Model-based comparison of hybrid propulsion systems for railway diesel multiple units

Sebastian Schmid [a], Kambiz Ebrahimi [b], Antonios Pezouvanis [b] and Walter Commerell [c]

[a] *Voith Turbo GmbH & Co. KG, Heidenheim, Germany*

[b] *Department of Aeronautical and Automotive Engineering, Loughborough University, Leicestershire, UK*

[c] *Institutes of Energy and Drive Technology, University of Applied Sciences Ulm, Ulm, Germany*

Sebastian Schmid
Voith Turbo GmbH & Co. KG, Alexanderstraße 2, 89522 Heidenheim
Sebastian.Schmid@voith.com

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In order to reduce operating costs, railway vehicle operators need to find technical solutions to improve the efficiency of railway diesel multiple units on non-electrified railway routes. This can be achieved by hybridization of diesel multiple unit propulsion systems with electrical energy storage systems to enable brake energy recuperation. After highlighting the state of the art of hybrid railway vehicles and electrical energy storage systems, a simulation model of a generic diesel multiple unit in a 3-car formation is developed and equipped with three types of hybrid power transmissions. Simulations on realistic service profiles with different driving strategies show the potential for fuel consumption reduction for the different transmission types. On a suburban service profile a 3-car diesel multiple unit is able to achieve simulated fuel savings of up to 24.1 % and up to 18.9 % on a regional service profile.

Keywords: *1D multi-domain simulation, hybrid railway vehicles, diesel multiple unit, electrical energy storage systems, driving strategy, energy management*

1. Introduction

The share of electrified versus non-electrified railway lines remained fairly constant in the years 2000 to 2010 [1], which shows that diesel-driven railway vehicles will continue to play an important role for passenger transport and constantly need to be improved in terms of fuel efficiency to reduce their emissions.

One of the reasons why railway vehicles receive increasing attention in terms of hybridization is due to the fact that their driving behaviour can be forecasted because of fixed routes with predetermined station stops and timetables. This allows for a precise prediction of fuel consumption with the help of simulation software [2-4].

Another aspect of railway vehicle hybridization comes from recovery of brake energy which in standard diesel-driven railway vehicles is dissipated as heat by hydrodynamic retarders, mechanical brakes or electric resistors. Different energy storage technologies have emerged in the past for brake energy recovery purposes in the transport sector [5], but literature shows that three technologies are especially suited for on-board energy storage in railway vehicles: double-layer capacitor, flywheel and li-ion battery on-board energy storage systems [6-10].

Based on these three on-board electrical energy storage technologies, several examples of hybrid diesel multiple units (DMUs) being tested or already in service have been developed in the past years [11-19]. The high potential of railway vehicle hybridization especially for non-electrified railway systems are highlighted in a number of research projects [20-26].

Two different types of DMU propulsion systems, namely diesel-hydromechanic and diesel-electric are considered here, which are common types of railway vehicles used for passenger transportation.

The structure of this paper is as follows: After an elaboration of the state of the art of hybrid propulsion systems for DMUs, a literature review on electrical energy storage technologies suitable for an usage in railway vehicles is conducted. Based on a realistic use case of a DMU in a 3-car formation, the potentials in terms of fuel reduction are analysed for different combinations of power transmissions and electrical energy storage systems. The corresponding simulation results are discussed and the paper concludes with a recommendation for further research in terms of use of electrical energy storage systems for railway vehicles.

2. Hybrid diesel multiple units with electrical energy storage systems: state of the art

The following sub-sections highlight the most important hybrid railway vehicle prototypes and research projects for different types of DMU propulsion systems, namely diesel-hydromechanic (DHM) and diesel-electric (DE). The literature review focuses on railway vehicles used for passenger transportation. Freight and shunter locomotives are not considered since they represent a different use case. Light railway vehicles (e.g. trams) running under catenaries that do not make use of an on-vehicle diesel engine as prime mover are per definition not hybrid vehicles [27] and will not be considered in this work.

2.1. Hybrid diesel-hydromechanic railway vehicles

In the automotive industry a growing number of vehicles already make usage of a hybrid hydromechanic transmission, such as the ZF hybrid 8HP transmission [28]. In the rail sector a similar approach has so far only been addressed by MTU. In 2008 MTU presented the concept of a parallel hybrid powerpack for railway vehicles. It consists of a 275 kW diesel engine, a crankshaft starter generator (CSG) and a ZF Ecomat 5-speed automatic hydromechanic gearbox. During braking the CSG converts kinetic energy of the railway vehicle into electrical power and temporarily stores it in a lithium-ion battery module. According to simulation results the fuel consumption for a typical regional speed profile can be reduced by 16 % with this system [14]. During trial runs a Class 642 equipped with two hybrid MTU powerpacks was able to achieve a 15% reduction in fuel consumption [15].

2.2. Hybrid diesel-electric railway vehicles

In 2003 the East Japan Railway Company (JR East) developed a test platform for different innovative propulsion systems in collaboration with Hitachi Ltd. The vehicle called New Energy (NE) train has been equipped with a series hybrid system based on a diesel engine as prime mover in combination with a lithium ion battery as energy storage. Several alternatives have been considered when choosing the most suitable type of energy storage technology (double-layer capacitors, lead acid battery, NiMH battery or Li-Ion battery). The decision was made in favour of a Li-Ion battery with an energy content of 10 kWh since it offers the best compromise of energy and power density [16].

Based on the results achieved with the NE train, JR East and Hitachi Ltd. decided to build three further series hybrid diesel-electric multiple-units (DEMU) called Kiha E200 Hybrid. The vehicle has a diesel-electric propulsion system with a Li-Ion battery connected to the DC link as secondary energy source. In addition to the battery an auxiliary power supply module is connected to the DC link. This allows for an emission free operation during standstill of the vehicle with shut off diesel engine. The following results were achieved when comparing the Kiha E200 series hybrid vehicle to a non-hybrid DEMU on the same route [17].

- Fuel saving of 10 % on the Koumi-line
- 60 % less exhaust emission by using a Common Rail diesel engine
- 30 dB noise reduction by using a pure electric mode up to a speed of 25 km/h

In 2007, Hitachis' hybrid propulsion system using lithium-ion batteries was installed in a British Class 43 railcar to allow realistic trials of the prototype technology. The trials demonstrated fuel savings on the single railcar ranging from 12 % on long runs up to 20 % on duties with frequent braking [18].

An Alstom Coradia LIREX$^{®}$ test carrier DEMU was equipped with a flywheel energy recuperation system in the year 2001 [19]. The carbon fibre and epoxy resin flywheel had a diameter of 700 mm and a maximum speed of 25.000 rpm. The DEMU test carrier was equipped with two flywheel systems but literature is not providing any measured figures about the achieved improvements in fuel efficiency with the flywheel energy storage system. Simulation results have shown that the energy consumption on a 90 km long track in Germany would reduce from 295 kWh to 264 kWh [20]. That's a simulated energy reduction of 10.5 %.

2.3. European railway vehicle hybridization projects

In 2002, one of the first EU projects dealing with hybrid propulsion systems for railway vehicles was ULEV-TAP 2 co-funded by the European Commission, which focused on series electric hybrid concepts for light rail applications [21]. The main objective of the project was to research and develop the central hardware required for a series electric hybrid drive based on a flywheel technology energy storage system. The result of the simulations showed that the developed control strategy and the development of the hybrid power train concept are highly efficient. The fuel consumption was significantly reduced by 42% in the particular case of Karlsruhe, Germany.

A further EU project which was settled in the area of railway vehicle optimization was CleanER-D. Sub-project 7 of CleanER-D was dealing with the simulation of hybrid systems for railway vehicles. Different generic vehicles and duty cycles were defined in order to compare energy storage technologies against each other. Five different energy storage technologies were considered in the study: double-layer capacitor, hydrostatic accumulator, flywheel, lithium-ion battery and a combination of lithium-ion battery and double-layer capacitor. The simulated hybrid vehicles achieved fuel reductions in the range of 10.9 % up to 26.6 % depending on system architecture, energy storage system and duty cycle [24].

The UK Department of Transport (DfT) study DfTRG/0078/2007 investigated the benefits of a hybrid high-speed train (HST) on UK routes and gave future design considerations based on simulation results. The study was divided into two phases. In phase one a British Rail Class 220 DEMU was modelled in MATLAB/Simulink©. Two high-speed routes in England have been simulated with the vehicle model. One of them was on the Great Western Railway (GWR) from London Paddington to Bristol Temple Meads and the second route was based on the East Coast Mainline (ECML) and went from Newcastle to London Kings Cross. The simulated fuel consumption on the two routes was 1.32 litres per 100 seat kms on the GWR route and 1.14 litres per 100 seat kms on the ECML route [25]. In phase two of the study, the diesel-electric propulsion system was equipped with a nickel metal hydride (NiMH) chemistry battery pack having an energy content of 500 kWh [25]. With the final battery state of charge (SOC) being the same as the initial SOC, an improvement in cumulative fuel consumption of 16 % for the GWR drive cycle was achieved. The reduction for the ECML route was in the order of 8 %. The scope of the DfT study was extended in a second step and the existing model was adapted to simulate a two coach Class 150 and a two coach Class

144 DMU [26] operating on routes around the Welsh Valleys and the Birmingham Area. Similar to the preceding study a NiMH battery pack was chosen and simulation results for both routes showed overall fuel consumption improvements of up to 25 %.

2.4. Overview of fuel saving potentials

As described in the preceding sections, vehicle prototypes of different rail companies, as well as European and governmental projects have been dealing with railway vehicle hybridization. Most of the results promise double-digit improvements in terms of fuel consumption. Table 5 shows a compilation of the analysed literature and the stated figures on fuel savings. Only electric energy storage systems are regarded in the table, since these types of technologies will be discussed and evaluated in the present paper.

Table 1. Overview of potential fuel savings of hybrid diesel multiple units as described in [14-21, 24-26].

Vehicle	Propulsion System	ESS	Fuel Savings	Type of Research	Reference
Siemens Desiro Classic Hybrid	DHM	Li-Ion battery	16 %	Simulation study	[14]
Siemens Desiro Classic Hybrid	DHM	Li-Ion battery	15 %	Field test	[15]
Hitachi New Energy Train	DE	Li-Ion battery	n/a	Prototype	[16]
Hitachi Kiha E200	DE	Li-Ion battery	10 %	Field test	[17]
British Class 43	DE	Li-Ion battery	12 – 20 %	Field test	[18]
Alstom Coradia LIREX®	DE	Flywheel	10.5 %	Simulation study	[19, 20]
Siemens Avanto Hybrid	DE	Flywheel	48 %	Simulation study	[21]
CleanER-D suburban vehicle	DHM	Flywheel	12 %	Simulation study	[24]
CleanER-D suburban vehicle	DE	Double-Layer Capacitor	10.4 %	Simulation study	[24]
CleanER-D regional vehicle (360 kW diesel engine)	DHM	Li-Ion battery	16.5 %	Simulation study	[24]

CleanER-D regional vehicle (360 kW diesel engine)	DE	Li-Ion battery	24.2 %	Simulation study	[24]
CleanER-D regional vehicle (560 kW diesel engine)	DE	Flywheel	18.7 %	Simulation study	[24]
CleanER-D regional vehicle (560 kW diesel engine)	DE	Double-Layer Capacitor	16.2 %	Simulation study	[24]
CleanER-D regional vehicle (560 kW diesel engine)	DE	Double-Layer Capacitor /Li-Ion battery	26.6 %	Simulation study	[24]
Class 220 Hybrid	DE	NiMH Battery	8-16 %	Simulation study	[25]
Class 150 Hybrid	DE	NiMH Battery	18-26 %	Simulation study	[26]
Class 144 Hybrid	DE	NiMH Battery	17-26 %	Simulation study	[26]

2.5. Literature review on electrical energy storage technologies

2.5.1. Double-layer capacitors

Double-layer capacitors (DLCs) are gaining importance in terms of using them as energy storage in hybrid railway vehicles as highlighted in [11-13]. Because of their low internal resistance, higher power densities can be realized compared to Li-Ion batteries. For this reason, as well as their cyclic lifetime of up to 1 million cycles as shown in [29], they are used for short-time storage of brake energy in railway vehicles. One example of an existing solution is the Sitras® mobile energy storage system by Siemens [30]. One manufacturer of DLCs for “Heavy Duty” applications (e.g. buses and train vehicles) is Maxwell Technologies. A specially designed DLC module BMOD0063 with an usable energy content of 137 Wh is commercially available [29]. This DLC module will be used for the regarded hybrid DMU since it is commercially available and has already been used for hybrid heavy duty applications [31].

2.5.2. Flywheel technology

In a flywheel energy is stored by accelerating a rotor to a high rotational speed of up to 36,000 rpm [32]. By decelerating the rotor with the help of an electric generator, the rotational kinetic energy can be transformed to electric energy. In order to increase the efficiency of flywheel energy storage systems, current developments try to reduce friction losses as far as possible by evacuating the chamber in which the rotor is spinning. Another means is using almost frictionless magnetic bearings which require a sophisticated control system.

In 2011 a US Department of Energy study assessed high power flywheel energy storage systems for hybrid vehicles [33]. Different concepts of flywheel ESS where evaluated in terms of important factors for an use in light and heavy duty hybrid vehicles. The study divided the examined flywheel ESS in systems which are especially suited for light duty applications (e.g. cars) and systems for heavy duty applications (e.g. trucks, trams and trains). For heavy duty applications such as a hybrid DMU, a minimum delivered energy of 2 kWh and a power output above 150 kW was suggested. The two potential suppliers who fell into this category are the centre for concepts in mechatronics (CCM) and the L-3 Communications Magnet-Motor GmbH (L-3 MM). The CCM offers flywheel ESS in four different configurations [34], two of which (RxV-I and RxV-II) are of interest for railway vehicles in terms of power output and storable energy. Table 6 shows a comparison of the CCM RxV-I, CCM RxV-II and the flywheel offered by L-3 MM. Empty cells indicate that no values are given in literature.

The RxV-II with a maximum power output of 300 kW and an energy content of 4 kWh has already been used in a LRV project [21]. The weight of the flywheel ESS including power electronics and cooling system was 1100 kg, which results in an overall system energy density of 3.6 Wh/kg and power density of 272 W/kg, which is in good accordance with the values achieved with the Alstom Coradia LIREX® test carrier DEMU (5 Wh/kg and 269 W/kg) [19].

Table 2. Technical data of CCM and L-3 MM flywheel ESS [33, 34].

	CCM Flywheel RxV-I	CCM Flywheel RxV-II	L-3 MM Flywheel
Energy Content	2 kWh	4 kWh	2 kWh
Type of Motor/Generator	Synchronous machine, permanent excitation	Synchronous machine, permanent excitation	Synchronous machine, permanent excitation
Maximum Power	150 kW (50 sec max)	300 kW (50 sec max)	300 kW
Continuous Power	no information available	200 kW	100 kW
Round-trip efficiency	no information available	90 %	87 %
Voltage	no information available	420 – 800 VDC	Up to 750 VDC
Flywheel ESS Mass	225 kg	375 kg	400 kg
Specific Energy	8.9 Wh/kg	10.6 Wh/kg	5 Wh/kg
Specific Power	666 W/kg	800 W/kg	750 W/kg

2.5.3. Lithium-Ion batteries

Due to the achievable power and energy densities, Lithium-Ion (Li-Ion) batteries are regarded as the key technology for current and upcoming hybrid and electric vehicles. Various manufacturers offer Li-Ion batteries based on different cell chemistries, either suited for high power or high energy applications. A high power output is ideal for applications where electric traction is required in heavy duty transportation (e.g. hybrid railway vehicles), while a high energy density ensures enough range for battery electric vehicles.

For the simulative analysis of hybrid DMUs as described in this paper, SCiB™ li-ion cells of Japanese manufacturer Toshiba based on lithium nickel manganese cobalt oxide (NMC) chemistry with a lithium titanium oxide (LTO) anode and 20 Ah nominal capacity will be used. They offer a good compromise between energy density, power density and achievable lifetime according to [35, 36].

2.6. Definition of hybrid DMU case studies for simulative analyses

In order to simulate potential fuel savings by hybridizing DMUs with electrical ESS, a generic 3-car DMU is defined in this paper. The vehicle is equipped with two or three railpacks (cf. Figure 1) depending on the installed diesel engine power.

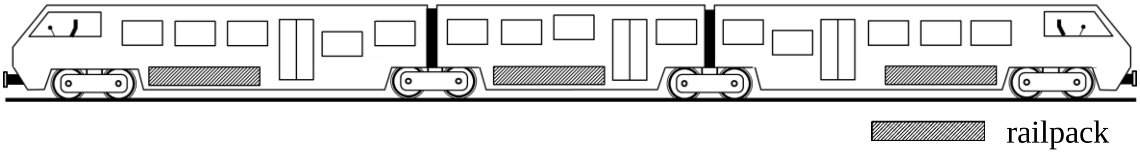


Figure 1. Schematic drawing of three-car diesel multiple unit.

Table 3 summarizes the main vehicle parameters used for the simulation studies described in this paper. The parameters correspond with DMUs commonly used for passenger transportation on non-electrified railway routes and the overall weight of the vehicle includes an average load factor with all seats occupied by passengers.

Table 3. Vehicle parameters of standard DMU-3 without hybrid system components.

Parameter	Unit	Value	Description
m_{train}	(t)	125.0	Overall mass of rail vehicle
η_{mech}	(%)	97	Efficiency of final drive
D_{w}	(m)	0.85	Wheel diameter
v_{Max}	(km/h)	160	Top speed of vehicle
a_{max}	(m/s^2)	1.2	Maximum permitted acceleration
a_{min}	(m/s^2)	0.6	Average deceleration during braking phases
A	(m^2)	10.3	Vehicle frontal area
c_{w}	(-)	0.8	Vehicle drag coefficient
m_{adh}	(t)	57.0	Adhesion mass
f_{adh}	(-)	0.25	Adhesion factor wheel/rail contact

2.7. Standard and hybrid powertrain configurations

Three different types of power transmissions to transfer power to the wheels are simulated in the present paper. Two of them are hydromechanic and one is diesel-electric. In Table 4 the main parameters used for the simulation of the power transmissions are summarized.

Table 4. Parameters and weight of power transmission and hybrid components.

Vehicle	3-car DMU	3-car DMU	3-car DMU
Power transmission	Diesel-hydromechanic (4-speed transmission)	Diesel-hydromechanic (6-speed automatic gearbox)	Diesel-electric
Diesel engine power output	390 kW	588 kW	588 kW
Number of railpacks	3	2	2
Maximum permissible power input to transmission	up to 320 kW	up to 588 kW	588 kW (mechanical input power to generator)
Maximum permissible torque input to transmission	up to 1,900 Nm	up to 3,350 Nm	3,350 Nm (mechanical input torque to generator)
Mean mechanical auxiliaries power demand during traction	11 kW	16 kW	16 kW
Mean mechanical auxiliaries power demand during idling	3 kW	5 kW	5 kW
Mean mechanical auxiliaries power demand during braking	15 kW	30 kW	15 kW
Mean mechanical auxiliaries power demand during coasting	3 kW	5 kW	5 kW
Type of E-Motor	AC induction motor	Synchronous machine, permanent excitation	Two AC induction motors per railpack
E-Motor peak power output	230 kW	230 kW	2 x 250kW
E-Motor maximum speed	2,640 rpm	2,000 rpm	6,000 rpm

E-Motor maximum continuous torque output	2,915 Nm [42]	1,100 Nm [42]	2 x 5,000 Nm
E-Motor mean efficiency	85 %	90 %	85 %

As described by Paukert in [23] a maximum permissible weight for the hybrid components per railpack is defined. The authors of this paper have chosen an additional weight of 1000 kg per railpack for the sum of the following hybrid components: E-motor, energy storage cooling system (ESC), propulsion control system (PCS) and energy storage system (ESS). This results in a permissible weight for the ESS as highlighted in Table 5.

Table 5. Weight of hybrid components and restrictions for energy storage system.

Description	Unit	Hybrid 3-coach DMU with DHM 4-speed transmission	Hybrid 3-coach DMU with DHM 6-speed transmission	Hybrid 3-coach DMU with diesel-electric propulsion system
E-Motor (EM)	(kg)	400 [42]	150 [42]	-
Energy storage cooling system (ESC)	(kg)	150 [44]	150 [44]	150 [44]
Propulsion control system (PCS)	(kg)	100 [44]	100 [44]	100 [44]
Sum	(kg)	650	400	250
Restriction for hybrid components	(kg)	1000 [23]	1000 [23]	1000 [23]
Permissible weight for energy storage system (ESS)	(kg)	350	600	750

2.8. Track characteristics

Two generic track profiles namely ‘suburban service’ and ‘regional service’ are used for the studies as defined in [43]. The first one is based on a suburban service profile with an overall length of 40 km and 12 station stops and the second one on a regional service profile with an overall length of 70 km and 15 station stops. Both profiles are flat with no gradients.

Table 6 shows the journey and station dwell times for the suburban and regional service profiles. To simulate a realistic behaviour of a railway vehicle, first an outward journey is undertaken in the simulation which is then followed by a 10 minute driver break. After this break the return journey is simulated until the vehicle arrives again at the start position. During the break the engine is kept idling for the studies conducted in this paper, which is a common procedure for railway vehicles in order to provide energy for the auxiliaries (e.g. air condition and brake system).

Table 6. Journey and station dwell times for the suburban and regional service profile [22, 43].

		Length		Journey time		Station dwell time	
Start	Stop	Suburban	Regional	Suburban	Regional	Suburban	Regional
Station A	Station B	2 km	2 km	140.0 sec	142.0 sec	60 sec	60 sec
Station B	Station C	3 km	3 km	154.0 sec	157.0 sec	60 sec	60 sec
Station C	Station D	2 km	5 km	117.0 sec	221.0 sec	60 sec	60 sec
Station D	Station E	3 km	8 km	153.0 sec	319.0 sec	60 sec	120 sec
Station E	Station F	5 km	3 km	218.0 sec	155.0 sec	60 sec	60 sec
Station F	Station G	6 km	5 km	245.0 sec	217.0 sec	60 sec	60 sec
Station G	Station H	5 km	9 km	214.0 sec	332.0 sec	60 sec	120 sec
Station H	Station I	3 km	3 km	153.0 sec	155.0 sec	60 sec	60 sec
Station I	Station J	2 km	6 km	117.0 sec	245.0 sec	60 sec	60 sec
Station J	Station K	7 km	10 km	319.0 sec	348.0 sec	60 sec	120 sec
Station K	Station L	2 km	6 km	141.0 sec	244.0 sec	600 sec	60 sec
Station L	Station M		4 km		187.0 sec		60 sec
Station M	Station N		3 km		156.0 sec		60 sec
Station N	Station O		3 km		172.0 sec		600 sec

2.9. 1D simulation models of hybrid diesel-driven railway vehicles

2.9.1. Simulation approach and general outline

A generic outline of a hybrid propulsion system for a railway vehicle is shown in Figure 2. Using a forward simulation approach the output of a virtual driver is used to control the railpack, consisting of the internal combustion engine (ICE), power transmission, auxiliary systems and the energy storage system. An engine control is implemented to ensure that the ICE and power transmission operate within their boundaries (e.g. permissible rotational speed, torque and power limits). Energy management functions regulate the power distribution between the energy storage system, auxiliary systems, power transmission and the internal combustion engine. A driving strategy state machine is implemented to control the different driving phases (e.g. acceleration and braking) and to guarantee a realistic behaviour of the simulated railway vehicle.

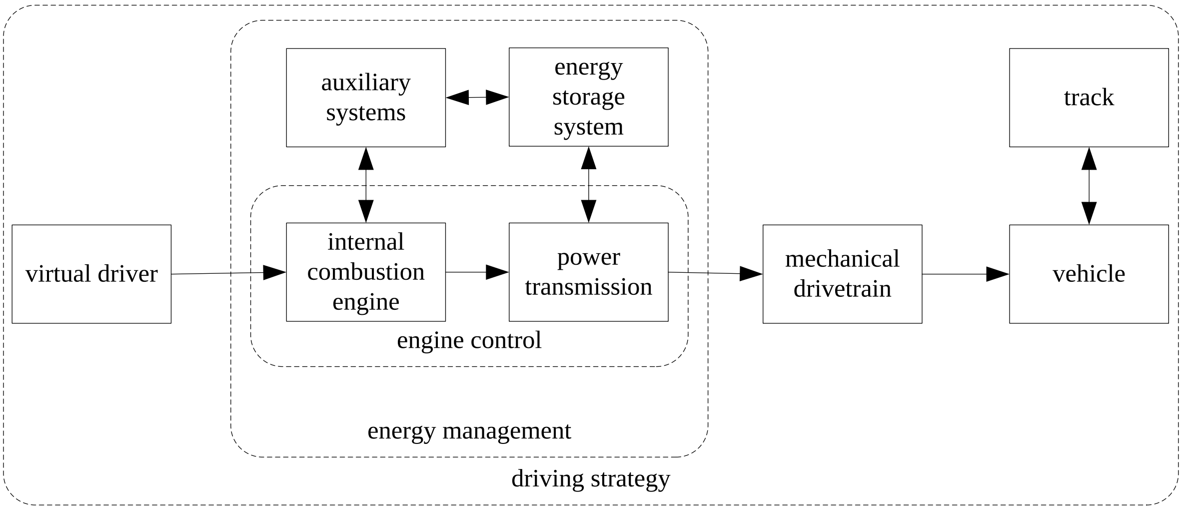


Figure 2. General outline of a hybrid propulsion system for a railway vehicle including necessary control systems.

The function of engine control is to limit the torque and power output of the ICE according to the maximum permissible input torque and power of the used power transmission. In terms of a hydromechanic transmission, another important aspect is the maximum transferable tractive force via the wheel/rail contact limited by the adhesion factor. Engine control also ensures that the current tractive effort stays below this limit.

The following energy management function is used to control the power distribution between ICE and energy storage system (ESS) during different driving conditions: In boost mode the ESS provides additional power to the power transmission during acceleration phases. Hence, the vehicle achieves a better performance compared to a standard vehicle with no ESS. During braking phases kinetic energy of the vehicle is fed back to the ESS. A parameter ‘boost’ is introduced which defines the ratio between E-motor and diesel engine power output during traction phases.

2.9.2. Driving strategy

A driving condition state machine controls the overall vehicle behaviour to ensure that the vehicle doesn’t violate any speed limits on the track and that all stations are reached as specified by the timetable. A typical speed profile of a DMU between two station stops can generally be divided into four phases: acceleration phase, speed holding phase, coasting phase and braking phase as described in [37, 38].

- During acceleration phases all of the currently available diesel engine power is used to accelerate the railway vehicle. In case of a hybrid DMU additional power is supplied by the ESS to the power transmission. The diesel engine power is limited in terms of permissible input power or torque to the power transmission and the maximum transferable traction force via the wheel/rail contact.
- The transition from acceleration to speed holding usually occurs when the current speed limit on the track is reached. During this phase two different driving styles can be applied. The virtual driver either holds the speed constant

at the given speed limit or a so called ‘saw tooth’ driving style is used, which is characterized by a regular switch from traction over to coasting phases and vice versa.

- The speed holding phase, either constant or with a saw tooth driving style, is followed by a final coasting phase before the vehicle brakes into the station stop. Coasting phases are a very effective tool used by experienced railway vehicle drivers to save traction energy and they refer to the time when no traction force is applied to the wheels.
- Before the DMU comes to a stop in the station, a braking phase with constant deceleration of 0.6 m/s^2 is used and in case of a hybrid DMU this kinetic energy can be used to charge the ESS.

In the present paper a new approach is introduced to investigate on different driving strategies and to find the most favourable for standard vehicles and for hybrid vehicles in terms of fuel consumption. An automated train control was implemented in the simulation models on the basis of research conducted by Milroy and Forsythe [39] in order to arrive at the next station within a variation of ± 1 % of the given journey time for the current section. The user of the simulation models has the ability to choose if a saw tooth driving style shall be applied and if the virtual driver shall make use of coasting phases. The idea behind this variability is to investigate if a hybrid DMU requires different driving strategies compared to a conventional DMU. Figure 3 shows the four types of driving strategies which are feasible with the programmed automated train control for an exemplary journey.

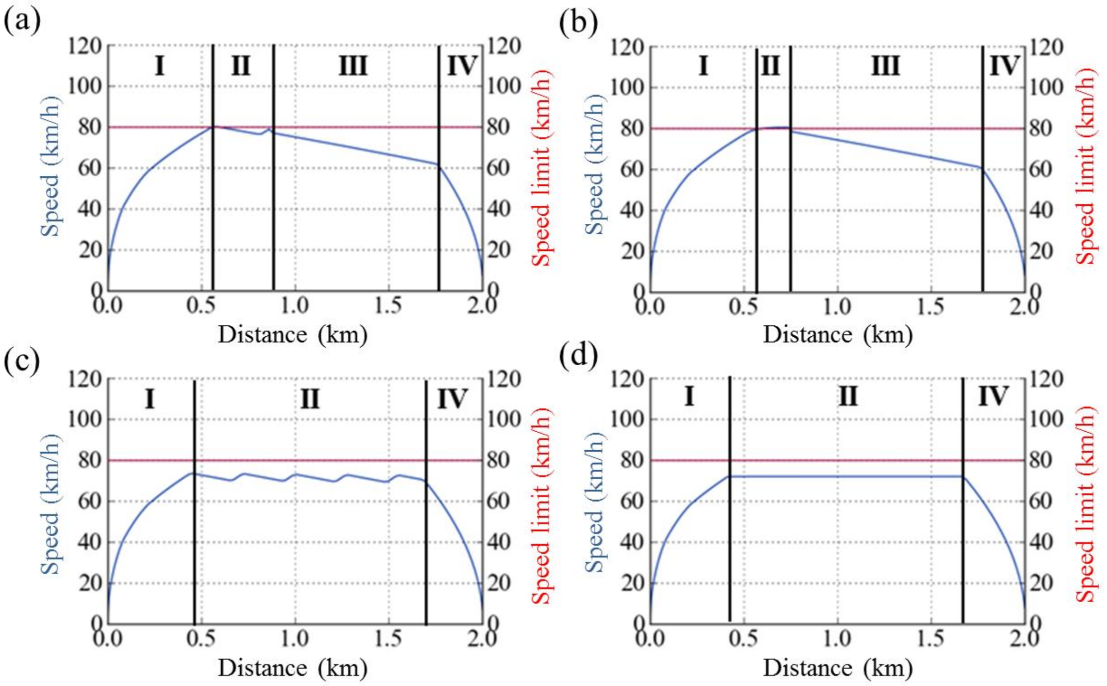


Figure 3. (a) Acceleration (I), saw tooth speed holding (II), coasting (III), braking phase (IV) - (b) Acceleration (I), constant speed holding (II), coasting (III), braking phase (IV) - (c) Acceleration (I), saw tooth speed holding (II), braking phase (IV) - (d) Acceleration (I), constant speed holding (II), braking phase (IV).

2.9.3. Modelling approach for power transmission subsystems

Two types of hydromechanic transmissions are regarded in this work:

(1) A 4-speed automatic transmission [40] based on a power split principle between a hydrodynamic converter and planetary gear sets. In the first gear the input power is divided steplessly between a hydrodynamic converter and the mechanical part of the transmission. In gears two to four the traction power is transmitted mechanically.

(2) A six-speed automatic transmission [41] using a combination of starting converter for low speeds with three planetary gear sets to allow for six gear ratios at higher speeds.

For the 4-speed transmission, hybridization is achieved by combining a summation gearbox with an electric motor at the secondary side of the hydromechanic gearbox as shown in the bottom half of Figure 4. For the parameterization of the electric motor, the same values as for the commercially available traction motor HDS 300 by BAE Systems are used. The peak power output is 230 kW and the maximum continuous torque 2,915 Nm. The operating range is from 0 to 2,640 rpm [42].

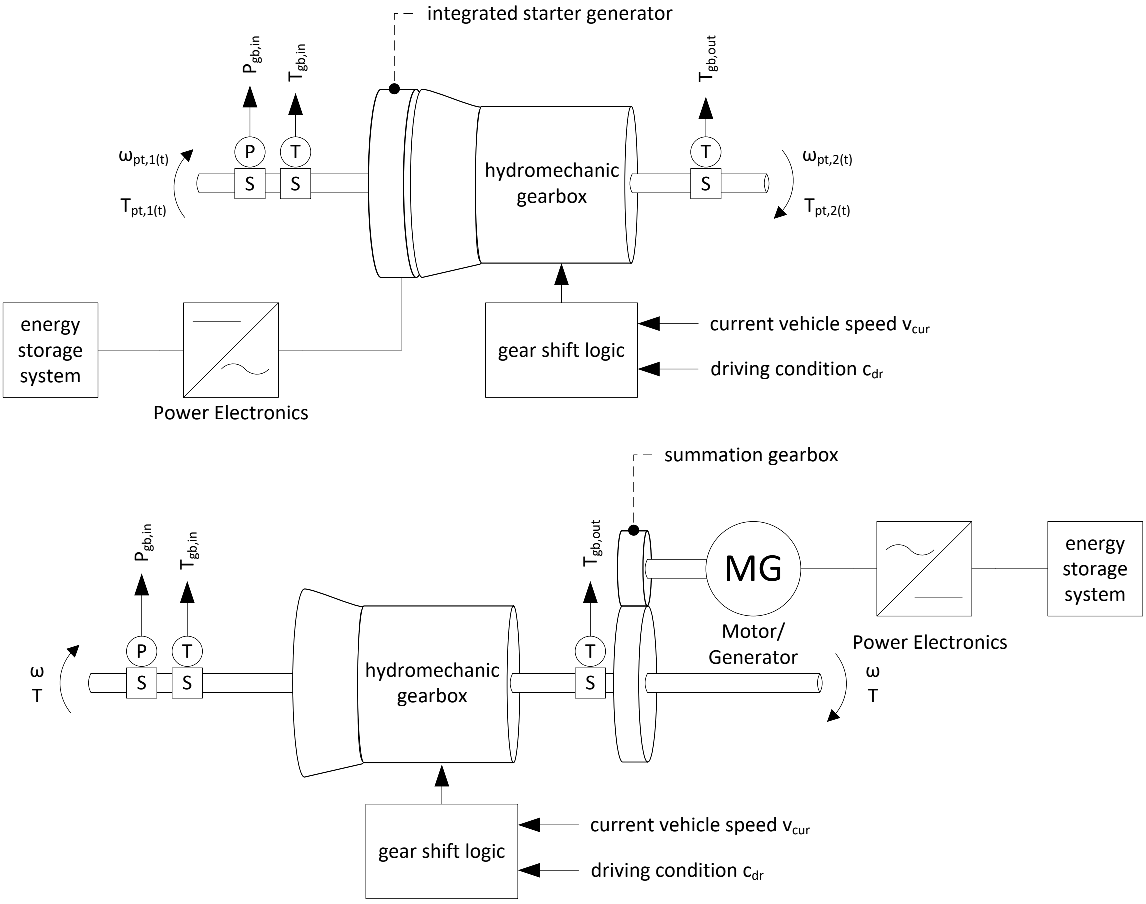


Figure 4. General Outline of hybridized hydromechanic gearboxes.

The hybrid version of the six-gear transmission uses an integrated starter generator (ISG) at the primary side to allow for electric boosting and energy recuperation during braking phases. The top half of Figure 4 shows the general outline. The ISG is parameterized according to a product offered by BAE Systems with the

HDS 300 traction generator. It has a maximum power output of 230 kW, an operating speed range of 0 – 2,000 rpm and a maximum continuous torque of 1,100 Nm [42].

A diesel-electric propulsion system consists of a diesel engine which is connected to a generator. This generator feeds energy to a DC link via a rectifier. To drive the vehicle, one or several controllable electric motors are connected to the DC link. The general outline of the simulation model of electric power transmission is shown in Figure 5. For simplification purposes, only one electric motor is used in the simulation and the overall power and torque is set accordingly. One main advantage of electric transmissions in terms of hybridization is the reduced complexity of ESS integration since a DC link is already available and hence only a DC/DC controller is necessary to connect the ESS with the propulsion system (cf. Figure 5). A further benefit is the possibility to replace the generator with an alternative power generation source, e.g. a fuel cell as shown by Washing and Pulugurtha in [4].

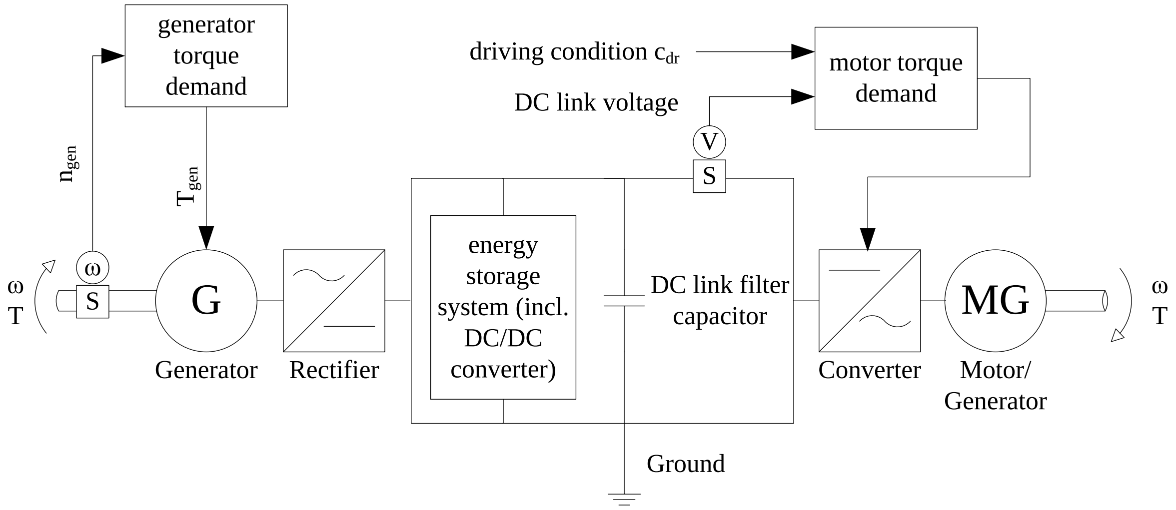


Figure 5. General outline of an electric power transmission with an ESS integrated in the DC link.

2.9.4. *Modelling approach for electrical energy storage subsystems*

Three different energy storage technologies as described in the preceding sections are modelled with the help of the multi-domain LMS Imagine.Lab Amesim simulation software. The additional weight of the hybrid components is added to the weight of the railway vehicle for the simulation studies.

Double-layer capacitor simulation model: The DLC storage simulation model is based on the equivalent circuit shown in Figure 6. It is comprised of the nominal capacitance of one DLC cell in parallel with a leakage resistance to account for leakage losses (cf. Equation 1).

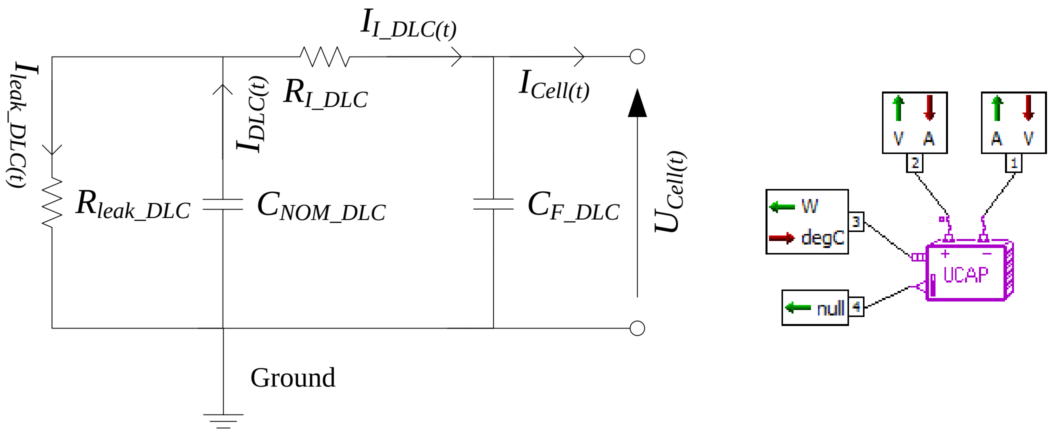


Figure 6. Equivalent circuit diagram of double-layer capacitor and Amesim simulation component.

A resistor at the input terminal represents the internal resistance of one DLC cell. A filtering capacitance is used to break algebraic loops which would otherwise occur in the simulation (cf. Equation 2).

$$\frac{dU_{DLC(t)}}{dt} = \frac{dU_{Leak_{DLC(t)}}}{dt} + \frac{1}{C_{NOM\_DLC}}\left(I_{I\_DLC(t)} - I_{Leak(t)}\right) \quad (1)$$

$$\frac{dU_{Cell(t)}}{dt} = \frac{1}{C_{F\_DLC}}\left(I_{Cell(t)} - I_{I\_DLC(t)}\right) \quad (2)$$

The DLC component can simulate a whole module, therefore the number of cells in series and parallel have to be parameterized. Table 7 shows all the necessary global parameters for the DLC component.

Table 7. Double-Layer capacitor energy storage system configurations for DMU use cases.

	Hybrid 3-coach DMU with DHM 4-speed transmission	Hybrid 3-coach DMU with DHM 6-speed transmission	Hybrid 3-coach DMU with diesel-electric propulsion system
Number of parallel branches	1	2	2
Number of cells in series	6	5	6
Rated capacitance of one cell	63 F	63 F	63 F
Cell maximum continuous charge/discharge current	240 / 240 A	240 / 240 A	240 / 240 A
Cell minimum/maximum voltage	12.5 / 125.0 V	12.5 / 125.0 V	12.5 / 125.0 V
Energy content	0.8 kWh	1.4 kWh	1.6 kWh
Efficiency of converter	98 %	98 %	98 %
Specific energy of ESS	2.3 Wh/kg	2.3 Wh/kg	2.3 Wh/kg
Weight of ESS	357 kg	594 kg	713 kg

Flywheel simulation model: In Figure 7 the analogical model and the LMS Imagine.Lab Amesim simulation model for the electric flywheel energy storage system is depicted.

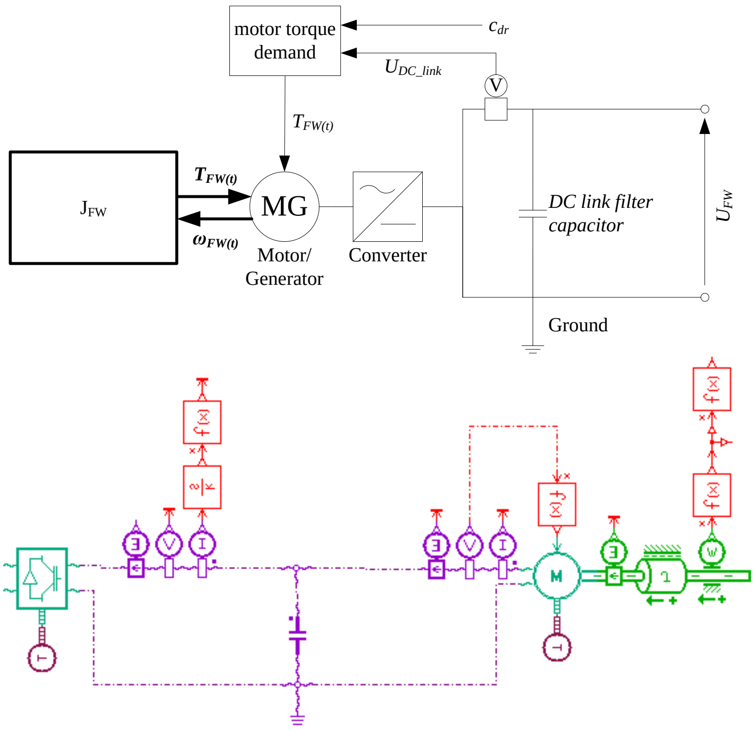


Figure 7. Equivalent circuit diagram of flywheel energy storage system and Amesim simulation component.

The rotor of the flywheel is modelled as a rotary mass with an inertia *I* calculated by the user given parameters *EMax_Fw* describing the energy content of the flywheel and the maximum rotary speed of the flywheel *nMax_EMotor_Fw* and minimum rotary speed *nMin_EMotor_Fw* with the following equation 3. A similar approach is used by Wu et al. in [3].

$$I = 2 \cdot 3600 \cdot \frac{EMax\_Fw}{(nMax\_EMotor\_Fw \cdot \frac{\pi}{30})^2 - (nMin\_EMotor\_Fw \cdot \frac{\pi}{30})^2} \tag{3}$$

The flywheel is connected to an electric motor/generator to accelerate and decelerate the rotor. The electric motor/generator is connected to a DC link and its torque output is controlled by keeping the voltage of the DC link constant. A model of a converter is added to the DC link to account for converter losses which would occur in a real flywheel energy storage system. Table 8 shows all the parameters necessary to parameterize the flywheel ESS.

Table 8. Flywheel energy storage system configurations for DMU use cases.

	Hybrid 3-coach DMU with DHM 4-speed transmission	Hybrid 3-coach DMU with DHM 6-speed transmission	Hybrid 3-coach DMU with diesel-electric propulsion system
Number of parallel flywheels	1	1	2
Maximum power output of flywheel E-Motor / Generator	300 kW (50 sec max)	300 kW (50 sec max)	300 kW (50 sec max)
Efficiency of flywheel E-Motor	95 %	95 %	95 %
Maximum speed of flywheel	22,000 rpm	22,000 rpm	22,000 rpm
Energy content of Flywheel	4 kWh	4 kWh	4 kWh
Specific energy of ESS	10.6 Wh/kg	10.6 Wh/kg	10.6 Wh/kg
Efficiency of converter	98 %	98 %	98 %
Weight of ESS	375	375	750

Lithium-Ion battery simulation model: LMS Imagine.Lab Amesim offers a special library for the simulation of electrical energy storage systems. One submodel of the library is designed for the simulation of a lithium-ion battery. It is based on the equivalent electrical circuit of a battery as shown in Figure 8, which consist of a constant voltage source connected to a resistor (cf. equation 4). The voltage source is equal to the open circuit voltage of the battery and the resistor accounts for the internal losses during current flow. The battery model allows simulating a complete battery pack, therefore the number of cells in series and in parallel have to be given by the user.

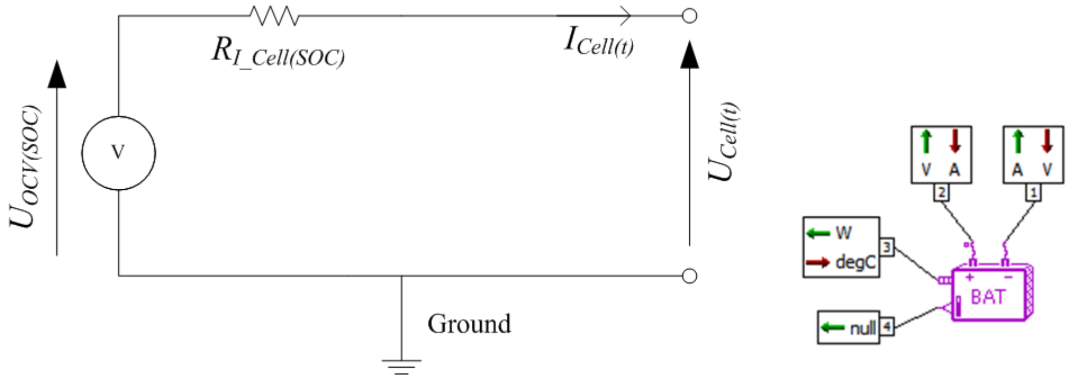


Figure 8. Equivalent circuit diagram of Li-Ion battery and Amesim battery simulation component.

$$\mathbf{U_{Cell(t)} = U_{OCV(SOC)} - I_{Cell(t)} \cdot R_{I\_Cell(SOC)}} \qquad (4)$$

Next to the terminal voltages, the battery model has two additional output signals for the lost power and the battery SOC. The information about the current SOC in addition with the sensor signals for the voltage and the current at the output of the battery, are used to control the battery with the help of a battery safety control unit model as shown in Figure 9.

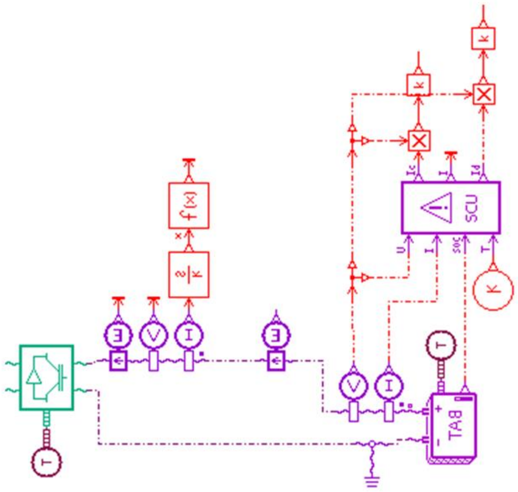


Figure 9. Model of the Li-Ion battery with safety control unit and converter.

This unit uses a range of parameters from the battery designer to control that the battery doesn't exceed specified current and voltage limits depending on time and battery temperature. The dependence on battery temperature will not be regarded in this work because detailed information about temperature dependent battery characteristics is hardly available. Table 9 shows all the parameters necessary for the battery model parameterization.

Table 9. Li-Ion energy storage system configurations for DMU use cases.

	Hybrid 3-coach DMU with DHM 4-speed transmission	Hybrid 3-coach DMU with DHM 6-speed transmission	Hybrid 3-coach DMU with diesel-electric propulsion system
Number of parallel branches	2	3	4
Number of cells in series	285	326	306
Capacity of one cell	20 Ah	20 Ah	20 Ah
Cell maximum continuous charge/discharge current	160 / 160 A	160 / 160 A	160 / 160 A
Cell maximum pulse charge/discharge current (max. 30 sec)	355 / 355 A	355 / 355 A	355 / 355 A
Cell nominal voltage	2.3 V	2.3 V	2.3 V
Cell minimum/maximum voltage	1.8 / 2.8 V	1.8 / 2.8 V	1.8 / 2.8 V
Energy content	26.2 kWh	45.0 kWh	56.3 kWh
Efficiency of converter	98 %	98 %	98 %
Specific energy of ESS	75 Wh/kg	75 Wh/kg	75 Wh/kg
Weight of ESS	350 kg	600 kg	751 kg

2.10. Discussion of simulation results

2.10.1. Suburban service profile

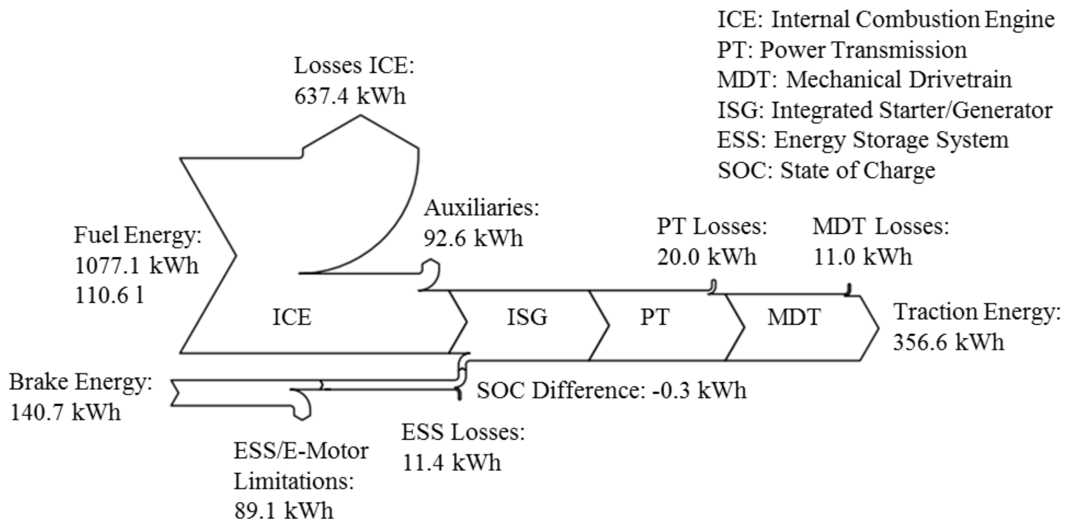
Table 10 shows the simulated fuel consumptions for the generic 3-car DMU on the 40 km long suburban service profile [43] with 10 % added contingency time between stations for unscheduled service disruptions or signal stops. A combination of diesel-electric transmission and battery ESS achieves the lowest fuel consumption of 103.6 litres of diesel fuel for the given route, which equals a saving of 21.6 %. The results shown in Table 10 represent the driving style with the lowest fuel consumption for each simulated combination of power transmission and ESS. It can be seen that in case of a 4-speed transmission based on a power-split principle driving strategy a) has to be favoured for the hybrid configurations. The same applies for the diesel-electric powertrain. The regarded six-speed automatic transmission with a flywheel ESS or battery ESS achieves the lowest fuel consumptions with driving strategy b), where no sawtooth driving style is applied. Only the DLC ESS requires driving strategy a) to minimize the fuel consumption.

Table 10. Simulated fuel consumptions and utilized driving strategy in brackets for the generic 3-car DMU on suburban service profile with 10 % added contingency time.

Vehicle	Generic3-car DMU		
Power transmission	Diesel-hydromechanic (4-speed automatic transmission)	Diesel-hydromechanic (6-speed automatic transmission)	Diesel-electric
Standard vehicle	145.8 ltr (c)	126.5 ltr (b)	132.2 ltr (b)
Hybrid with DLC ESS	123.3 ltr (a)	114.3 ltr (a)	122.2 ltr (a)
Hybrid with flywheel ESS	110.7 ltr (a)	111.2 ltr (b)	111.8ltr (a)
Hybrid with battery ESS	113.2 ltr (a)	110.6 ltr (b)	103.6 ltr (a)

In Figure 10 Sankey diagrams for the two hybrid configurations with the highest fuel savings, namely diesel-hydromechanic (6-speed) with battery ESS and diesel-electric with battery ESS, are depicted. The two electric motors of the diesel-electric powertrain with a combined power output of 500 kW per railpack allow for more brake energy being recovered compared to the diesel-hydromechanic powertrain with an ISG power of 230 kW. This leads to a lower fuel consumption on the route despite the fact that the automatic transmission has a higher efficiency since no energy needs to be converted via a DC link. The tank-to-wheel efficiency of the diesel-hydromechanic (6-speed) powertrain is 29.0 % for the standard powertrain and 33.1 % for the hybrid powertrain with battery ESS. Regarding the diesel-electric DMU-3, the tank-to-wheel efficiency is increased from 22.2 % to 28.3 %.

DMU-3 / suburban / diesel-hydromechanic (6-speed) / battery ESS / strategy b)



DMU-3 / suburban / diesel-electric / battery ESS / strategy a)

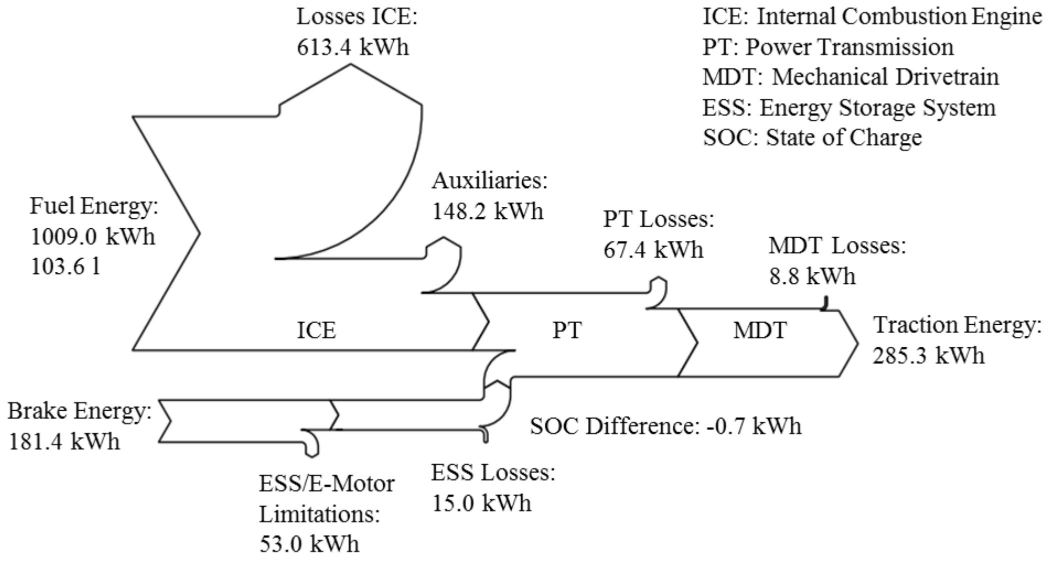


Figure 10. Sankey diagrams representing the simulated energy flow for the two hybrid propulsion systems with the lowest fuel consumption on the suburban service profile.

2.10.2. Regional service profile

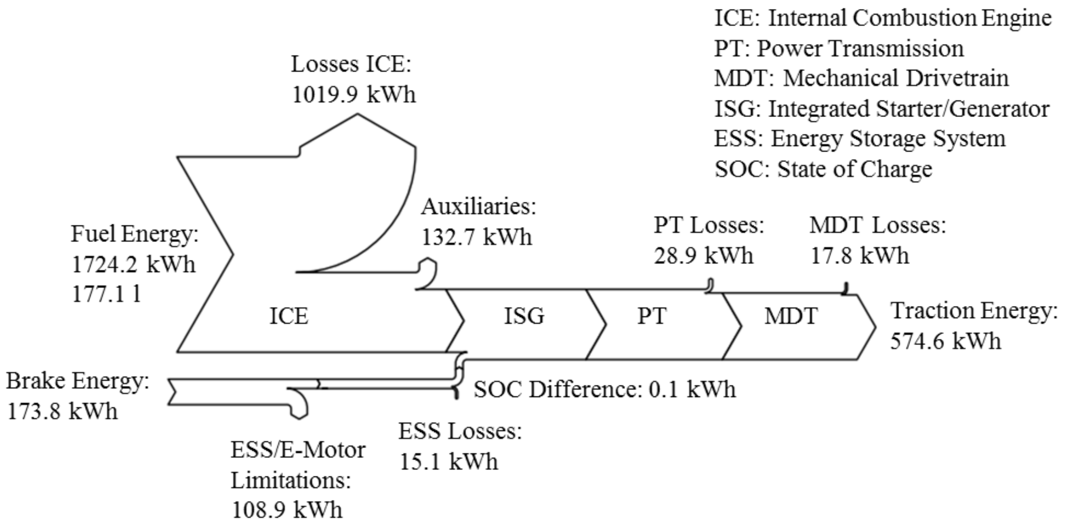
On the regional service profile [43] with a length of 70 km and 15 station stops, the following simulations results are achieved (see Table 11). The lowest overall fuel consumption of 170.9 litres of diesel fuel is achieved with a combination of diesel-electric powertrain with a battery ESS. The fuel saving for this hybrid configuration is 18.5 %. In general, the fuel savings are slightly lower due to the longer average station distance of 5.0 km compared to 3.6 km for the suburban service profile.

Table 11. Simulated fuel consumptions and utilized driving strategy in brackets for the generic 3-car DMU on regional service profile with 10 % added contingency time.

Vehicle	Generic3-car DMU		
Power transmission	Diesel-hydromechanic (4-speed automatic transmission)	Diesel-hydromechanic (6-speed automatic transmission)	Diesel-electric
Standard vehicle	218.5 ltr (a)	198.7 ltr (b)	209.7 ltr (a)
Hybrid with DLC ESS	193.1ltr (a)	182.6 ltr (b)	195.3 ltr (b)
Hybrid with flywheel ESS	177.3 ltr (a)	178.6 ltr (b)	184.4 ltr (b)
Hybrid with battery ESS	180.7 ltr (a)	177.1 ltr (b)	170.9 ltr (a)

Figure 11 shows Sankey diagrams for the two hybrid DMU-3 configurations diesel-hydromechanic (6-speed) with battery ESS and diesel-electric with battery ESS as depicted in the preceding section for the suburban service profile. The diesel-electric vehicle with battery ESS achieves better acceleration characteristics and therefore needs less traction energy, since it can make better use of coasting phases. Similar to the suburban service profile the benefit of the more powerful electric motor in the diesel-electric powertrain to allow for more brake energy recovery leads to a lower overall fuel consumption. For the simulated diesel-hydromechanic (6-speed) powertrain the tank-to-wheel efficiency is improved from 29.8 % to 33.3 % by hybridization with the regarded battery ESS. For the diesel-electric powertrain an increase from 22.7 % to 27.7 % is achieved.

DMU-3 / regional / diesel-hydromechanic (6-speed) / battery ESS / strategy b)



DMU-3 / regional / diesel-electric / battery ESS / strategy a)

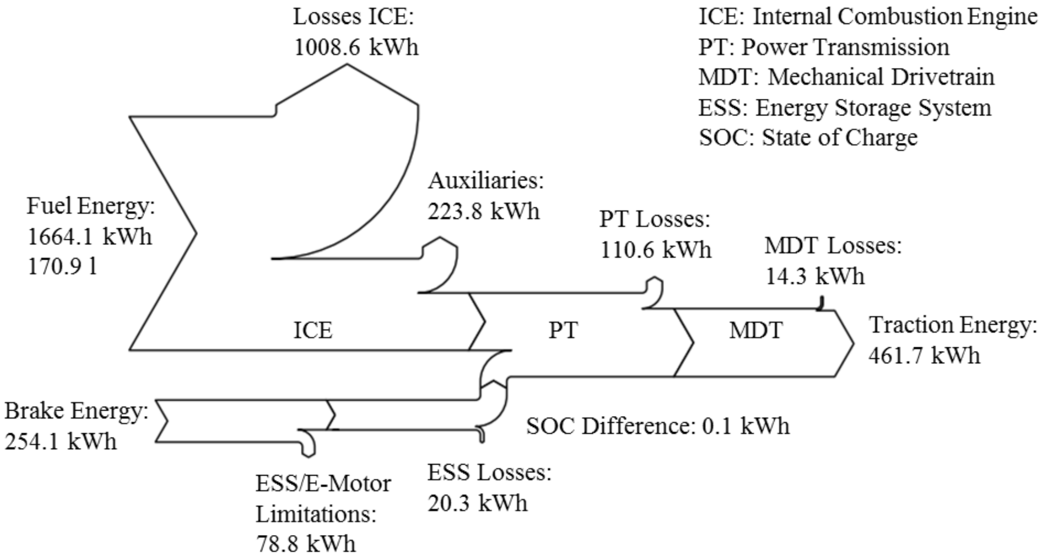


Figure 11. Sankey diagrams representing the simulated energy flow for the DMU-3 with the two hybrid propulsion systems diesel-hydromechanic with battery ESS and diesel-electric with battery ESS on the regional service profile.

3. Conclusion

The aim of the study discussed in this paper is to analyse the potential for hybridization of a generic DMU in a three-car formation based on multi-domain simulation models. Three different types of propulsions systems are regarded: a 4-speed hydromechanic transmission, a 6-speed hydromechanic transmission and an electric transmission. In order to store brake energy and support the diesel engine during acceleration phases, three type of electrical ESS are considered in the study (double layer capacitor, flywheel and lithium-ion battery).

The simulation results show that the standard DMU-3 with a six-speed hydromechanic transmission achieves the best fuel economy on the suburban and regional service profile based on the given use case. For the regarded hybridized powertrain configurations, on both routes a diesel-electric powertrain with a battery ESS has the lowest fuel consumption. Sankey diagram analyses show that this type of powertrain allows for a high rate of brake energy recovery. In addition to fuel savings, hybridizing a diesel-electric powertrain to a series hybrid has further benefits in terms of reduced integration efforts compared to hydromechanic parallel hybrid powertrains. The availability of a DC-link and an electric traction motor allows for reduced costs of hybrid components, which is an important area for further research.

In order to increase the future significance of the developed simulation models, follow-on work of the authors will investigate on improved energy management functions as well as driving strategies to achieve higher improvements in fuel consumption for hybrid DMUs. One important aspect to be regarded is the electrification of auxiliary systems to allow for engine shut off in station stops as well as locally emission free driving with all of the traction energy supplied by the ESS. In addition, powerful future battery technologies could allow for diesel engine downsizing and in the long run for a complete replacement of the diesel engine, which would result in an electric multiple unit (EMU) with a traction battery used for propulsion.

Considering all information highlighted in this paper, the authors have no doubt that the widespread advent of hybrid DMUs is only a matter of time in order to secure the future competitiveness of diesel engines for passenger transportation.

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