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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.

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 CO_2 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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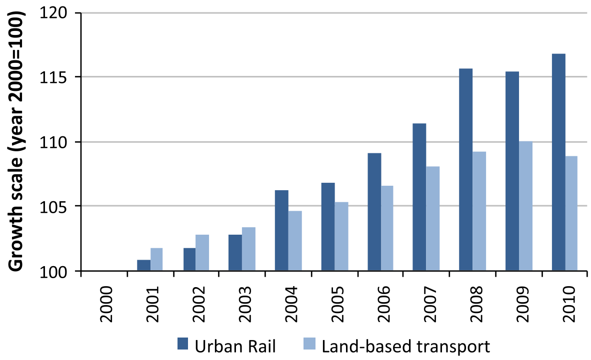

Fig. 1. Evolution of urban rail transport demand in the EU: comparison with total land-based passenger transport.

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