wayside ESSs owing to the absence of line losses. However, they typically require large space on vehicles and introduce a considerable increase of weight, which may hinder their installation in existing rolling stock. In turn, stationary ESSs present fewer weight and space restrictions; besides, their installation and maintenance do not affect services.

Regarding the technologies available for ESSs in urban rail, electrochemical double layer capacitors (EDLCs), batteries and flywheels are the most suitable options [61,62]. EDLCs offer high power density, fast response, high cycle efficiency and long lifecycle, features that make this technology the most widely used in urban rail applications so far [28]. However, their energy density is very low, being replaced by (or combined with) high specific power Li-ion or NiMH batteries in systems providing high degrees of autonomy [63–65]. Composite flywheels also offer attractive features for energy recovery and storage in urban rail [66,67], although their commercial application has been generally limited to wayside systems so far [28].

3.3.3. Reversible substations

Unlike conventional DC substations using diode rectifiers, reversible substations (also known as bidirectional or inverting substations) include inverters enabling a bidirectional power flow. This means that the regenerated energy surplus may be driven back to the upstream AC grid and so used in the operator's network (lighting, escalators, offices, etc.) or also sold back to the energy provider, depending on the current legislation. Compared to ESSs, reversible substations operate with fewer transformation losses, although the resistive losses in the line may be considerable depending on the substation's location. Furthermore, they offer the possibility of full braking energy recovery since AC lines are permanently receptive. In contrast, they do not allow catenary-less operation and they cannot be used for voltage stabilisation or power peak reduction purposes. Additionally, they present relatively high investment costs. A few studies demonstrate that this

technology may save up to 7–11% of the traction energy consumption in existing urban rail systems [18,68,69].

3.4. Energy-efficient driving

3.4.1. Eco-driving techniques

Eco-driving 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.

Acceleration profiles and maximum speed limits are critical factors determining the traction energy consumption in rail services. Hence, their optimisation within safety and schedule restrictions may lead to important energy savings. For instance, a readjustment of the speed limits in the Brussels metro (from 72 to 60 km/h and from 60 to 50 km/h) resulted in traction energy savings of 15%, although an additional train was necessary to compensate for the slight increase in the journey length [70]. Interestingly, for the Sao Paulo system the most energy-efficient driving profile consisted in reducing the maximum speed at the expense of increasing the acceleration rates [71].

Coasting means not applying power to the traction motors so that the vehicles decelerate due to motion resistance when approaching stations. Different methodologies to determine the optimal coasting points and the associated speed profiles have been suggested in the literature, see for example [72–77]. Despite the short distances between stations characterising urban rail, applied studies have demonstrated that significant reductions in traction energy consumption are possible by coasting. For instance, energy savings of about 20% with an increase of 5% in the running time were reported for specific lines of London and Istanbul metro systems, respectively [78,79].

The effect of gravity in both accelerating and decelerating phases is another important aspect to be considered in designing energy-efficient driving strategies for urban rail. For example, in systems where stations are at a higher level than the track, the uphill gradient may help stop the rail vehicles with less braking effort, whereas downhill gradient may contribute to save energy while accelerating [80,81].

The potential offered by the above energy-efficient driving techniques may be exploited in large part by operational or simple technological measures. Thus, installing trackside information systems advising on optimal speeds and coasting points [82] and training drivers in eco-driving techniques will lead to significant short-term traction savings with relatively low investment costs [13]. Note that keeping a high degree of awareness and motivation among the drivers is crucial for the success of these measures.

Additionally, on-board Driving Advice Systems (DASs) are gaining increasing acceptance as a tool to save energy in urban rail. Based on preloaded algorithms and data defining each individual trip, these kinds of systems advise the driver on the best strategies to follow according to the running time and the train position [83,84]. DAS allow for greater energy savings than just operational measures, but they necessarily imply refurbishment of current rolling stock.

A further step towards more energy-efficient driving in urban rail is the implementation of Automatic Train Operation (ATO) systems, which allows for a real time control of the optimum speed profile with no influence from the driver [85–88]. Both driverless and semi-automated operation are possible in ATO systems; nevertheless its implementation in existing systems may face important barriers such as drivers' opposition [10].

3.4.2. Optimised traffic management

Eco-driving strategies generally imply an increase in the running time, so their successful application depends on the availability of time buffers. Optimising these recovery margins (typically included in timetables as an allowance for impeded running) is therefore indispensable to save energy while ensuring service quality [73,89].

Reducing platform dwell time may substantially increase the potential for energy-efficient driving. Furthermore, this measure may help improve the satisfaction of passengers, who generally prefer longer running times between stations rather than longer platform dwell time. Aside from schedule reformulations, implementing explicit and accurate information systems in vehicles and stations may shorten both boarding and alighting times [10].

Automatic Train Regulation (ATR) systems, typically designed to ensure safety and punctuality in complex urban rail systems, can also be used for energy saving purposes. Thus, ATR may be linked to DAS so that coasting can be used to avoid conflicting movements (as well as for station stops), hence minimising energy waste in stopping and restarting. A real-time traffic regulation from an energy efficiency point of view can be achieved by implementing optimisation algorithms such those proposed in [90,91].

3.5. Energy-efficient traction systems

3.5.1. Reducing energy losses in the power supply network

The resistive losses in the power distribution network are a quadratic function of the current. Therefore, they can be significantly reduced by limiting the power peaks caused by the simultaneous acceleration of different trains in the network. The optimisation of timetables and the use of regenerative braking technologies are key measures for this purpose, as previously discussed. Likewise, energy losses may be minimised by selecting higher electrification voltages, although this may imply excessively high investment costs in existing systems.

Another option to reduce energy losses in the power supply network is selecting low-resistance materials for the feeder lines. Despite requiring relatively high investment costs, an increasing number of third rail powered systems (e.g. the London Underground) are replacing the standard steel conductor rails by aluminium-based ones, which offer up to 50% less resistance [92]. Superconducting cables may represent an alternative to conventional line conductors but, though promising, this technology is still in the research and development stage [26,93].

3.5.2. Reducing losses in on-board traction equipment

Energy losses in on-board traction equipment are predominantly due to inefficiencies in the motors themselves, whereas losses in power converters and transmissions systems are relatively minor (see Section 2.2.1). Hence, the greatest improvements in traction efficiency can be achieved by using more efficient motors. In this regard, the Permanent Magnet Synchronous Motor (PMSM) represents a very promising alternative to the state-of-the-art asynchronous machines because of its very high efficiency of up to 97% [94].

PMSMs utilise permanent magnets in the rotor instead of the conventional excitation current to generate the magnetic field, which minimises electric losses. Moreover, their lower cooling requirements enable PMSMs to be mounted in totally enclosed configurations, which allows for lighter and more compact designs with less maintenance and lower noise emissions [95]. Additionally, the high torque offered by PMSMs makes a direct drive configuration (gearless) easier to implement, which can further reduce energy losses, mass and noise emissions [96,97]. A major drawback of synchronous motors is, however, the need for dedicated inverters [98–100], which raises the investment cost. PMSM is a

commercially available technology that has been successfully verified in urban rail applications. For example, PMSMs have been tested in the Hankyu commuter railway and Tokyo metro systems (Japan) with traction energy savings of 9% and 12–13%, respectively [101].

Optimal management of the traction equipment according to the operating conditions may also lead to increases in traction efficiency of 1–5% [10,13]. For instance, shutting off some of the traction groups instead of operating them all at partial load during coasting, cruising or standstill, may reduce energy losses in motors and converters. These are operational measures that essentially require an on-board traction software optimisation, which means their implementation costs are relatively low.

3.5.3. Vehicle mass reduction

Lighter vehicles present lower mechanical resistance to advance and require less kinetic energy to reach the same level of performance; therefore, minimising the overall mass of rail vehicles will reduce their traction energy consumption. The ratio of the traction energy saving percentage over the mass reduction percentage is estimated to be about 0.6–0.8 for urban rail [102,103], although it may be slightly lower when using regenerative braking. Furthermore, reducing the weight of rolling stock will result in less damage to the track and reduced wear of wheels and brakes, consequently lowering the operational and maintenance costs of the system [104].

A straightforward method to reduce the vehicle's weight is to introduce lightweight materials such as composites. Robinson and Carruthers [105] have identified that the proportion of a vehicle's tare mass that can be potentially influenced by material substitutions is around 80%; this includes bodyshell, windows, exterior attachments, bogies, passenger interior, seats, driver's cab interior and cabinets, external doors and couplers. Some examples of mass reduction projects using lightweight materials in urban rail include the following: development of composite grab rails (50% lighter than existing stainless steel bars) [103]; replacement of current floor planes by 40% lighter sandwich constructions [106]; development of a crashworthy driver's cab using advanced composite sandwich materials up to 40% lighter [107]. These measures should be primarily implemented at design stages, although retrofitting may be also viable in some cases.

In addition to the use of lightweight materials, the overall mass of rail vehicles can be reduced by upgrading the traction equipment. For example, the use of PMSMs, gearless drives and power converters based on new semiconductors [108] may result in significant mass reductions. Furthermore, controlling the suspension and guidance functions electronically (mechatronics) is likely to be implemented in future, lightweight rail vehicles [109]. Lastly, adjusting the train length according to passenger demand is also an interesting approach for saving energy through mass reduction, especially during off-peak periods [14,27].

3.6. Reducing the energy consumption of comfort functions

3.6.1. Rolling-stock-related measures for service mode

Just as in household applications, the HVAC demand in rail vehicles can be reduced by minimising the heat transfer to (or from) outdoors, which primarily requires improving the thermal insulation of walls, doors, windows, floor and ceiling of vehicles. Furthermore, the use of smart windows automatically adjusting their opacity according to the sunlight intensity can significantly reduce the cooling demand, particularly in surface-level services [110]. Note these measures are generally preferred for new vehicle designs, although they may be also considered in retrofitting to some extent.

Additionally, an optimal control of the fresh air supply can significantly reduce the HVAC demand. Thus, demand-controlled ventilation based on the concentration of CO₂ (i.e., according to the

actual occupation of the vehicle) guarantees that no energy is wasted in conditioning unnecessary fresh air intakes [111–113], which may imply energy savings of up to 55% [114]. In this sense, reducing avoidable door openings may also play an important role [115]. Another advantage of smart control of ventilation is the so-called “free-cooling”, which essentially involves lowering the indoor temperature by introducing greater amounts of outside air.

Alternatively, the thermal demand in rail cars can be minimised by optimally adjusting the comfort temperatures [116]. Thus, a slight decrease in the target indoor temperature in the heating mode (or a slight increase in the cooling mode) may yield substantial energy savings without affecting passenger satisfaction; what is more such an adjustment may even improve passenger comfort in many cases.

On the other hand, improving the efficiency of the HVAC systems will generally require upgrading the existing equipment. Thus, the use of heat pumps may lead to important energy savings in heating as they can perform between twice and four times more efficiently than common electrical resistors. This technology is particularly suitable for applications where the ambient temperatures are normally above 5–7 °C, e.g. in tunnel environments [117]. Moreover, heat pumps have the capability to work as air-conditioning machines when cooling is required, avoiding the duplication of equipment and consequently allowing for weight savings. An optimal regulation of their capacity according to demand, for instance by means of variable frequency compressors, would notably increase the performance of heat pumps in both cooling and heating modes [117,118]. As an alternative to heat pumps, air-cycle refrigeration systems have been proposed for air-conditioning functions mainly because of their high reliability and the absence of environment-harmful refrigerants; however, their coefficient of performance is approximately half that of heat pumps [119,120].

The recovery of waste heat produced by the traction equipment might also be regarded as an alternative to reduce the energy consumption of HVAC systems. In fact, this energy could be directly used for heating purposes [10], for driving absorption cooling machines [121], or for on-board generation of electric power [122]. This would also reduce the thermal loads in tunnels and, consequently, the air-conditioning demand inside the vehicles. However, the dispersion of the heat sources and their relatively lower temperature hinder the application of these innovative concepts in urban rail.

With regard to lighting consumption in vehicles, it may be notably reduced by using efficient light-emitting diodes (LEDs). This technology has been widely proved in household applications [123] and its usage in rail vehicles is gaining increasing attention [124]. Furthermore, the use of more efficient lighting will help reduce the air-conditioning demand in vehicles [125].

3.6.2. Rolling-stock-related measures for parked mode

Several of the previously discussed technological measures can clearly reduce the energy consumption of comfort functions during standstill. However, the greatest energy saving potential in parked mode seems to lie in optimising the setup and control of the comfort functions [14]. Thus, redefining the threshold temperatures during hibernation and maintenance/cleaning operations, alongside the implementation of automatic control systems for heating and lighting, may reduce the energy consumption in parked mode by up to 50% [10].

3.6.3. Infrastructure-related measures

Cooling the tunnel environment can significantly reduce the HVAC demand in subway stations, but also in the rolling stock itself [120,126]. In this regard, maximising the natural ventilation is a key solution as it permits the evacuation of heat gains with no energy consumption [127–131]. For that, it is important that stations and tunnels are designed with adequate ventilation shafts,

as it is normally problematic to build them into existing systems. Other non-conventional, energy-efficient options to minimise the thermal loads at infrastructure level are: using heat pipes to enhance the capacity of the surrounding soil to absorb heat from the tunnel environment [132]; using groundwater as a direct cooling source [133,134]; using phase-change materials (PCMs) to absorb heat from tunnels during operational hours while releasing it at night [126].

Additionally, the use of platform edge doors may prevent the heat transfer from the tunnel to the station, although their use may considerably increase the ventilation demand in tunnels [135]. Furthermore, there is concern about their effect on passenger evacuation during emergencies [136].

In order to enhance the performance of conventional heat pump systems providing heating and/or cooling in stations, geothermal technology appears to be a very promising option [137,138]. The higher performance offered by geothermal heat pumps lies in the fact that they interchange heat with underground sources (soil or groundwater), whose temperature is much more constant than air temperature throughout the year. Moreover, geothermal systems consume no water in cooling towers, which is a very important advantage in hot climates where this is a scant source. However, they require higher investment and their feasibility depends on the availability of proper underground sources [139].

Wherever possible, the use of solar thermal energy is also an interesting way to reduce the consumption of HVAC systems in stations. Thus, it can be used directly for heating purposes [140] or to power absorption cooling machines [141,142]. However, the potential of this alternative has not been entirely exploited in railway systems so far.

The implementation of dynamic control strategies may lead to large energy savings in HVAC and significant improvements in comfort with relatively small investments [143]. Hence, understanding and predicting passenger flows, air circulation and temperature distribution are key factors to achieve optimal operation of HVAC systems in stations [144–147].

Regarding energy consumption in lighting, the introduction of more efficient lamps may account for significant energy savings. Thus, energy savings of 32% and 40% were achieved in Bielefeld and Hong Kong underground stations, respectively, by replacing the existing lighting equipment with fluorescent and LED lamps [27,70]. Also, an optimal adjustment of lighting intensity to passenger demand (e.g. automatically switching off the station lighting during no operation times) may lead to noticeable energy savings [148].

As for escalators, lifts and other passenger conveyor systems, the greatest energy efficiency improvements lie in the optimisation of their number and allocation (at design phases) and in the implementation of a demand-based control. In this sense, understanding passenger behaviour is of vital importance [149–151].

Finally, energy savings in stations can be maximised through integrated management of all their subsystems. Thus, reductions of 5–10% in the energy consumption of underground stations may be expected when collectively applying adaptive control strategies to HVAC, lighting and passenger conveyor systems [29,152].

3.7. Energy measurement and smart management

This section discusses energy metering, local renewable power generation and smart power management as key actions for achieving greater energy savings in urban rail.

3.7.1. Energy metering

Using automated metering systems to collect energy consumption data in vehicles and other urban rail subsystems is not an energy efficiency action by itself, but it is indeed a valuable tool for

optimising energy usage within the system. In fact, a good understanding of energy flows is paramount to identify areas with greater energy saving potential and to monitor the effects of the implemented measures [153,154]. Furthermore, the information provided by energy meters is essential for energy billing purposes, an issue with growing relevance in liberalised railway markets [155]. Allowing private operators to pay for real energy consumption, rather than using average estimations, may represent a major incentive for them to apply energy efficiency measures. In this regard, the standardisation of metering equipment and procedures is a key matter to be addressed [156–158].

3.7.2. Micro-generation of renewable power within the system

Depending on the characteristics of the system and on the availability of renewable energy sources in the area, the local generation of electricity may be an interesting solution to reduce power consumption from the public network. Thus, photovoltaic solar panels may be installed in stations and depots to partially meet their own demands [40,159]. Similarly, solar panels could be installed along the track helping to feed the signalling systems and the substations auxiliaries [160]. Furthermore, the use of solar panels on the rail vehicles' roof could provide enough power to supply their auxiliary systems [161], but the introduction of such additional weight is regarded as a serious concern. This hurdle might be overcome yet by utilising flexible, light panels based on polymer solar cells [162,163]. Interestingly, using wind turbines in depots, stations or along the track could be an alternative (or a complement) to solar power systems [27,40]. Regardless of the kind of energy source, optimal integration of renewable power generation in railway systems will typically require the use of ESSs alongside dedicated power management controls, which may compromise the economic viability of these measures.

3.7.3. Smart energy management

The foreseeable increase in the use of both regenerative braking and renewable energy generation in urban rail systems will result in the need for optimised management of energy flows within the network. In this regard, the application of the smart grid concept – primarily developed for electric networks with distributed power generation – is gaining growing attention [12,164,165]. This approach enables efficient management of all the energy sources in the network according to actual demand. This means, for instance, that the power from renewable sources, from regenerative braking or from the public grid can be either used to instantly meet the power demand of the system, or stored for later use shaving peak consumptions, which may account for important cost savings. Applying the smart grid concept requires the development of an automatic control of voltage distribution within the network [166]. This alone often fails to be economically viable [148], although selling the energy back to the grid could help reduce its payback period. As a pioneer attempt to integrate smart grids into urban rail systems, it is worth mentioning the energy optimisation project recently launched by SEPTA in Pennsylvania (USA) [167].

Furthermore, the integration of urban rail networks with other energy independent systems in their vicinity such as buildings, other urban mobility systems or renewable power generation plants, has been proposed as an extension of the smart grid concept for a “smart city” energy management [168,169]. For instance, the excess regenerative braking energy from metro systems could help to power an urban network of electric vehicles [170]. Likewise, the heat from large underground systems could be used for heating purposes in buildings close to stations or to ventilation shafts [171,172]. Additionally, the power generated in nearby renewable energy plants could be used to feed the urban rail system itself, consequently reducing its environmental impact and improving its social image [27,173].

4. Methodology for optimal implementation of energy efficiency measures in urban rail

All the measures described above can be considered as effective avenues to minimise energy consumption of urban rail systems; however it is neither realistic nor effective to apply them all in a particular system. This is especially true for the case of existing systems, where the restrictions for their application are greater. Therefore, an effective methodology is needed when defining and implementing a programme of measures to reduce the energy consumption of urban rail systems.

4.1. Methodology description

A systematic procedure to reduce energy consumption in urban rail fundamentally consists of the steps shown in Fig. 6. Note that although this diagram was primarily developed for application to existing systems, it can also be used in brand-new ones.

As seen in Fig. 6, analysing the actual energy consumption of the system in question should be the starting point of any energy efficiency programme. Thus, an accurate understanding of the energy flows within the system will enable identification of the areas with greater potentials for improvement, and preselect a set of suitable measures accordingly. Then, these preliminary solutions must be globally evaluated in order to prioritise their possible implementation. The principal criteria to be considered in this evaluation are:

- The energy saving potential of the solutions, which has to be assessed from a systems perspective taking into account the synergies and conflicts that may emerge between the measures.
- Their technical suitability for the system in question; e.g. depending on whether the system is underground or surface operated, the disruption time involved in their application, etc., some measures may be considered impractical.
- Their economic viability, which is influenced by their potential energy savings at systems level and by their technical suitability, among other economic factors concerning different stakeholders that will not be considered herein.

The solutions judged as the most promising after the evaluation process have to be fully defined in an implementation programme, which should also include a set of key performance indicators (KPIs) to monitor their real effect. The comparison between the expected and the actual energy savings will allow readjusting the original programme so as to obtain optimal results.

4.2. Guidelines for the global evaluation of measures

This section exemplifies the assessment and rating of energy efficiency measures for urban rail. This includes a general analysis of the interdependences between the main measures described in Section 3, alongside a qualitative assessment of their individual potential energy savings, investment costs and technical suitability for current systems. Note that this can only be seen as a reference for quick assessments. Given that the differences between systems may be very significant, dedicated software tools have to be developed for a precise evaluation of the measures in a particular system, which is out of the scope of this paper.

4.2.1. Interdependences between energy efficiency measures in urban rail

Most energy efficiency measures for urban rail are strongly interdependent. As such, a combination of measures may lead to either a higher or lower potential benefit than if applied separately,

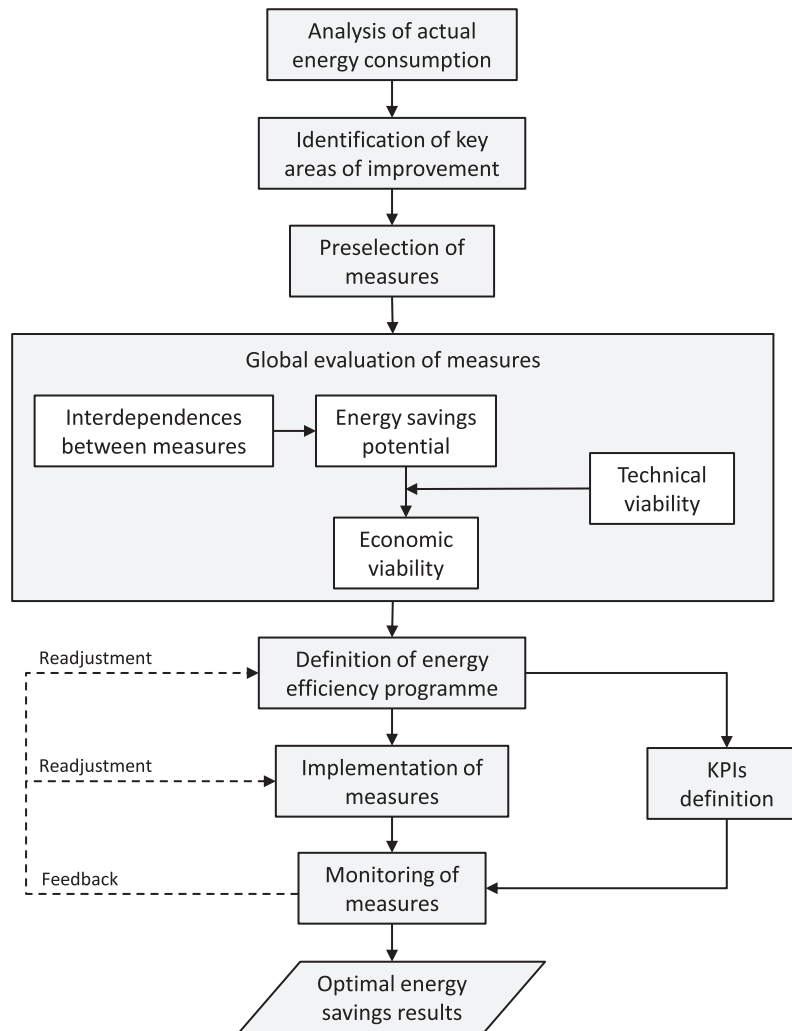


Fig. 6. Methodology for a successful implementation of energy efficiency measures in urban rail.

depending on their compatibility. Therefore, when evaluating a group of solutions, their benefits cannot be assessed individually, but the interactions between them must be considered.

Fig. 7 is a graphical representation of the interdependences between, and also within, the four groups of energy efficiency measures and technologies mentioned in Section 3. As can be seen, there are two different types of arrows in this figure, which illustrate whether the interdependence between any two measures is positive or negative. Rather than interacting with these four groups on an individual level, the cluster of measures detailed in Section 3.7 is considered as useful for their global success. Through such measures as continuous monitoring of the implemented energy efficiency technologies and procedures, or smart management of system-wide energy flows, a more assured and confident approach to urban rail energy efficiency can be achieved.

Regarding regenerative braking measures, the benefit of their combination may be lower than the sum of the potential of each solution. For example, the higher the regenerated energy transferred between trains is, the lower the potential for energy recovery through ESSs and substations will be, and vice versa. However, the combination of all three options may be needed to use the whole braking energy potential. Therefore the implementation of regenerative braking measures requires a complex optimisation study to obtain the greatest energy savings with the lowest investment cost. The interdependences of these technologies with other

energy efficiency solutions can be summarised as follows: they may reduce consumption in comfort functions (both at infrastructure and vehicle level) as they avoid the dissipation of braking energy in tunnels and stations; they minimise the losses in the supply network since they reduce power peaks in the line; they may reduce vehicle mass as they minimise the need for on-board braking resistors; however, if on-board ESSs are used, the additional weight may increase the traction energy consumption.

As illustrated in Fig. 7, an improved traffic flow control helps to apply energy-efficient driving strategies. Besides, before implementing driving assistance tools, a careful study determining the best driving techniques and optimal traffic control strategies are needed. In general, eco-driving measures minimise resistive losses in the power supply line as they contribute to reduce current flow in the network. Besides, they may lower the thermal load in tunnels and stations because they reduce the intensity of the braking processes. Interestingly, the use of efficient traffic control systems may facilitate better interchange of braking energy between vehicles. Moreover, deceleration profiles that match the characteristics of the traction motors will lead to fewer losses in braking energy recovery.

Synergies must be expected from the combination of measures aimed at reducing energy consumption of comfort functions in vehicles and stations; that is, reducing the thermal load in tunnels and stations will lower the cooling demand in vehicles, and vice

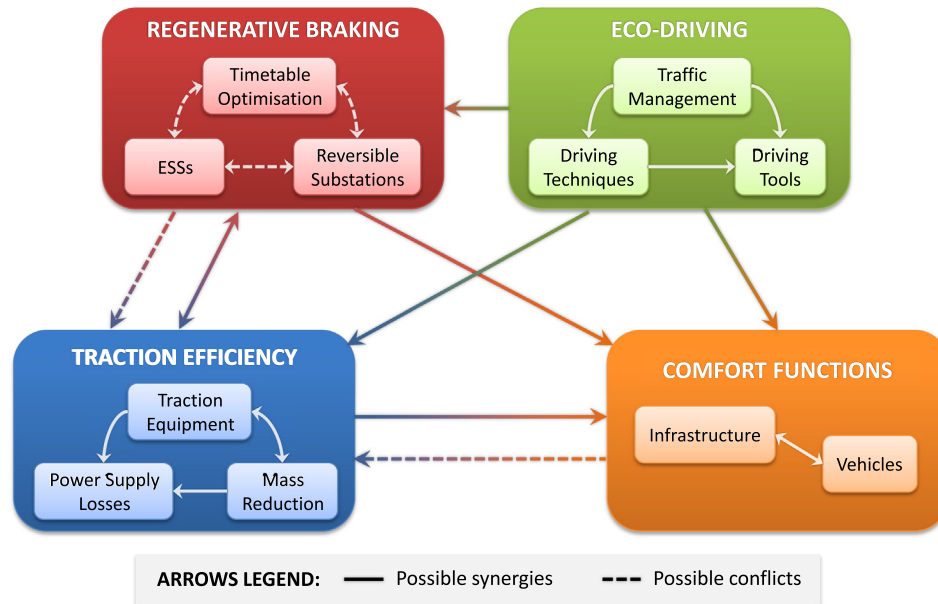


Fig. 7. Interdependences between energy efficiency measures.

versa. In turn, some measures like upgrading the HVAC systems of vehicles (e.g. heat pumps) may increase their mass and, therefore, the traction energy consumption.

Lastly, actions to increase energy efficiency of the traction system are fully interconnected to each other, as shown in Fig. 7. Thus, reducing traction energy consumption through enhanced drives will lead to less resistive losses in the line. Moreover, improvements in traction equipment will generally imply a mass reduction, and any mass reduction in vehicles will result in reduced traction

consumptions and fewer losses in the line. Furthermore, minimising the losses of traction equipment will enhance the braking energy regeneration and will reduce the thermal load in both tunnels and stations.

4.2.2. General assessment and rating of energy efficiency measures

Table 2 shows illustrative figures of the energy saving potential at system level for the main measures discussed in Section 3 (only the commercially available and tested solutions are included

Table 2
General evaluation of energy efficiency measures in urban rail systems.

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
	Reversible substations	Stationary	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
		Heat 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

^{*} Estimated energy savings at system level for a standard case of application.

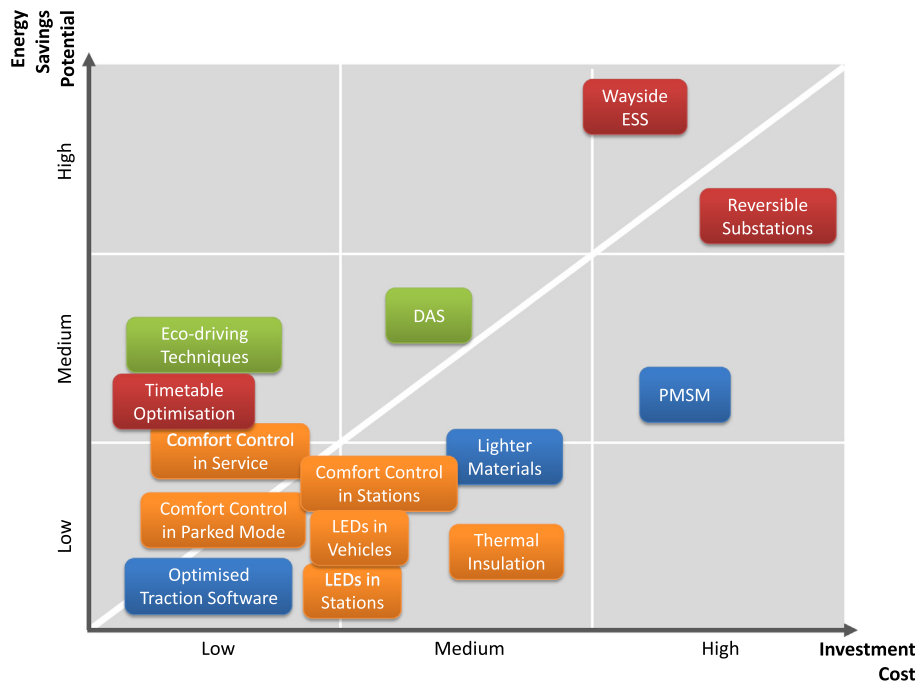


Fig. 8. Comparison between measures for existing urban rail systems.

herein). The range of values given is the result of applying the average figures found in the literature covered by this paper to a standard system where traction energy accounts for 80% of the total energy consumption (same distribution as shown in Fig. 3), and where stations are responsible for the remaining 20%. Therefore, these are only approximate figures for the reader to have a better idea of the order of magnitude of the energy saving potential offered by each measure individually.

Additionally, Table 2 assesses the suitability of the analysed measures for implementation in existing urban rail systems. This indicator of technical viability is comparatively rated as low, medium and high, depending on the barriers that can be found to their implementation in actual systems. Thus, infrastructure-related measures that imply major modifications in the system will normally be regarded as less adequate solutions. Likewise, measures requiring the introduction of heavy and bulky systems in existing vehicles, e.g. on-board ESSs or heat pumps, are likely to be declined.

Lastly, Table 2 gives a qualitative, comparative estimation of the investment cost for each measure. This assessment aims to enable a quick contrast between measures and is not intended to be an accurate valuation of their implementation cost.

Considering only measures rated as highly suitable for existing systems in Table 2, Fig. 8 represents their individual energy saving potential against their relative implementation cost. Taking into account the interdependences between these measures, it can be concluded that the most promising solutions for existing systems are, in principle, the following:

- Improving the control of comfort functions, both in service and in parked mode.
- Applying eco-driving techniques and driver advisory systems.
- Optimising the timetable to maximise the interchange of regenerative braking energy between vehicles.
- Installing wayside ESSs for recovering and reusing the surplus regenerated energy.

Therefore, if we consider a hypothetical urban rail system with the standard energy consumption share described above, and

where no energy efficiency schemes have been implemented yet, the combination of these measures might realistically lead to energy consumption reductions of 25–35% at system level (15–20% from regenerative measures, 5–10% from eco-driving and about 5% from comfort functions improvement), with a relatively short payback period.

5. Conclusions

This paper has given an insightful overview on the potential of urban rail systems to reduce their energy consumption. Firstly, an analysis of the breakdown of urban rail energy usage was performed based on data published for different European systems. Then, a comprehensive review of the main practices, strategies and technologies available to reduce urban rail energy consumption was presented. Lastly, the key points of a clear, logical methodology for optimal implementation of energy efficiency measures in urban rail were discussed. The core findings of this investigation are summarised below.

In general, it has been observed that 70–90% of the total energy consumption in urban rail is due to rolling stock operation, whereas the rest is used in stations and other infrastructure within the system. Moreover, it has been found that approximately 50% of traction energy may be dissipated during braking phases, which highlights the great energy saving potential offered by the use of regenerative braking. In turn, the auxiliary equipment of the rolling stock (mainly the comfort functions) may account for approximately 20% of its total energy consumption, with significant dependencies on the type of service and climate conditions.

There is a broad range of energy efficiency measures that have proven to be successful in minimising the energy consumption of different urban rail subsystems, such as traction drives, vehicle comfort functions or stations. However, when considering their application, their potential energy savings should not be seen individually, but at system level. A good understanding of the subsystems' interactions is vital for an effective implementation of any energy efficiency programme. Furthermore, a continuous monitoring of energy consumption is a key aspect for the definition and tracking of such programmes.

For existing urban rail systems, the implementation of operational measures is normally preferred to the introduction of new technologies, as significant energy savings may be achieved with relatively low investment costs and minor modifications. Thus, enhancing the control of the vehicle comfort functions, optimising service timetables from an energy-saving point of view, or applying eco-driving techniques have been identified as the most promising solutions for those systems. Additionally, the use of wayside ESSs may maximise the use of regenerative braking energy with relatively low payback periods. The implementation of these four measures all together might realistically lead to energy consumption reductions of about 25–35% in standard existing systems without previous energy efficiency schemes.

This paper contributes to the current literature by providing a comprehensive overview and assessment on how energy is managed in urban rail systems, the most promising actions to minimise its use and an estimate of the scale of potential savings. It can therefore prove useful as a reference for all parties involved in addressing urban rail energy consumption. Nevertheless, since this investigation has highlighted the significant variability between different systems, its conclusions should be regarded as guidelines, with the evaluation of individual systems requiring a specific, in-depth analysis.

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References

- [1] IEA and UIC, Railway handbook 2012 – energy consumption and CO₂ emissions, International Energy Agency; 2012. <http://www.uic.org/IMG/pdf/iea-uic_energy_consumption_and_co2_emission_of_world_railway_sector.pdf>.
- [2] European Commission, Roadmap to a single European transport area – towards a competitive and resource efficient transport system; 2011. <<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:en:PDF>>.
- [3] Official Journal of the European Union, Decision No 406/2009/EC on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020; 2009. <<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0136:0148:EN:PDF>>.
- [4] European Commission, A Roadmap for moving to a competitive low carbon economy in 2050 – Ref. COM(2011) 112 final; 2011. <<http://www.eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF>>.
- [5] Vuchic VR. Urban transit systems and technology. Hoboken: John Wiley & Sons; 2007.
- [6] European Commission, EU transport in figures – statistical pocketbook 2012; 2012. <<http://ec.europa.eu/transport/facts-fundings/statistics/doc/2012/pocketbook2012.pdf>>.
- [7] Chan CC. The state of the art of electric, hybrid, and fuel cell vehicles. Proc IEEE 2007;95:704–18.
- [8] Koseki T. Technologies for saving energy in railway operation: general discussion on energy issues concerning railway technology. IEEJ Trans Elect Electron 2010;5:285–90.
- [9] Nicola DA, Rosen MA, Bulucea CA, Brandusa C. Some sustainability aspects of energy conversion in urban electric trains. Sustainability 2010;2:1389–407.
- [10] UIC, Energy efficiency technologies for railways. <<http://www.railway-energy.org>> (accessed September 2013).
- [11] ECORails, Guidelines for Public Transport Administrations in Europe, ECORails project–energy efficiency and environmental criteria in the awarding of regional rail transport vehicles and services; 2011. <http://www.ecorails.eu/media/de/ecorails_guide_english_freigabe_final.pdf>.
- [12] Chéron C, Walter M, Sander J, Wiebe E. ERRAC – European railway energy roadmap: towards 2030. In: 9th world congress on railway research – WCRR 2011, Lille, France; 2011.
- [13] Sander J, Wiebe E, Bergendorff M, Recagno V, Nolte R. Smart and efficient energy solutions for railways – the “Railenergy” results. In: 9th World congress on railway research – WCRR 2011, Lille, France; 2011.
- [14] Günselmann W. Technologies for increased energy efficiency in railway systems. In: 2005 European conference on power electronics and applications – EPE 2005, Dresden, Germany; 2005.
- [15] ERRAC and UITP, Metro, light rail and tram systems in Europe, ERRAC Roadmaps; 2009. <http://www.uitp.org/files/ERRAC_MetroLR&TramSystemsInEurope.pdf>.
- [16] Matsuoka K, Kondo M. Energy saving technologies for railway traction motors. IEEJ Trans Elect Electron 2010;5:278–84.
- [17] García Álvarez A, Martín Cañizares MP. Análisis sistemático del consumo energético en líneas ferroviarias metropolitanas, de cercanías y de alta velocidad, con valoración del impacto energético y del resultado económico, incluyendo el desarrollo y contraste de modelos y simuladores parametriza (in Spanish), Fundación de los Ferrocarriles Españoles; 2012. <http://www.investigacion-ffe.es/documentos/elecraill/M13-ElecRail_InformeFinal.pdf>.
- [18] Ortega JM, Ibañondo H. Kinetic energy recovery on railway systems with feedback to the grid. In: 9th World congress on railway research – WCRR 2011, Lille, France; 2011.
- [19] Barrero R, Tackoen X, van Mierlo J. Stationary or onboard energy storage systems for energy consumption reduction in a metro network. P I Mech Eng F-J Rai 2010;224:207–25.
- [20] Steiner M, Klotz M, Pagiola S. Energy storage system with UltraCaps on board of railway vehicles. In: 2007 European conference on power electronics and applications – EPE, Aalborg, Denmark; 2007.
- [21] Struckl W, Strübsky A, Günselmann W. Life cycle analysis of the energy consumption of a rail vehicle. In: International workshop of alianz pro schiene: improvement of the environmental impacts of rail transport – challenges, good practices and future challenges, Berlin, Germany; 2006.
- [22] Chymera M. Reducing energy consumption on the Underground. In: IMechE railway division seminar “gaining traction in energy efficiency”, London, UK; 2012.
- [23] Chymera M, Renfrew A, Barnes M. Analyzing the potential of energy storage on electrified transit systems. In: 8th World congress of railway research – WCRR 2008, Seoul, South Korea; 2008.
- [24] Henning U. MODENERGY: energy related aspects. In: MODURBAN final conference and demonstration, Madrid, Spain; 2008.
- [25] Pilo de la Fuente E, Pérez Arriaga JI, Ruiz A, López-Hierro Ausín I, Jiménez J. Flujos de la energía de la electricidad para el transporte (in Spanish), Monografías EnerTrans; 2008. <http://www.investigacion-ffe.es/documentos/enertrans/EnerTrans_Flujos_electricidad.pdf>.
- [26] Takagi R. Energy saving techniques for the power feeding network of electric railways. IEEJ Trans Elect Electron 2010;5:312–6.
- [27] Anderson R, Maxwell R, Harris NG. Maximizing the potential for metros to reduce energy consumption and deliver low-carbon transportation in cities. Delhi, India: MetroRail Asia; 2009.
- [28] González-Gil A, Palacin R, Batty P. Sustainable urban rail systems: strategies and technologies for optimal management of regenerative braking energy. Energy Convers Manage 2013;75:374–88.
- [29] Fuentes A, Casals M, Gangoles M, Puigdollers O. Overcoming challenges for energy management in underground railway stations: the SEAM4US project. In: European conference on product and process modelling – ECPPM 2012, Reykjavik, Iceland; 2012.
- [30] Transport for London, LU Carbon footprint report 2008, Mayor of London; 2009. <<http://www.tfl.gov.uk/assets/downloads/corporate/london-underground-carbon-footprint-2008.pdf>>.
- [31] Ampofo F, Maidment G, Missenden J. Underground railway environment in the UK Part 1: review of thermal comfort. Appl Therm Eng 2004;24:611–31.
- [32] Abbaspour M, Jafari MJ, Mansouri N, Moattar F, Nouri N, Allahyari M. Thermal comfort evaluation in Tehran metro using relative warmth index. Int J Environ Sci Technol 2008;5:297–304.
- [33] Ordódy P. Thermal comfort in the passenger areas of the Budapest metro. Period Polytech Mech 2000;44:309–17.
- [34] Awad AHA. Environmental study in subway metro stations in Cairo, Egypt. J Occup Health 2002;44:112–8.
- [35] Múgica-Álvarez V, Figueroa-Lara J, Romero-Romo M, Sepúlveda-Sánchez J, López-Moreno T. Concentrations and properties of airborne particles in the Mexico city subway system. Atmos Environ 2012;49:284–93.
- [36] Hong W, Kim S. A study on the energy consumption unit of subway stations in Korea. Build Environ 2004;39:1497–503.
- [37] Zhang W, Wei J. The experimental research on Beijing subway air-conditioning system energy-saving. Appl Mech Mater 2012;170:2494–8.
- [38] Leung PCM, Lee EWM. Estimation of electrical power consumption in subway station design by intelligent approach. Appl Energy 2013;101:634–43.
- [39] Wang L, Qu J, Song J, Li Z, Du X, Li S, et al. The impacting factors discussions on the thermal environment and energy consumption of the subway tunnel and the station units. In: 3rd International conference on measuring technology and mechatronics automation – ICMTMA 2011, Shanghai, China; 2011.
- [40] TramStore21, Building sustainable and efficient tram depots for cities in the 21st century, TramStore21 project; 2013. <http://www.tramstore21.eu/sites/default/files/brochures/Tramstore_Publication_ENG_DVD_v2.pdf>.
- [41] UIC and UNIFE, TecRec 100_001: Specification and verification of energy consumption for railway rolling stock; 2010. <http://www.unife.org/uploads/TECREC_100_001_ENERGY_STANDARD_VER_1_2_final_signed.pdf>.
- [42] Nasri A, Fekri Moghadam M, Mokhtari H. Timetable optimization for maximum usage of regenerative energy of braking in electrical railway

- systems. In: International symposium on power electronics, electrical drives, automation and motion – SPEEDAM 2010, Pisa, Italy; 2010.
- [43] Peña-Alcaraz M, Fernandez A, Cucala AP, Ramos A, Pecharroman RR. Optimal underground timetable design based on power flow for maximizing the use of regenerative-braking energy. *P I Mech Eng F-J Rai* 2011;226:397–408.
 - [44] Boizumeau JR, Leguay P, Navarro E. Braking energy recovery at the Rennes metro. In: Workshop on braking energy recovery systems – ticket to kyoto project, Bielefeld, Germany; 2011.
 - [45] Kim KM, Kim KT, Han MS. A model and approaches for synchronized energy saving in timetabling. In: 9th World congress on railway research – WCRR 2011, Lille, France; 2011.
 - [46] Albrecht T. Reducing power peaks and energy consumption in rail transit systems by simultaneous train running time control. *Adv Transport* 2004;15:885–94.
 - [47] Chen JF, Lin RL, Liu YC. Optimization of an MRT train schedule – reducing maximum traction power by using genetic algorithms. *IEEE Trans Power Syst* 2005;20:1366–72.
 - [48] Barrero R, van Mierlo J, Tackoen X. Energy savings in public transport. *IEEE Veh Technol Mag* 2008;3:26–36.
 - [49] Domínguez M, Cucala AP, Fernández A, Pecharroman RR, Blanquer J. Energy efficiency on train control – design of metro ATO driving and impact of energy accumulation devices. In: 9th World congress on railway research – WCRR 2011, Lille, France; 2011.
 - [50] Ciccirelli F, Iannuzzi D, Tricoli P. Control of metro-trains equipped with onboard supercapacitors for energy saving and reduction of power peak demand. *Transport Res C-Emerg* 2012;24:36–49.
 - [51] Iannuzzi D, Tricoli P. Speed-based state-of-charge tracking control for metro trains with onboard supercapacitors. *IEEE Trans Power Electron* 2012;27:2129–40.
 - [52] Steiner M, Scholten J. Energy storage on board of DC fed railway vehicles. In: IEEE annual power electronics specialists conference – PESC, Aachen, Germany; 2004.
 - [53] Moskowitz JP, Cohuau JL. STEEM: ALSTOM and RATP experience of supercapacitors in tramway operation. In: IEEE vehicle power and propulsion conference – VPPC 2010, Lille, France; 2010.
 - [54] Rufer A, Hotellier D, Barrade P. A supercapacitor-based energy storage substation for voltage compensation in weak transportation networks. *IEEE Trans Power Deliv* 2004;19:629–36.
 - [55] Destraz B, Barrade P, Rufer A, Klotz M. Study and simulation of the energy balance of an urban transportation network. In: 2007 European conference on power electronics and applications, Aalborg, Denmark; 2007.
 - [56] Lee H, Song J, Lee H, Lee C, Jang G, Kim G. Capacity optimization of the supercapacitor energy storages on DC railway system using a railway powerflow algorithm. *Int J Innov Comput* 2011;1(7):2739–53.
 - [57] Teymourfar R, Asaei B, Iman-Eini H, Nejati fard R. Stationary super-capacitor energy storage system to save regenerative braking energy in a metro line. *Energy Convers Manage* 2012;56:206–14.
 - [58] Iannuzzi D, Lauria D, Ciccirelli F. Wayside ultracapacitors storage design for light transportation systems: a multiobjective optimization approach. *Int Rev Electr Eng-I* 2013;8:190–9.
 - [59] Iannuzzi D, Ciccirelli F, Lauria D. Stationary ultracapacitors storage device for improving energy saving and voltage profile of light transportation networks. *Transport Res C-Emerg* 2012;21:321–37.
 - [60] Allègre AL, Bouscayrol A, Delarue P, Barrade P, Chattot E, El-Fassi S. Energy storage system with supercapacitor for an innovative subway. *IEEE Trans Ind Electron* 2010;57:4001–12.
 - [61] Vazquez S, Lukic SM, Galvan E, Franquelo LG, Carrasco JM. Energy storage systems for transport and grid applications. *IEEE Trans Ind Electron* 2010;17:3881–95.
 - [62] Kadhim R. Energy storage systems for railway applications – phase 1, Rail Safety and Standards Board (RSSB); 2009. <http://www.rssb.co.uk/SiteCollectionDocuments/pdf/reports/research/T779_rpt_phase1.pdf>.
 - [63] Ogasa M. Application of energy storage technologies for electric railway vehicles – examples with hybrid electric railway vehicles. *IEEE Trans Elect Electron* 2010;5:304–11.
 - [64] Ogura K, Nishimura K, Matsumura T, Tonda C, Yoshiyama E, Andriani M, et al. Test results of a high capacity wayside energy storage system using Ni-MH batteries for DC electric railway at New York City Transit. In: IEEE green technologies conference – green 2011, Baton Rouge, USA; 2011.
 - [65] Meinert M. New mobile energy storage system for rolling stock. In: 13th European conference on power electronics and applications – EPE'09, Barcelona, Spain; 2009.
 - [66] Bolund B, Bernhoff H, Leijon M. Flywheel energy and power storage systems. *Renew Sust Energy Rev* 2007;11:235–58.
 - [67] Tzeng J, Emerson R, Moy P. Composite flywheels for energy storage. *Compos Sci Technol* 2006;66:2520–7.
 - [68] Warin Y, Lanselle R, Thiounn M. Active substation. In: 9th World congress on railway research – WCRR 2011, Lille, France; 2011.
 - [69] Cornic D. Efficient recovery of braking energy through a reversible dc substation. In: 9th World congress on railway research – WCRR 2011, Lille, France; 2011.
 - [70] Ticket to Kyoto, Overview of quick wins implemented by partners in the public transport field, Ticket to Kyoto project; 2011. <http://www.tickettokyoto.eu/sites/default/files/T2K_Quick-Wins-Report.pdf>.
 - [71] Alves FT, Pires CL. Energy saving strategy in São Paulo metro. In: IET conference on railway traction systems – RTS 2010, Birmingham, UK; 2010.
 - [72] Bocharnikov YV, Tobias AM, Roberts C, Hilmanen S S, Goodman CJ. Optimal driving strategy for traction energy saving on DC suburban railways. *IET Electr Power Appl* 2007;1.
 - [73] Ding Y, Liu H, Bai Y, Zhou F. A two-level optimization model and algorithm for energy-efficient urban train operation. *J Transport Syst Eng Inf Technol* 2011;11:96–101.
 - [74] Chuang HJ, Chen CS, Lin CH, Hsieh CH, Ho CY. Design of optimal coasting speed for saving social cost in mass rapid transit systems. In: 3rd International conference on deregulation and restructuring and power technologies – DRPT 2008, Nianjing, China; 2008.
 - [75] Malavasi G, Palleschi P, Ricci S. Driving and operation strategies for traction-energy saving in mass rapid transit systems. *P I Mech Eng F-J Rai* 2011;225:475–82.
 - [76] Ke BR, Lin CL, Yang CC. Optimisation of train energy-efficient operation for mass rapid transit systems. *IET Intell Transport Syst* 2012;6:58–66.
 - [77] Miyatake M, Ko H. Optimization of train speed profile for minimum energy consumption. *IEEJ Trans Elect Electron* 2010;5:263–9.
 - [78] Hathway R. Energy efficient train regulation on the Victoria Line. In: IMechE Railway Division Seminar “Gaining traction in Energy Efficiency”, London, UK; 2012.
 - [79] Açıkbaş S, Söylemez MT. Coasting point optimisation for mass rail transit lines using artificial neural networks and genetic algorithms. *IET Electr Power Appl* 2008;2:172–82.
 - [80] Hoang HH, Polis MP, Haurie A. Reducing energy consumption through trajectory optimization for a metro network. *IEEE Trans Automat Contr* 2019;59:5–9.
 - [81] Duarte MA, Sotomayor PX. Minimum energy trajectories for subway systems. *Optim Control Appl Method* 1999;20:283–96.
 - [82] Ke BR, Chen MC, Lin CL. Block-layout design using max-min ant system for saving energy on mass rapid transit systems. *IEEE Trans Intell Transport Syst* 2009;10:226–35.
 - [83] Jin J, Kadhim R. Driver advisory information for energy management and regulation. In: 9th World congress on railway research – WCRR 2011, Lille, France; 2011.
 - [84] Wong KK, Ho TK. Dynamic coast control of train movement with genetic algorithm. *Int J Syst Sci* 2004;35:835–46.
 - [85] Domínguez M, Fernández A, Cucala AP, Łukaszewicz P. Optimal design of metro automatic train operation speed profiles for reducing energy consumption. *P I Mech Eng F-J Rai* 2011;225:463–73.
 - [86] Chang CS, Sim SS. Optimising train movements through coast control using genetic algorithms. *IEE Proc-B* 1997;144:65–72.
 - [87] Liu R, Golovitcher IM. Energy-efficient operation of rail vehicles. *Transport Res A-Pol* 2003;37:917–32.
 - [88] Ke BR, Chen N. Signalling blocklayout and strategy of train operation for saving energy in mass rapid transit systems. *IEE Proc-B* 2005;152:129–40.
 - [89] Wong KK, Ho TK. Dwell-time and run-time control for DC mass rapid transit railways. *IET Electr Power Appl* 2007;1:956–66.
 - [90] Chang SC, Chung YC. From timetabling to train regulation – a new train operation model. *Inform Software Technol* 2005;47:575–85.
 - [91] Sheu JW, Lin WS. Automatic train regulation with energy saving using dual heuristic programming. In: 2011 IEEE international conference on control applications (CCA), Denver, USA; 2011.
 - [92] Hartland D. Heating the countryside or saving the kilowatt hours? In: IMechE railway division seminar “gaining traction in energy efficiency, London, UK; 2012.
 - [93] Tomita M, Fukumoto Y, Suzuki K, Miryata M. Development of prototype DC superconducting cable for railway system. *Phys C Supercond* 2010;470:S1007–8.
 - [94] Kondo K. Recent energy saving technologies on railway traction systems. *IEEJ Trans Elect Electron* 2010;5:298–303.
 - [95] Kondo M, Shimizu Y, Kawamura J. Development of totally enclosed permanent magnet synchronous motor. *Quart Rep RTRI* 2008;49:16–9.
 - [96] Peroutka Z, Zeman K, Krús F, Košta F. New generation of trams with gearless wheel PMSM drives: From simple diagnostics to sensorless control. In: 14th International power electronics and motion control conference – EPE-PEMC 2010, Ohrid, Macedonia; 2010.
 - [97] Germishuizen J, Jöckel A, Hoffmann T, Teichmann M, Löwenstein L, Wangelin FV. Syntegra™ – next generation traction drive system, total integration of traction, bogie and braking technology. In: International symposium on power electronics, electrical drives, automation and motion – SPEEDAM 2006, Taormina, Italy; 2006.
 - [98] Koerner O, Binder A. Feasibility of a group drive with two permanent magnet synchronous traction motors for commuter trains. *EPE J* 2004;14:32–7.
 - [99] Barcaro M, Fornasiero M, Bianchi N, Bolognani S. Design procedure of IPM motor drive for railway traction. In: IEEE international electric machines and drives conference – IEMDC 2011, Niagara Falls, Canada; 2011.
 - [100] Uzel D, Peroutka Z. Control and design considerations for wheel mounted drive of tram: Interesting features offered by IPMSM technology. In: 14th international power electronics and motion control conference – EPE-PEMC 2010, Ohrid, Macedonia; 2010.
 - [101] Toshiba Corporation. Energy efficient traction system utilizing permanent magnet synchronous motor (PMSM). In: IMechE railway division seminar “gaining traction in energy efficiency”, London, UK; 2012.
 - [102] García Álvarez A, Martín Cañizares MP. Metodología de cálculo del consumo de energía de los trenes de viajeros y actuaciones en el diseño del material rodante para su reducción (in Spanish), Fundación de los Ferrocarriles

- Españoles; 2012. <http://www.investigacion-ffe.es/documentos/elecrail/M5-ElecRail_Calculo-consumo.pdf>.
- [103] Carruthers JJ, Calomfirescu M, Ghys P, Prockat J. The application of a systematic approach to material selection for the lightweighting of metro vehicles. *P I Mech Eng F-J Rai* 2009;223:427–37.
 - [104] Eickhoff B, Nowell R. Determining the benefit of train mass reduction. In: 9th World congress on railway research – WCCR 2011, Lille, France; 2011.
 - [105] Robinson M, Carruthers J. Composites for lightweighting in mass transit applications. *JEC Compos Mag* 2006;43:35–7.
 - [106] Hudson CW, Carruthers JJ, Robinson AM. Multiple objective optimisation of composite sandwich structures for rail vehicle floor panels. *Compos Struct* 2010;92:2077–82.
 - [107] Carruthers J, O'Neill C, Ingleton S, Robinson M, Grasso M, Roberts J, et al. The design and prototyping of a lightweight crashworthy rail vehicle driver's cab. In: 9th World congress on railway research – WCCR 2011, Lille, France; 2011.
 - [108] Railway Gazette News, Hitachi introduces smaller EMU inverter, *Railway Gazette International* [online]; 2012. <<http://www.railwaygazette.com/news/single-view/view/hitachi-introduces-smaller-emu-inverter.html>>.
 - [109] Goodall RM, Kortüm W. Mechatronic developments for railway vehicles of the future. *Control Eng Pract* 2002;10:887–98.
 - [110] Baetens R, Jelle BP, Gustavsen A. Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: a state-of-the-art review. *Sol Energy Mater Sol C* 2010;94:87–105.
 - [111] Chow WK. Ventilation of enclosed train compartments in Hong Kong. *Appl Energy* 2002;71:161–70.
 - [112] Chow WK, Yu PCH. Simulation on energy use for mechanical ventilation and airconditioning (MVAC) systems in train compartments. *Energy* 2000;25:1–13.
 - [113] Kokken K. The reduction of energy consumption in EMU-trains of NS. In: 6th World congress on railway research – WCCR 2003, Edinburgh, UK; 2003.
 - [114] Amri H, Hofstädter RN, Kozek M. Energy efficient design and simulation of a demand controlled heating and ventilation unit in a metro vehicle. In: IEEE forum on integrated and sustainable transportation systems – FISTS 2011, Vienna, Austria; 2011.
 - [115] Kwon SB, Park D, Cho Y, Park EY. Measurement of natural ventilation rate in Seoul metropolitan subway cabin. *Indoor Built Environ* 2010;19:366–74.
 - [116] Li W, Sun J. Numerical simulation and analysis of transport air conditioning system integrated with passenger compartment. *Appl Therm Eng* 2013;50:37–45.
 - [117] Amaya J, Asahi T, Román R, Sánchez JA. Simulation of thermal conditions in tunnels and platforms for an underground transportation system, *ModUrban Project*, 2009, <http://www.modurban.org/file.php?id=199&save_dialogue=1>.
 - [118] Kumar M, Kar IN. Design of model-based optimizing control scheme for an air-conditioning system. *HVAC&R Res* 2010;16:565–97.
 - [119] Wang X, Yang X. Reuse of condensed water to improve the performance of an air-cycle refrigeration system for transport applications. *Appl Energy* 2007;84:874–81.
 - [120] Ampofo F, Maidment G, Missenden J. Underground railway environment in the UK Part 3: methods of delivering cooling. *Appl Therm Eng* 2004;24:647–59.
 - [121] Javani N, Dincer I, Naterer GF. Thermodynamic analysis of waste heat recovery for cooling systems in hybrid and electric vehicles. *Energy* 2012;46:109–16.
 - [122] Chen H, Goswami DY, Stefanakos EK. A review of thermodynamic cycles and working fluids for the conversion of low-grade heat. *Renew Sust Energy Rev* 2010;14:3059–67.
 - [123] Han HJ, Jeon YI, Lim SH, Kim WW, Chen K. New developments in illumination, heating and cooling technologies for energy-efficient buildings. *Energy* 2010;35:2647–53.
 - [124] Railway Gazette News, Amsterdam orders 23 metro trains, *Railway Gazette International* [online]; 2010. <<http://www.railwaygazette.com/news/single-view/view/amsterdam-orders-23-metro-trains.html>>.
 - [125] Ampofo F, Maidment G, Missenden J. Underground railway environment in the UK Part 2: investigation of heat load. *Appl Therm Eng* 2004;24:633–45.
 - [126] Thompson JA, Maidment GG, Missenden JF. Modelling low-energy cooling strategies for underground railways. *Appl Energy* 2006;83:1152–62.
 - [127] Raines KM. Underground passenger comfort: Rethinking the current thermal and lighting standards. In: 26th Conference on passive and low energy architecture – PLEA2009, Quebec, Canada; 2009.
 - [128] Lin CJ, Chuah YK, Liu CW. A study on underground tunnel ventilation for piston effects influenced by draught relief shaft in subway system. *Appl Therm Eng* 2008;28:372–9.
 - [129] Kim JY, Kim KY. Effects of vent shaft location on the ventilation performance in a subway tunnel. *J Wind Eng Ind Aerod* 2009;97:174–9.
 - [130] Huang YD, Gong XL, Peng YJ, Lin XY, Kim CN. Effects of the ventilation duct arrangement and duct geometry on ventilation performance in a subway tunnel. *Tunn Undergr Space Technol* 2011;26:725–33.
 - [131] Huang YD, Gao W, Kim CN. A numerical study of the train-induced unsteady airflow in a subway tunnel with natural ventilation ducts using the dynamic layering method. *J Hydrodyn* 2010;22:164–72.
 - [132] Thompson JA, Maidment GG, Missenden JF, Ampofo F. Geothermal cooling through enhancement of the natural heat sink effect – proof of concept. *Exp Therm Fluid Sci* 2007;31:551–8.
 - [133] Maidment GG, Missenden FF. Evaluation of an underground railway carriage operating with a sustainable groundwater cooling system. *Int J Refrig* 2002;25:569–74.
 - [134] Ampofo F, Maidment GG, Missenden JF. Application of groundwater cooling scheme for London Underground network. *Int J Refrig* 2011;34:2042–9.
 - [135] Hu SC, Lee JH. Influence of platform screen doors on energy consumption of the environment control system of a mass rapid transit system: case study of the Taipei MRT system. *Energy Convers Manage* 2004;45:639–50.
 - [136] Qu L, Chow WK. Platform screen doors on emergency evacuation in underground railway stations. *Tunn Undergr Space Technol* 2012;30:1–9.
 - [137] Yuan Z. Construction technology and economic analysis of ground-source heat pump system. *Appl Mech Mater* 2013;268:978–82.
 - [138] Kuo C, Liao H. The feasibility of using circulating groundwater as renewable energy sources for air-conditioning in Taipei basin. *Renew Energy* 2012;39:175–82.
 - [139] Self SJ, Reddy BV, Rosen MA. Geothermal heat pump systems: status review and comparison with other heating options. *Appl Energy* 2013;101:341–8.
 - [140] Cui K, Pan Y, Shan L. Designs and practices of energy saving in Lhasa Railway Station. *Front Energy Power Eng China* 2010;4:106–16.
 - [141] Eicker U, Pietruschka D, Pesch R. Heat rejection and primary energy efficiency of solar driven absorption cooling systems. *Int J Refrig* 2012;35:729–38.
 - [142] González-Gil A, Izquierdo M, Marcos JD, Palacios E. Experimental evaluation of a direct air-cooled lithium bromide-water absorption prototype for solar air conditioning. *Appl Therm Eng* 2011;31:3358–68.
 - [143] Fong KF, Hanby VI, Chow TT. HVAC system optimization for energy management by evolutionary programming. *Energy Build* 2006;38:220–31.
 - [144] Fukuyo K. Application of computational fluid dynamics and pedestrian-behavior simulations to the design of task-ambient air-conditioning systems of a subway station. *Energy* 2006;31:706–18.
 - [145] Yuan FD, You SJ. CFD simulation and optimization of the ventilation for subway side-platform. *Tunn Undergr Space Technol* 2007;22:474–82.
 - [146] Ke MT, Cheng TC, Wang WP. Numerical simulation for optimizing the design of subway environmental control system. *Build Environ* 2002;37:1139–52.
 - [147] El-Bialy EM, Khalil EE. Flow regimes and thermal patterns in a subway station. *AIP Conf Proc* 2011;1376:357–61.
 - [148] Hayashiya H, Watanabe Y, Fukasawa Y, Miyagawa T, Egami A, Iwagami T, et al. Cost impacts of high efficiency power supply technologies in railway power supply – Traction and Station. In: 15th International power electronics and motion control conference and exposition – EPE-PEMC 2012 ECCE Europe, Novi Sad, Serbia; 2012.
 - [149] Ma W, Liu X, Li L, Shi X, Zhou CQ. Research on the waiting time of passengers and escalator energy consumption at the railway station. *Energy Build* 2009;41:1313–8.
 - [150] Zhu Y, Zhao K, Shu Y, Sun C. Metro station pedestrian organization optimization through space analysis. In: 3rd International conference on transportation engineering – ICTE 2011, Chengdu, China; 2011.
 - [151] Zhang Q, Han B. Simulation model of pedestrian interactive behaviour. *Phys A Stat Mech Appl* 2011;390:636–46.
 - [152] Giretti A, Lemma M, Vaccarini M, Ansuini R, Larghetti R, Ruffini S. Environmental modeling for the optimal energy control of subway stations. In: World conference on robotics and automation in construction – ISCRS/ISARC2012, Eindhoven, The Netherlands; 2012.
 - [153] Stewart E, Weston P, Hillmans S, Roberts C. The merseyrail energy monitoring project. In: 9th World congress on railway research – WCCR 2011, Lille, France; 2011.
 - [154] Evans J. Energy saving measures on the class 390 Pendolino. In: IMechE railway division seminar “gaining traction in energy efficiency”, London, UK; 2012.
 - [155] Stømer T. How much longer can we afford to wait? *Eur Rail Rev* 2012;5.
 - [156] Gatti A, Ghelardini A. The European energy measurement system on board trains. In: 9th World Congress on Railway Research – WCCR 2011, Lille, France; 2011.
 - [157] CENELEC, EN 50463 – railway applications: energy measurement on board trains; 2007.
 - [158] UIC, UIC leaflet 930: Exchange of data for cross-border railway energy settlement; 2009.
 - [159] Faranda R, Leva S. Energetic sustainable development of railway stations. In: 2007 IEEE power engineering society general meeting – PES, Tampa, USA; 2007.
 - [160] Vignaud G. Substation with zero auxiliary consumption. In: 9th World congress on railway research – WCCR 2011, Lille, France; 2011.
 - [161] Vorobiev P, Vorobiev Y. About the possibilities of using the renewable energy power sources on railway transport. *J Adv Transport* 2011. <http://dx.doi.org/10.1002/jatr.189>.
 - [162] Li G, Zhu R, Yang Y. Polymer solar cells. *Nat Photonics* 2012;6:153–61.
 - [163] Railway Gazette News, Solar power on the roof, *Railway Gazette International* [online]; 2010. <<http://www.railwaygazette.com/news/single-view/view/solar-power-on-the-roof.html>>.
 - [164] Barsali S, Giglioli R, Poli D, Vellucci F. Demand response of urban transport systems: A help for deploying the new smart grid paradigm. In: CIGRE 2011 Bologna symposium – the electric power system of the future: integrating supergrids and microgrids, Bologna, Italy; 2011.
 - [165] Díez AE, Díez IC, Lopera JA, Bohorquez A, Velandia E, Albarracín A, et al. Trolleybuses in smart grids as effective strategy to reduce greenhouse emissions. In: IEEE international electric vehicle conference – IEVC 2012, Greenville, USA; 2012.
 - [166] Brenna M, de Berardinis E, Delli Carpini L, Foidellì F, Paulon P, Petroni P, et al. Automatic distributed voltage control algorithm in smart grids applications. *IEEE Trans Smart Grid* 2013;4:877–85.

- [167] Poulin J, Gillespie A, Morelock K, McDowall J, Inniss B. SEPTA recycled energy optimization project with regenerative braking energy storage, SEPTA Recycled Energy & Optimization Project; 2012. <http://www.envitech.com/PDF/APTA_white_paper_on_SEPTA_Recycled_Energy_Optimization_Project_FINAL.pdf>.
- [168] Falvo MC, Martirano L. From smart grids to sustainable energy microsystems. In: 10th International conference on environment and electrical engineering – IEEEIC.EU 2011, Rome, Italy; 2011.
- [169] Brenna M, Falvo MC, Foadelli F, Martirano L, Massaro F, Poli D, Vaccaro A. Challenges in energy systems for the smart-cities of the future. In: IEEE international energy conference and exhibition – ENERGYCON 2012, Florence, Italy; 2012.
- [170] Falvo M, Lamedica R, Bartoni R, Maranzano G. Energy management in metro-transit systems: an innovative proposal toward an integrated and sustainable urban mobility system including plug-in electric vehicles. *Electr Power Syst Res* 2011;81:2127–38.
- [171] le Clech A. Heat extraction in underground railway tunnels. *Eurotransport* 2005;3:35–40.
- [172] Gilbey MJ, Duffy S, Thompson JA. The potential for heat recovery from London underground stations and tunnels. In: CIBSE Technical Symposium, Leicester, UK; 2011.
- [173] Transport for Greater Manchester, TfGM water power project. In: Ticket to Kyoto Public Conference, Bielefeld, Germany; 2011.