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Energy storage technologies and hybrid architectures for specific diesel-driven rail duty cycles: Design and system integration aspects ☆

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HIGHLIGHTS

- We assessed integration of energy storage systems into hybrid system architectures.
- We considered mechanical and electrical energy storage systems.
- Potential of different combinations has been analyzed by standardized duty cycles.
- Most promising are diesel-driven suburban, regional and shunting operations.
- Double-layer capacitors and Lithium-ion batteries have the highest potential.

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ABSTRACT

The use of diesel-driven traction is an intrinsic part of the functioning of railway systems and it is expected to continue being so for the foreseeable future. The recent introduction of more restrictive greenhouse gas emission levels and other legislation aiming at the improvement of the environmental performance of railway systems has led to the need of exploring alternatives for cleaner diesel rolling stock. This paper focuses on assessing energy storage systems and the design of hybrid system architectures to determine their potential use in specific diesel-driven rail duty cycles. Hydrostatic accumulators, flywheels, Lithium-ion batteries and double-layer capacitors have been assessed and used to design hybrid system architectures. The potential of the different technology combinations has been analyzed using standardized duty cycles enhanced with gradient profiles related to suburban, regional and shunting operations.

The results show that double-layer capacitors and Lithium-ion batteries have the highest potential to be successfully integrated into the system architecture of diesel-driven rail vehicles. Furthermore, the results also suggest that combining these two energy storage technologies into a single hybridisation package is a highly promising design that draws on their strengths without any significant drawbacks.
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1. Introduction

1.1. Background

Diesel rail vehicles remain an integral part of many rail systems and will continue to be so for the foreseeable future, especially on routes whereby the installation of expensive infrastructure to supply electricity is not cost effective. It is necessary for the rail industry to adapt to the predicted rise in energy costs (e.g. 50% in UK by 2019) by lowering the dependence on diesel fuel, and to help adhere to air quality, Green House Gas (GHG) emissions, noise emissions and energy efficiency legislation [1–5].

The use of Energy Storage Systems (ESSs) can help fulfil these requirements by absorbing, storing and re-emitting regenerative braking energy. They can be used to power the traction motor or the auxiliaries for a limited period, either in conjunction with the diesel engine or as a standalone power source. When powered solely by the ESS, noise levels are lower and no diesel fumes are produced [6]. This can prove highly beneficial in stations, tunnels,

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depots or other highly populated areas where diesel trains currently idle.

Developments in the ESSs over the past decade have been significant. Technologies that were not financially viable only a few years ago are now commercially available, allowing for greater energy efficiencies to be achieved. Similarly, the capacity of such ESSs has improved dramatically in recent times. All of which increases the prospects of the use of such technologies as a viable solution to optimize the consumption and performance of transport vehicles.

Regenerative braking is a wide spread practice in rail-way transport. It consists in recovering and reusing the vehicles' braking energy [7]. ESSs play a key role when attempting to harness such energy as they can be combined with existing and new diesel-driven rail vehicles to form hybrid system architectures. Using this type of arrangements can lead to a significant reduction in fuel consumption and GHG emissions as a result. In addition, European legislation has been introduced to restrict further the level of GHG emissions from diesel railways. The application of the EU Non-Road Mobile Machinery (NRMM) Directive to rail diesel vehicles, through the introduction of Stage III B emissions limits, raises significant challenges in terms of vehicle design, reliability and life cycle cost [8].

This paper briefly describes the most promising technologies applicable to railway diesel-power train hybridisation, to then explore a number of novel potential system architectures for finding an optimum configuration based on selected duty cycles. To the authors' knowledge, this combined assessment of ESSs technologies and realistic standardized duty cycles for railway application with an operational insight is not covered in the literature.

The energy saving potential and design of such ESSs on rail vehicles is described in [7,9,10].

1.2. Rail duty cycles

Duty cycles for different types of rail operation are defined by the TS 50591 standard [11]. Of these, diesel multiple units (DMUs) for suburban and regional services and shunting locomotives have been selected given their duty cycles requiring frequent stopping patterns that maximize the potential of using ESSs.

Additionally, gradients have been added to the flat characteristics of the regional duty cycle defined in TS 50591 to explore the impact of using ESSs on routes using flat and non-flat topography [11]. No altitude has been introduced to the suburban duty cycle. In both cases, the travelling time defined in the standard has been increased from 40 min to 46 min to allow for the lower power of diesel-driven rail vehicles [12].

TS 50591 do not consider a duty cycle for shunting operations. However, the authors consider this an area of high potential application for ESSs given their low speed, very high braking energy recuperation rate and significant acceleration and stopping pattern. Experimental data from industry have been used to build this duty cycle [13,14].

1.3. Methodology

A simulation model has been developed in MATLAB/SIMULINK, without using a pre-programmed toolbox, to run a number of ESS configurations on the duty cycles described using synthetic vehicles. Specifically:

- suburban: a two-coach DMU with a 2 × 360 kW internal combustion engine (ICE),
- regional: a three-coach DMU with 3 × 560 kW or 3 × 360 kW ICE,
- shunter: a locomotive with a 1000 kW ICE.

Based on a model library (Fig. 1), different system architectures can be configured including the three main transmission types of rail vehicles:

- hydromechanic,
- hydrodynamic and
- electric transmission.

Furthermore, five different ESSs can be applied to the system architectures:

- hydrostatic ESS,
- flywheel ESS,
- Lithium-ion battery ESS,
- DLC ESS and
- hybrid ESS of Lithium-ion battery and DLC.

Due to up to three hybrid ESSs of Lithium-ion battery and DLC combinations were investigated, a theoretical number of 84 possible simulations could be done. However only 54 of them were considered as plausible and therefore investigated in detail.

2. Relevant ESSs technologies considered

2.1. Hydrostatic ESS

The hydrostatic ESS described in this paper is based on the physical principle of pressure storage in which a non-compressible fluid is held under pressure by an external source. The external source for high-energy storage content is compressible inert gas. Contrary to the other ESS technologies described in this paper, hydrostatic ESSs are purely mechanical systems. No electric motor/generator is needed to store the kinetic energy of the vehicle during braking phases. A general concept of a hydrostatic ESS is explained in [15].

Hydrostatic ESSs have proven their robustness and ability to improve driveline efficiency in several applications as described in [16,17] and are currently in use in various construction machines and commercial vehicles. Even for passenger cars, hydraulic hybrids are gaining more and more attention over the past years [18].

For a rail application the key advantages of Hydrostatic ESSs are:

- proven energy storage technology without any powerful electric components (no high currents/voltages),
- designed service life equal to the rail vehicle,
- virtually maintenance free (visible inspection every 10 years),
- fast charging and discharging rates,

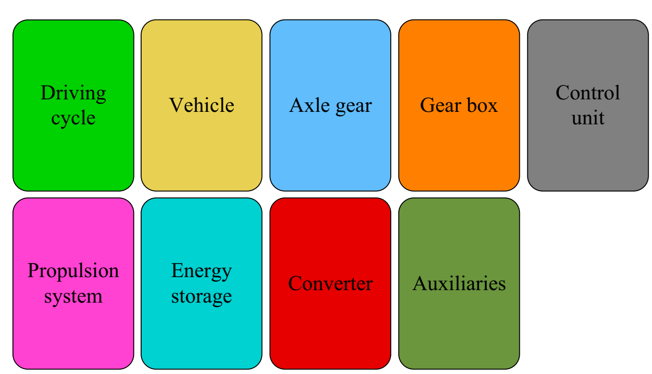

Fig. 1. *MATLAB/SIMULINK* model library.

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