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WAYS TO REDUCE THE FUEL CONSUMPTION AND EMISSIONS OF DIESEL MULTIPLE UNITS WITH HYDRALIC POWER TRANSMISSION

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Abstract

The hybridisation of diesel multiple units is a promising chance to improve the energy efficiency. The authors discuss the impact of several measures to save and regain energy during the operation of diesel multiple units (DMU) on regional and local railway lines. The problem of recuperating and storing kinetic energy on vehicles with hydrodynamic power transmissions is raised. Different operating modes are compared to each other and the major limitations as well as influencing factors are considered. The second aspect that is taken up, is a strategy of using the exhaust gas heat of the diesel engine. An approach to use a closed steam cycle process is brought forward.

Keywords: diesel-hydraulic vehicle, hybrid, energy storage, exhaust gas, heat recovery, environmental protection, energy efficiency

1 Introduction

Over the past decades a rising awareness of problems connected to the phenomenon of global warming has emerged around the world. Railways have always and deservedly been viewed as an environmentally friendly means of transport. Nonetheless there is now a growing pressure on both the railway industry and train operators to meet increasingly strict legal requirements concerning exhaust gas emissions. Moreover, the price of diesel fuel has risen significantly over the last years and it is very likely that it will continue to do so. That is why all principal participants in the railway market are working on strategies to improve the energy efficiency of their present and future diesel fleets.

In Germany all major rail operators have followed a strategy of replacing loco-hauled trains by railcars and multiple units. Diesel versions of these vehicles play an important role in regional and local traffic. Taking into account that roughly 50 % of the German fleet of diesel multiple units and railcars feature hydraulic power transmission, it is vital to evaluate different strategies of energy recuperation for these kinds of vehicles. Hereafter, the authors will focus on ways to regain kinetic as well as exhaust gas energy and point out different strategies to operate hybrid drive trains in rail vehicles.

2 Retrieving kinetic energy

Rail vehicles feature comparatively high masses resulting in a huge amount of kinetic energy that has to be converted when braking. In order to regain energy, the conventional drive train has to be amended by adding an energy converter and an energy storage. Different energy storages can be considered such as flywheels [1], Double Layer Capacitors (DLCS) [2], electrochemical cells or hydraulic accumulators [3]. Electric storages appear to be most promising with regard to energy density, efficiency, safetey, self-discharging and the potential of future developments. Therefore the authors have picked some electric hybrid configurations for closer examination.

2.1 Operating modes

The authors differentiate between three basic practices to operate a hybrid drive train: boost mode, load level shifting mode and zero emission mode. All of them are shortly characterised in table 1.

Table 1 Operating modes of the hybrid drive train

	Boost	Load Level Shifting Mode (LLS)	Zero Emission Mode (ZEM)
Conventional drive train	full load	partial load	switched off
Hybrid branch	full load	full load	full load
Purpose	energy saving	energy saving	reduction of emissions in crucial line sections

The application of these different operating modes depends on several factors such as the available adhesion, timetable restrictions, environmental regulations and the fuel consumption map of the diesel engine.

2.2 Limitations to hybridisation

Although huge progress has been made over the past decade to enhance the energy content of batteries and double layer capacitors, the mass of electric energy storages is still a major factor limiting hybridisation. Figure 1 illustrates the energy potential of a 50 t - railcar against speed and slope, neglecting the energy dissipated through vehicle resistance. As a mass of 50 t rather represents the lower bound, it is evident that a potential of up to 10 kWh is not too far-fetched. The specific mass of energy storages consisting of DLCs can be assumed to be roughly 0.5 to 1.3 t/kWh [4,5]. Thus an absolute mass of up to 20 tons would be necessary to cover the entire potential shown in figure 1. An additional mass of this magnitude is of course not realistic, the limit applying to existing vehicles being 2-4 t.
A very important issue that has to be discussed regarding DLCs and batteries is their cycle life. It is strongly influenced by the operation temperature which is in turn related to current. As high temperatures reduce the service life of both

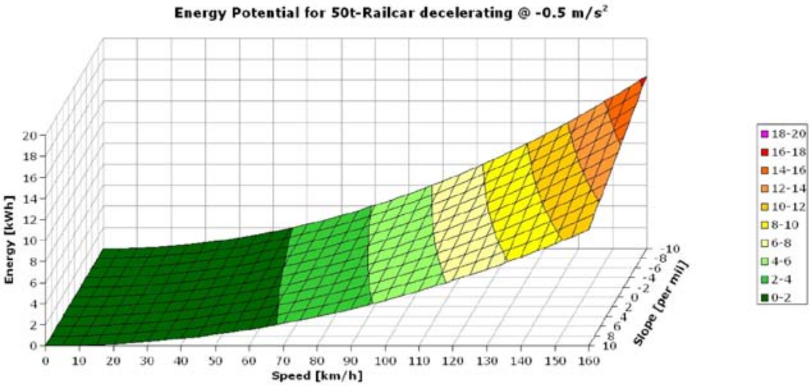

Figure 1 Potential of energy to be retrieved from railcar weighing 50 t

batteries and DLCs, measures have to be taken to either limit heat generation or intensify cooling. The first option results in a reduction of currents (and therefore power) whereas the second option increases the demand of auxiliary power on the vehicle, having a negative impact on the overall energy balance. Furthermore the upper voltage of DLCs has to be limited to shield the electrolyte from deterioration. For the reasons mentioned above this cannot be compensated by higher currents so that the effective (specific) power is reduced.

As for batteries, the range between maximum and minimum state of charge has to be reduced to 10...20 % in order to achieve a long service life. Thus a major fraction of the battery's energy remains unused resulting in lower effective (specific) energy content than implied by the nominal values.

Another factor that has to be taken into consideration is the power of the electric motors which is linked to their volume and weight. Modern traction motors feature specific masses of 1,5...2,0 kg/kW according to [6]. The application of 300 kW of power will thus lead to an extra mass of roughly half a ton.

3 Simulation results (electric hybrid)

At the Chair of Rail Vehicle Technology a simulation model of a DMU with hydrodynamic power transmission has been developed in cooperation with Voith Turbo GmbH & Co. KG. The simulation environment used is AMESim™ by LMS International. The design of the model is modular allowing different hybrid configurations to be examined.

To show the effects of hybridisation and different operating strategies the authors have picked a configuration according to table 2 as an example.

Table 2 Simulation Model Parameters

Basic Vehicle		**Hybrid Configuration**	
Vehicle mass	106 t	Energy storage	Li-Ion-Battery
Maximum speed	160km/h	Nominal voltage	690 - 960 V
Power of diesel eng.	2 x 550 kW	Eff. energy content	2 × 6.9 kWh
Wheel arrangement	2'B'+B'2'	Power of electric motor(s)	2 × 150 kW'
		Additional mass	3 t

The simulations were run for a flat line with a distance between stops of 6.5km to show the influence of different operating modes and eliminate the influence of curves and gradients.

In a first step the conventional vehicle was simulated running with maximum tractive effort in order to assess the shortest travelling time. Taking into account a time reserve of 3 % related to the time determined before, a period of coasting is then inserted where the tractive power is switched off and the diesel engine is left idling. By this means a decrease in fuel consumption can be achieved. This method is called Energy Saving Operation and sets the benchmark for travelling time and fuel consumption.

Operating the considered hybrid configuration in boost mode brings about higher acceleration. The maximum speed is thus reached earlier opening the chance to switch off the traction power earlier and prolong the coasting period. Due to the power restriction imposed by the energy storage, the deceleration level has to be decreased in order to ensure the replenishment of the batteries. This measure will become obsolete as soon as the charge acceptance of Lithium-Ion batteries can be further increased. Figure 2 shows a comparison of both speed and fuel consumption profiles of the examined versions of the vehicle. Simulation results show that fuel savings of around 8 % can be expected on the simulated line with this specific hybrid configuration. It is not surprising, that the reduction of the fuel consumptions is closely linked to the operation mode as table 3 illustrates. It is important to state that the simulation results given are only exemplary and range in the lower region of possible fuel sa-

vings. It is evident that operating the hybrid vehicle in zero emission mode will rather reduce emissions locally than fuel consumption globally.
The overall benefit of hybridisation is subject to complex dependencies such as the charge acceptance and the energy content of the storage, the line profile and the distance between stops [7]. Due to space limitations these issues cannot be discussed in detail.

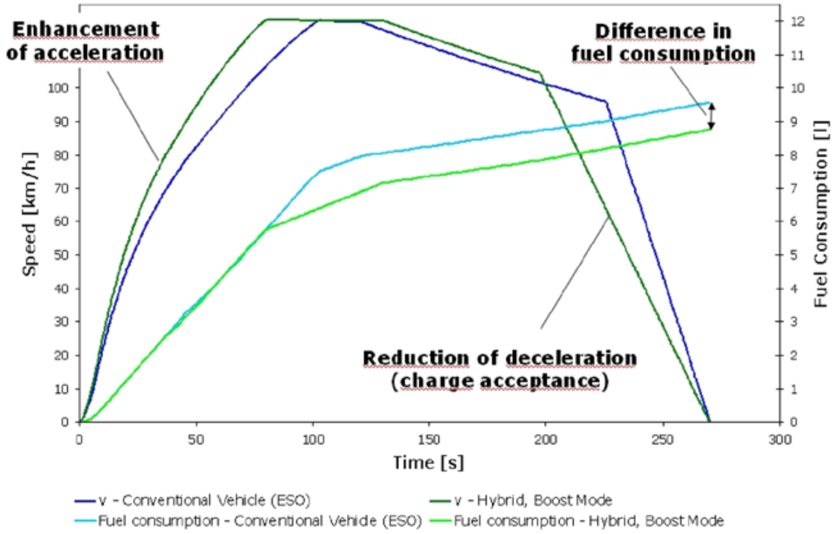

Figure 2 Comparison of speed and fuel consumption against time

Table 3 Exemplary simulation results for constant travelling time

Operation Mode	Conventional (ESO)	Boost Mode	LLS Mode	ZEM
Relative Fuel Consumption	100 %	91.5 %	96.3 %	99.8 %

4 Exhaust gas heat recovery

It is a well known fact that only about one third of the energy provided by the fuel can be converted into mechanical energy. In most cases the remaining two thirds are lost in contemporary vehicles. Due to its high temperature level, the exhaust gas appears to offer a good opportunity for waste heat recovery (WHR). Neglecting the utilisation for heating purposes, there are today basically two approaches to realise this feature: thermo-electric generators (TEGS) and systems using a bottoming cycle. The overall efficiency of the former is still very low and regarding the power level considered here, this technology is far from being ready for application. What is more, the number of electric drives on diesel hydraulic vehicles is limited to a few auxiliary devices. It thus seems convenient to convert the exhaust heat into mechanical rather than electric energy. That is why the authors prefer a WHR system which is based on a bottoming cycle.

4.1 Exhaust gas heat utilisation (EGU) system

For an in-depth examination of such a system, a simulation model was developed by the authors in cooperation with Voith Turbo GmbH & Co. KG [3]. The key components to be modelled are shown in figure 3 and comprise a feed pump, an evaporator, an expansion engine and a condenser.

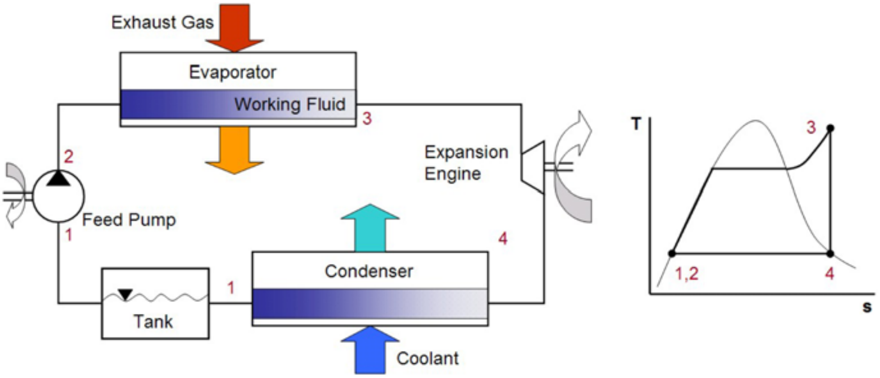

Figure 3 Schema of Exhaust Gas Utilisation System and related standard cycle (Clausius-Rankine) with water as a possible working fluid

4.2 Estimation of the recovery potential

To get an idea of the amount of energy that can be recovered from the exhaust gas, the authors have carried out a study based on simplified assumptions. Therefore the basic simulation model was parameterised according to table 4.

Table 4 Model parameters for analysis of waste heat energy recuperation potential

Nominal power output of diesel engines	2 x 380 kW
Type of hydrodynamic transmission	Torque Converter + Coupling
Maximum speed	120km/h
Tare mass	90 t

To illustrate the basic coherences, a simple operational cycle on a real line as shown in figure 4 (left chart) is examined. The red line illustrates the speed against relative time while the blue one represents the profile of the exhaust gas temperature relating to its maximum value. The mechanical power of the Exhaust Gas Utilisation System (EGU) can be estimated using the following equations:

$$\dot{Q}_{EG} = \dot{m}_{EG} \cdot c_p \cdot (T_{EG} - T_{ref}) \tag{1}$$

$$P_{EGU} = \dot{Q}_{EG} \cdot \eta_{EGU} \tag{2}$$

$$\eta_{EGU} = \eta_{HE} \cdot \eta_{CR} \cdot \eta_{Exp} \tag{3}$$

with: $\dot{Q}_{EG}$ – exhaust gas heat flow, $\dot{m}_{EG}$ – exhaust gas mass flow, c_p – specific heat capacity, T_{EG} – exhaust gas temperature, T_{ref} – reference temperature, η_{EGU} – overall efficiency of the EGU system, η_{HE} – heat exchanger efficiency, η_{CR} – thermal efficiency (Clausius-Rankine), η_{Exp} – expansion engine efficiency.

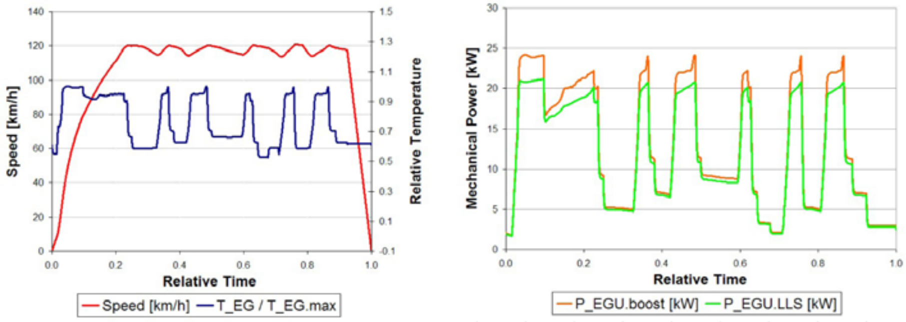

Figure 4 Characteristic of speed, exhaust gas temperature and EGU system power output while running (example)

The efficiencies are kept constant and the system specific inertia is neglected for simplification purposes in this first approach. Taking into consideration an overall system efficiency of 12 %, a power output of up to 25 kW is obtained for the EGU system (see figure 4, right chart). The maximum recoverable energy is limited as it is not advisable to fall below a minimum exhaust gas temperature. The reason behind this is the need to avoid corrosion damage to the exhaust gas system caused by condensation. Therefore the calculated power output applies for 180 °C as reference temperature.

This kind of hybrid vehicle can also be operated both in boost and load level shifting Mode. It must be kept in mind that load level shifting lowers the power output of the diesel engine P_{ICE} to $P_{ICE.LLS}$ and therefore the temperature characteristic of the exhaust gas is also altered. It is thus necessary to run an iteration in order to correct the output power of the EGU System P_{EGU}. Moreover, load level shifting in this case aims at keeping the power input to the turbo transmission P_{TTI} constant. Put into equations this means:

Boost Mode: $$P_{TTI} = P_{ICE} + P_{EGU} \tag{4}$$

LLS Mode: $$P_{TTI} = P_{ICE.LLS} + P_{EGU} \tag{5}$$

For LLS Mode the fuel consumption was calculated to decrease by 5 % using the simplified approach.

In addition, simular simulations on three lines (A,B,C) with different speed and grade profiles have been run. Line A features a plain profile as can be found in the north of Germany whereas lines B and C represent profiles typical for upland regions. The former is continually ascending while the latter is uneven. Fuel savings between 4 and 5 % could be projected for these lines as well.

4.3 Simulation Results (EGU System)

In conclusion, the authors have chosen a full load starting with an acceleration up to 120km/h to show some results of a simulation where all important effects and influences are taken into account. Figure 5 illustrates the speed against relative time (green) and the relative power output of the diesel engine (blue) associated to it. Furthermore the overall traction power output in boost mode (red) is shown in the chart. The inertia of the system can easily be recognised from the delayed power output of the EGU system. Compared to the conventional vehicle a fuel saving of 4 % in Boost Mode was simulated for the examined starting process. In case the EGU system is inactive, the additional mass of the equipment causes a negligible increase in fuel consumption of 0.5 %.

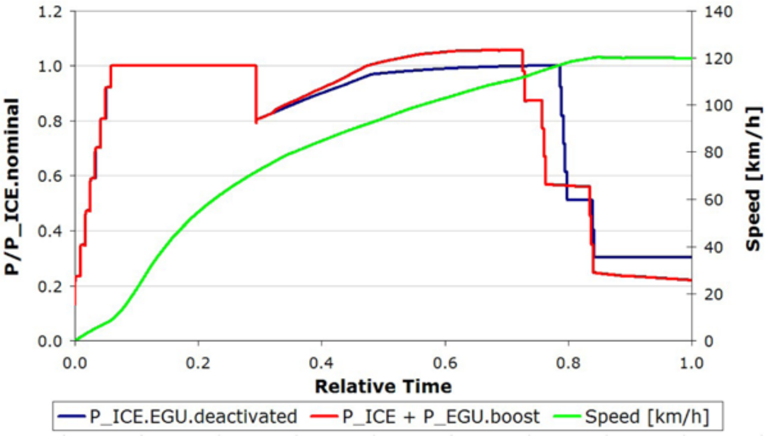

Figure 5 Simulation results for full load starting

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