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Assessment of energy-saving techniques in direct-current-electrified mass transit systems

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ABSTRACT

Railway rapid transit systems are key stones for the sustainability of mass transit in developed countries. The overwhelming majority of these railway systems are direct-current (DC) electrified and several energy-saving techniques have been proposed in the literature for these systems. The use of regenerative-braking in trains is generally recognised as the main tool to improve the efficiency of DC-electrified mass transit railway systems but the energy recovered in braking cannot always be handled efficiently, above all in low traffic-density situations. Several emerging technologies as energy storage systems or reversible traction substations have the potential for making it possible to efficiently use train-braking. However, a systematic evaluation of their effect is missing in the literature.

In this paper, a deep, rigorous and comprehensive study on the factors which affect energy issues in a DC-electrified mass transit railway system is carried out. This study clarifies what the actual potential is for energy saving in each situation. Then, a methodology to asses several energy-saving techniques to improve energy efficiency in DC-electrified mass transit systems is presented, constituting the main contribution of this paper. This methodology has been conceived to help operators in assessing the effect of railway-infrastructure emerging technologies in transit systems, so making it possible to shape planning, capacity, etc. It is stepped out in three basic movements. First of all, a traffic-density scan analysis is conducted in order to clarify the effect of the headway on system behaviour. Secondly, several traffic-density scenarios are simulated for a set of infrastructure-expanded cases. Finally, annual energy saving is evaluated by applying a realistic operation timetable. This methodology has been applied to a case study in Madrid Metro (Spain) to illustrate the steps of its application and the effect of several energy-saving techniques on this specific system. Results confirm that regenerative braking generally leads to an important increase of system energy efficiency – especially at high traffic-density scenarios. It has also been proved that infrastructure improvements can also contribute to energy savings and their contributions are more significant at low traffic densities. Annual energy results have been obtained, which may lead to investment decisions by carrying out an appropriate economic assessment based on cost analysis.

The main results of the study presented here are likely to apply to other electric traction systems, at least qualitatively.

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1. Introduction

Railway rapid transit systems are key stones for the sustainability of mass transit in developed countries. In urban environments, underground and commuter railway systems should be conceived to play an important role in order to achieve clean and energy-efficient transportation systems. First, because train energy efficiency is rather high, and then because CO_2 emissions are moved to generation centres which are often far away from over-polluted urban environments. In addition, the amount of CO_2 emissions depends on the energy generation mix and so it is expected to be minimised in a few decades (Peterson et al., 2011).

Although railway systems are characterised by very high efficiency ratios, there is still room for optimising them from an energy consumption point of view.

Most rapid transit systems are direct-current (DC) electrified (Profillidis, 2006; Östlund, 2012). For historical reasons (DC motors were easier to control), this kind of electrification spread in urban systems as tramway or underground. However, DC-electrified railway systems exhibit two main drawbacks in comparison with an alternating current (AC) system: first, it is much more difficult to manufacture high-voltage DC circuit breakers than AC breakers for eliminating large short-circuit currents. Then, it is not possible to step down a DC voltage by means of a transformer, and hence the electrification voltage in this type of system had to be that of the motors. As a result, in this type of system, feeder (overhead conductor or third rail) voltage is usually lower than that in AC-electrified systems. In addition, substations which are not able to give energy back to the utility grid are common. Hence, DC railway systems present in general lower energy efficiency than AC railway systems. A good overview of energy issues in both kinds of electrifications is presented in Koseki (2010).

Rolling stock has been continuously subject to design improvements. Hence, modern electric trains are highly efficient, and it is not easy to achieve qualitative improvements in their performance. A comprehensive study on the different factors affecting rolling stock efficiency and they way they may be changed to improve efficiency is presented in Kondo (2010).

If non-electric trains are considered, there is more room to optimise them from an energy point of view. Currently, several research efforts are being put into hybridisation (Hillmansen and Roberts, 2007), optimal energy management in diesel–fuel powered trains, etc.

Another hot topic in energy efficiency in railway systems is eco-driving. This designation collects strategies which are oriented to minimise train energy consumption in a given service. Studies in this field try to determine the speed and power profiles (driving strategy) which yield the minimum energy consumption for a given trip time. As a result, a pareto front gathering the best driving strategies for a set of trip times is obtained. Good examples of research on railway energy efficiency by optimising the driving strategy may be found in the studies by Bocharnikov et al. (2007), Domínguez et al. (2008), Sicre et al. (2010), Fernández-Cardador and Cucala (2010), Domínguez et al. (2010), Lin and Sheu (2011), Sheu and Lin (2012) and Miyatake and Ko (2010).

Railway energy efficiency may also be improved by optimising system infrastructure. The introduction of regenerative braking meant a qualitative reduction of energy consumption both in AC and DC railway systems. However, in DC-electrified railway systems regenerated energy is not always accepted by the system if substations work in one quadrant, and is hence wasted. Some techniques are emerging to manage regenerated energy in DC-electrified systems. They improve receptivity by returning regenerated energy to the utility grid, by storing it in dedicated locations for later releasing it or by making it easier the energy interchange for trains. Some of these techniques have been applied to an actual system in Takagi (2010), where achieved energy savings have been assessed. The effect of a novel reversible substation topology on an actual railway system in the Netherlands has been studied in Cornic (2010). A study on an actual Japanese system focused on Energy Storage Systems (ESSs) has been presented in Konishi et al. (2010).

This latter kind of systems (ESSs), both based on batteries or electric double-layer capacitors (EDLCs, also known as supercapacitors), have been conceived as the main tool to improve energy efficiency in railway systems in a number of references. Storage technologies and control schemes for ESS are constantly being improved under the influence of hybrid and pure electrical vehicles, which is bringing new possibilities to the railway sector. The influence of some design concerns on the efficiency of ESSs has been analysed in Allegre et al. (2009). An ESS-based system to reinforce a weak railway network has been designed in Rufer et al. (2004b). The study by Ciccarelli et al. (2012) researches on the improvement in train performance derived from the utilisation of advanced control techniques in supercapacitor-based onboard ESSs. The benefits of introducing onboard ESSs in a light tram system have been analysed in Barrero et al. (2008c) with good results, while a similar analysis has been conducted for static ESSs in a metro system in Barrero et al. (2008a). In the work by Rufer et al. (2004a) super-capacitor tanks properties have been studied with the aim of making it possible to supply energy to trains without using a feeding network, but using ESSs. An energy supply concept based on ESSs has been proposed in Allegre et al. (2010) with good results.

Some recent studies are focused on the application of optimisation techniques to railway systems. In this line, Abrahamsson et al. (2013) have presented a model which integrates the electrical and the mechanical part and makes it possible to study optimal power supply systems. An optimisation model which is aimed at obtaining the optimal deployment of ESSs in a given system has been presented in López López et al. (2012). A complete study on the optimal parameters of an ESS in a double-track line has been carried out in Ianuzzi et al. (2012). In Battistelli et al. (2009), a research study on the optimal ESS features has been presented. However, not so much research has been conducted on the evaluation of the goodness of each particular energy-saving technique for a particular system.