

ENHANCING THE ENERGY EFFICIENCY OF DIESEL MULTIPLE UNITS WITH HYDRODYNAMIC POWER TRANSMISSION

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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 as well as a strategy of using the waste heat of the diesel engine are examined. A model to simulate (hybrid) diesel hydraulic multiple units is presented, taking into account the influences of track and driver behaviour. The simulation results provided show a significant fuel saving potential for rail vehicles with hybrid drive trains.

Key words: hybrid, energy storage, waste heat recovery, simulation of rail vehicles, diesel multiple unit

1 Introduction

Enhancing the energy efficiency of transport processes has become a major issue for both the automotive and the railway industry. This development is on the one hand due to a growing awareness of problems related to global warming and air pollution. On the other hand, most railway operators have come under increasing pressure to save fuel in order to cut their expenses as the price for diesel fuel has risen significantly over the last years and will probably continue to do so. Even though railways have always been a comparatively clean and effective means of transport, especially when it comes to carrying bulk cargos and large numbers of passengers, there is a growing need to reduce emissions and fuel consumption in order to remain competitive. The Chair of Rail Vehicle Technology and Voith Turbo AG have therefore initiated a research project focusing on the improvement of diesel multiple units with hydrodynamic power transmission. This kind of vehicles is comparatively common with train operators in Central Europe. Thus, research activities aim at both refurbishing existing and equipping future rolling stock with “green technology”.

2 Basic Simulation Model

To understand the correlations of the different parts of dieselhydraulic drive trains, a basic simulation model has been developed at the Chair of Rail Vehicle Technology in cooperation with Voith Turbo. Its purpose is to supply the values for fuel consumption, running time, exhaust gas mass flow and

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temperature as outputs of the simulation of train runs on real lines. The simulation software used is Imagine.Lab AMESim™ by LMS, which is a one-dimensional multi-domain system simulation tool. The basic components included in the programme have been customized and adjusted to the specific needs of the project. Furthermore, distinct elements to complete the offered libraries have been developed by the authors.

Apart from simulating the interaction of the drive train components, the model allows to represent driver behaviour to a certain extent. In the course of modelling, real train runs have been recorded using Voith's fluid transmission control software. Analysing the recorded data allowed to estimate some parameters of the modelled control logic such as response times. According to the authors' observations of driver behaviour there is quite a big range of patterns of how drivers chose regulating notches and how fast the maximum tractive effort is applied. By changing the relevant parameters, the simulation model can be adapted to different driving styles though it has to be emphasized that this is all a matter of approximation as the actual focus of the simulation is not on the varying driver behaviour.

3 Recuperation of kinetic energy

Present diesel hydraulic multiple units are equipped with pneumatic brakes, often supported by a hydraulic retarder to minimize abrasive wear. It is inherent to the system that most of the vehicle's kinetic energy is lost to the transportation process as it is simply converted into heat by these types of brakes.

By adding hybrid components such as energy converters and energy storages to a conventional drive train some of the kinetic energy can be regained for the propulsion of the vehicle or selected components. Today there are four basic methods to store energy but none of them perfectly meets the demands of hybrid vehicle propulsion. While flywheels have recently fallen behind due to rigidity problems, electric energy storage devices are favoured by most train manufacturers. Presently there are two basic technologies for storing electric energy available: Batteries and electric double layer capacitors (EDLCs). Both technologies have specific advantages and disadvantages of which some are shown in Tab 1.

Tab 1: Comparison of electric energy storage technologies

Electric Double Layer Capacitor (EDLC)	Batteries (Nickel Metal Hydrid, Lithium-Ion)
+ high specific power	+ high specific energy
+ low ohmic resistance	+ voltage nearly constant over large interval of state of charge
+ high efficiency	- temperature sensitive
- voltage strongly depends on state of charge	- partly low (specific) power
- low specific energy	- prices and availability questionable for railway sector

Choosing either of these technologies implies accepting compromises with regard to energy capacity or power. The combination of both types of energy storage can be a suitable way to avoid

major disadvantages but is closely linked to a rising complexity of power electronics and the battery control system.

A third way to convert and store energy on diesel multiple units is to use hydrostatic components. The main advantage of this approach is the absence of additional electric equipment which may be desirable for train operators having all-diesel hydraulic fleets. Moreover, availability and obsolescence can be regarded as minor issues when it comes to hydrostatic equipment.

4 Hybrid Drive Train Simulation

To study the influence of hybridization on fuel consumption and traction mechanics several models have been built up, representing different parallel hybrid-configurations (see

Tab 2) on the basis of a diesel hydraulic multiple unit weighing 98t and being equipped with two diesel engines rated at 550kW. As a first step only electric hybrid drive trains are examined whereas a comparison between electric and hydrostatic hybrid configurations remains the long term goal of the simulation. Although there are different operation modes of hybrid drive trains, the focus of the studies presented here was on boosting, that is adding the maximum power of the hybrid components to that of the conventional drive train when accelerating the vehicle. All calculations were executed based on the following assumptions:

- Half the nominal voltage range of the EDLCs is used, thus keeping ohmic losses at an acceptable level.
- The electric resistance comprises both the inner resistance of each element and the resistance of the connectors.
- The resistance for charging is equal to the resistance for discharging.
- The batteries operate between 60% and 70% state of charge in order to achieve long durability.
- The influence of temperature on both EDLCs and batteries is neglected due to lack of reliable data.

Tab 2: Modelled configurations of parallel hybrid drive trains.

		Hybrid I	Hybrid II	Hybrid III	Hybrid IV	Hybrid V
energy storage		EDLC	EDLC	battery	EDLC+battery	EDLC+battery
voltage range	V	400-800	400-800	690-960	400-800/690-960	400-800/690-960
serviceable energy content	kWh	1,2	3,8	13,8	2,4+2,8	2,4+2,8
power of electric	kW	300	600	300	300	600
additional mass (estimation)	t	2	4	3	3	4

To show the effect of hybridization on fuel consumption the authors have chosen a railwayline with small gradients (max. 7‰ / min 5‰) likely to be found in the north of Germany as an example. The distance between stops varies between 4 and 7.5km, the maximum speed is limited to 120km/h. Some of the results of this examination are shown in Fig 1. When operating a hybrid in boost mode, the major effect on fuel reduction lies with the extension of the coasting section(s) of a train run. As higher accelerations can be achieved, the power of the diesel engine can be cut off earlier because the effective running time reserve increases with growing average acceleration. On the other hand, the aspect of deceleration limiting coasting has to be taken into account. For optimal efficiency high deceleration values have to be realized, leading to coasting sections of maximum length. As far as hybrid vehicles

are concerned, the achievable deceleration rates are closely linked to the power of the energy storage device, that is the maximum charging current in the case considered here. As the charge acceptance of EDLCs is generally higher than that of batteries. The same applies to the deceleration rates.

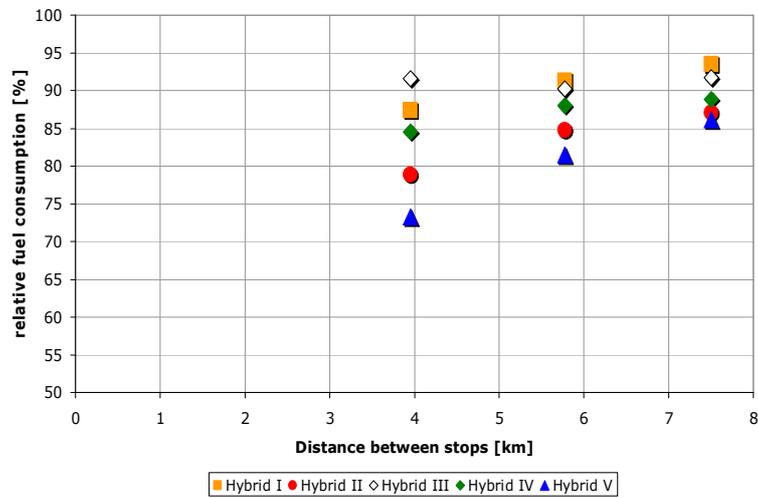


Fig 1: Simulation results for electric hybrid dmu with boost mode

Simulations show that fuel reductions between 5 and 25% can be considered to be realistic depending on the distance between stops and the hybrid configuration (i.e. the type of energy storage).

5 Waste Heat Recovery

It is commonly known that only about one third of the energy contained in the fuel can actually be made available at the crank shaft of today's diesel engines.

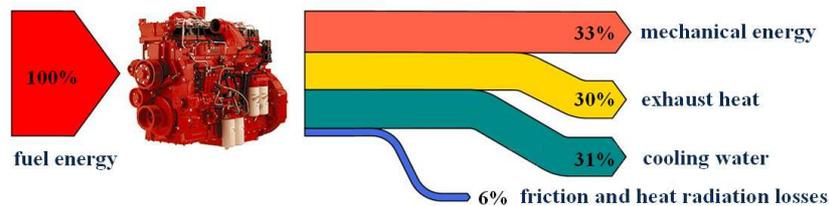


Fig 2: Energy balance of a conventional diesel engine

A significant part of the energy is transferred to the cooling water and the exhaust gas and can nowadays, if at all, be used for heating purposes only. Waste heat recovery systems are a promising way to overcome this situation and regain some of the "lost" energy by transforming it to mechanical or electric energy again. A comparably simple way to use the (kinetic) energy of the exhaust gas is to install a turbocharger but there are ways beyond this conventional feature such as turbo compound systems, thermoelectric generators or steam power cycles.

All systems aiming at the transformation of exhaust-gas heat are limited by the Carnot degree of efficiency:

$$\eta_c = 1 - \frac{T_{\min}}{T_{\max}} \quad (1)$$

where T_{\min} is lowest and T_{\max} the highest temperature of the process. To estimate the effect of a waste heat recovery system using a closed steam cycle process, the potential of exhaust gas as an energy source was examined, taking into account the specific conditions of train operation. Utilizing the basic AMESim model described above, train runs of a dmU with a rated power of 380kW and weighing 90t were simulated on lines with different natures. Three different lines were chosen, differing in elevation profile, total length and average distance between two stops.

The heat flow that is hypothetically available depends on the mass flow, the heat capacity and the temperature of the exhaust gas as well as on the ambient temperature. It can be determined by the following equation:

$$\dot{Q}_{th} = \dot{m}_{eg} c_{p,eg} (T_{eg} - T_{amb}) \quad (2)$$

Assuming an ambient temperature of 21°C a maximum heat flow of 380kW can be achieved. Bearing in mind that exhaust gas at temperatures below 180°C is likely to contain sulphuric acid causing damage to the exhaust system, equation (2) has to be modified as follows:

$$\dot{Q}_{th} = \dot{m}_{eg} c_{p,eg} (T_{eg} - 180^{\circ}\text{C}) \quad (3)$$

Due to this restriction the maximum available heat flow is reduced to circa 222kW. The efficiency of the entire system is estimated to be around 13% resulting in a maximum power output of 29kW.

The additional power produced by the waste heat recovery equipment can be used to shift the operating point of the diesel engine to keep the power input to the hydraulic transmission constant. This measure may result in a drop of exhaust gas temperature and/or mass flow leading to a reduction of the system's power output. Therefore, it has to be closely examined whether this strategy leads to the desired results. It is very important to keep in mind that altering the operating state of the diesel engine has a direct impact on the performance of the waste heat recovery system.

Tab 3: Results of simulation estimating potential of exhaust gas as an energy source

Track	A	B	C	
Altitude profil	flat	continuous slope	two-peak-track	
Track length	52.35	20.73	110.00	[km]
Average distance between stops	13.1	3.0	13.2	[km]
Average heat flow (related to T = 180°C)	62.5	62.5	95.5	[kW]
Total exhaust gas energy (related to T = 180°C)	41.7	30.9	126.2	[kWh]
Fuel consumption reduction through shift of operation point of diesel engine	5	5	5	[%]

Some results of the simulation are presented in Tab 3 showing a potential for fuel reduction of about 5%. Neither the character of the line nor the average distance between two stops seem to have an impact on this system making use of a shift of the operation point of the diesel engine. This fact underlines the assumption that using the waste heat recovery system to boost the conventional drive train might be a better option. Simulations to examine this more closely are now underway and will be presented at a later point in time.

6 Simulating a steam cycle process

Voith Turbo has chosen to develop a waste heat recovery system involving a closed steam cycle process to transfer heat of the exhaust gas to mechanical energy. The motivation behind this decision lies in avoiding electric components in a predominantly mechanical drive train. The main components of the arrangement are an evaporator, an expansion engine, a condenser and a feed pump. At the Chair of Rail Vehicle Engineering, a simulation model to represent a system of this kind has been designed in cooperation with Voith (see Fig 3).

The assumptions made modelling the different elements have yet to be validated using test bench data.

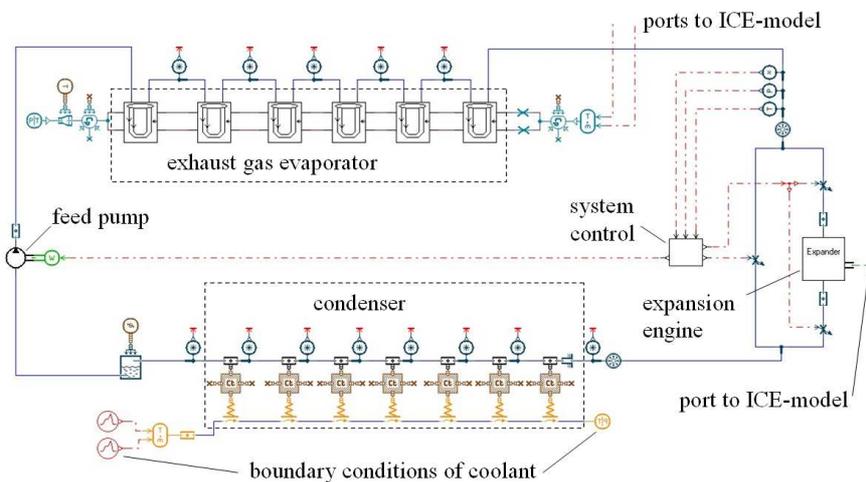


Fig 3: Simulation model of Waste Heat Recovery System using a closed steam cycle process

Preliminary simulation results point to a superiority of the boost concept over the concept of shifting the operating point of the diesel engine.

7 Conclusion

The hybridization of dieselhydraulic multiple units poses a promising chance to enhance the energy efficiency. The simulation model developed at the Chair of Rail Vehicle Engineering provides the basis for more detailed research on problems of energy conversion and storage.

First simulation results have shown that significant savings in fuel consumption and emissions can be expected although the recuperation of energy is linked to an increase of vehicle mass. An in-depth study on the influence of line characteristics (e.g. altitude profile, average distance between stops), driver behaviour and hybrid configuration have to be made in order to find the most suitable solutions for each case of operation.

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