Energy Storage System with UltraCaps on Board of Railway Vehicles

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Abstract

The on board energy storage system with Ultracaps for railway vehicles presented in this paper seems to be a reliable technical solution with an enormous energy saving potential. Bombardier Transportation already made a lot of experiences in this field, e.g. equipped one bogie of a prototype LRV (light rail vehicle) for the public transportation operator RNV in Mannheim with a *MITRAC* Energy Saver. Outstanding feature was the daily operation of the energy storage unit in daily passenger service, and this over remarkable 4 years, since September 2003. With 4 years revenue service the new technology can be seen now as reliable. The very positive experience was the base for an order to equip several LRVs with *MITRAC* Energy Saver, which was just placed –the best confirmation of successful experience the customer RNV could make.
The measured traction energy saving of approximately 30% confirmed fully the former calculations. The revenue service of the prototype LRV is stopped now to concentrate fully on the new order.
Running the energy storage device on board of a tram brings additionally following benefits:

- a dramatic reduction of the peak power demand, resulting on considerable benefits in the infrastructure. In the example presented in this paper a reduction to 6 substations from original 8 substations became feasible by introducing MITRAC Energy Saver on board of LRVs
- “catenary free operation” on several hundred meters without power supply from the catenary
- catenary free city center by on board storage and recharging stations

Applying the energy storage devices in Metro systems has a similar effect as in case of LRVs.

Very promising are energy storage applications in propulsion systems of Diesel-Electrical Multiple Units (DEMUs). These vehicles lack possibilities to use the braking energy of the train. Energy storage systems on board of DEMUs bring high fuel savings together with the corresponding emission reduction. On top of that the energy storage leads to a booster effect – extra power during acceleration from the storage, by adding the limited weight of the MITRAC Energy Saver.

Introduction

Modern LRVs and Metros have the ability to convert the mechanical braking energy of the train into electrical energy and to feed it back into the catenary or the third rail. However this energy can be only used if there are in the neighborhood of the braking vehicle simultaneously other trains with high energy demand (Note that typical LRV systems have cheap diode bridge rectifiers in the substation and can therefore not regenerate into the power grid). In cases, this requirement can’t be fulfilled the braking energy must predominantly be (useless) dissipated in the brake resistors of the vehicle converter.

The challenging alternative is to store the braking energy on the train and use it during the next acceleration of the vehicle. Bombardier Transportation has selected energy storage systems on basis of UltraCaps.

The most challenging operating conditions for storage devices on board of traction vehicles (LRVs, Metro-trains, DEMUS) are:
- high number of load cycles during the vehicle lifetime
- relatively short charge/discharge times
- high charge and discharge power values

Proposed storage technologies aiming at brake energy storage are UltraCaps or Flywheels, while batteries do not achieve the necessary load cycles, see [5,8,9]. Outstanding feature of our prototype vehicle is the operation in daily passenger service, and this even since September 2003. For pure catenary free applications further alternatives can be discussed, Batteries or a 750V ground power supply, of course not leading to similar energy saving effects, see [5,8]. Bombardier preferred UltraCaps (double-layer-capacitors) with outstanding features such as high load cycle capability, high energy density (ca.

6Wh/kg) and very high power density (ca. 6 kW/kg). For the railway applications discussed here they are seen as superior to NiMH batteries and flywheels.The drawback of NiMH batteries is a rather poor power cycle (charge/discharge) capability. Flywheel systems achieve a similar energy density on system level, but at reduced power and at the moment with open topics on safety.

***MITRAC* Energy Saver in regular passenger service**

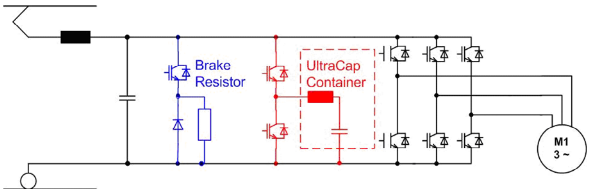


Fig. 1: left: Prototype Vehicle in Mannheim, right: circuit diagram

To demonstrate the benefits of using energy storage systems on traction vehicles Bombardier Transportation equipped one LRV (light rail vehicle) with a roof mounted *MITRAC* Energy Saver (Fig 1). This energy storage vehicle has the unique feature of passenger operation, which has not been achieved by other experimental railway vehicles. Since September 2003 the vehicle has been trouble-free running in the regular passenger service of the operator RNV in Mannheim.
The experimental LRV has two powered bogies with two motors each.
The *MITRAC* Energy Saver unit is connected to the dc-link of the traction inverter of the powered bogie in the front (Fig 1). The inverter of the other powered bogie in the rear remains without energy storage. Such configuration of the tram propulsion system allows comparison of the energy consumption of both bogie drives and leads directly to traction energy savings.

The *MITRAC* Energy Saver system installed on the vehicle in 2003 consists of:

- a UltraCap bank with energy content of about 1kWh, with housing dimensions of : 1900mm x 950mm x 455mm and a mass of about 450 kg
- a bidirectional IGBT chopper controlling the energy flow is installed in the converter

Reduction of the peak power demand and infrastructure losses

The current demand from the line is roughly halved by installing two energy storage units on the vehicle, see (Fig. 2). It means the MITRAC Energy Saver reduces not only the energy consumption of the vehicle but also reduces power losses in the infrastructure, which go with the square of the current.

The mass transit operator pays energy costs as well as peak power costs, both reduced by the energy storage system on board of the vehicle.

Reduction of the line current by 50% causes an identical reduction of the line voltage drop. It is obvious that UltraCap storage devices onboard of traction vehicles stabilize the catenary voltage. It can be confirmed by comparison of line voltages with and without ES in the bottom diagram of the Fig 2.
This significant advantage of system with energy storage can be exploited in different ways:

- Increasing of the distance between substations for the planned new lines
- Reducing of time intervals between following trains at existing lines
- Acceptance of longer trains on existing lines

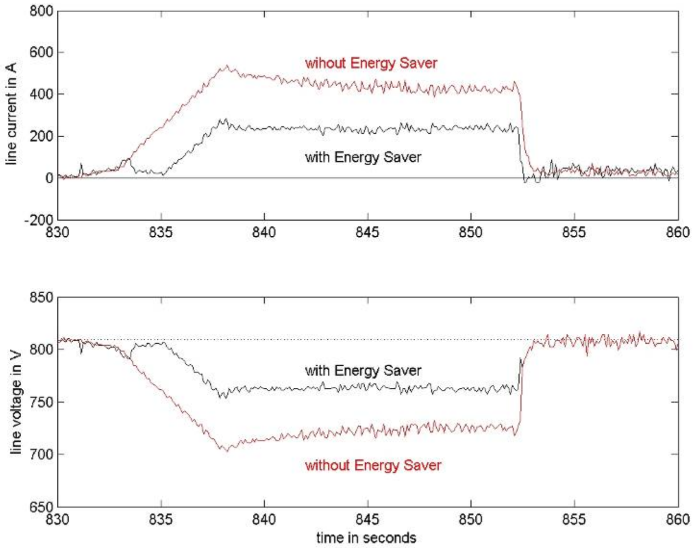


Fig. 2: Line current and voltage with and without *MITRAC* Energy Saver

There are also some disadvantages of the energy storage on board of traction vehicles, e.g.:

- Increase of the train mass by approximately 2%
- Additional space to accommodate the energy storage container is necessary

Reduction of the infrastructure investments

In a computer simulation the influence of the number of and distance between substations has been analyzed. The chosen example is a 17,7km line with a reduction from 8 to 6 substations, when using vehicles with on board energy storage. The headway is 5 min and the distance between stations is always 680m. All the vehicles with an operational maximum speed of 60km/h are either equipped with or without a 0.76kWh energy storage device.

The following system solutions have been directly compared:

a) Line section with 8 substations, all trains without energy storage devices
b) Line section with 6 substations, all trains equipped with ES systems

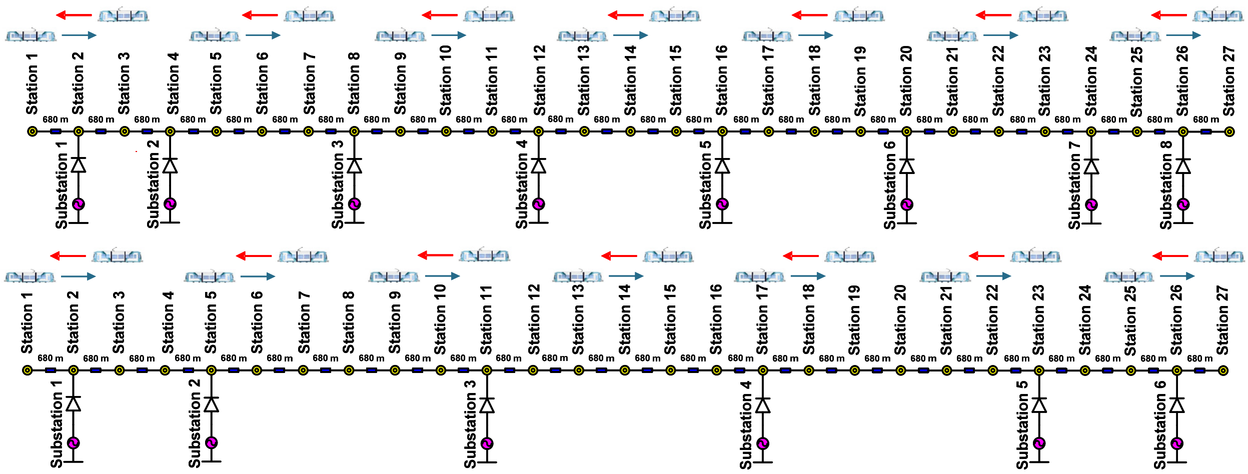


Fig. 3:. top: Reference line using conventional vehicles and 8 substations
bottom: Alternative with energy storage vehicles and only 6 substations.

The simulation results allow the following important conclusion:
The substation load currents as well as the catenary voltage drops remain in case b) despite of decreased number of substations in the same range or are even slightly lower than in case a).

Two main results were achieved by the simulation: The rated current of the substations in both cases remained in the same range as well as the voltage drop between 2 stations remained in the same region.

For example the effective values of the “Substation 2” load current are:

- **307.3A** for conventional vehicles and 8 substations
- **305.5 A** for vehicles with energy storage devices and 6 substations

The voltage drop between two substations measured on the pantograph of the vehicle is presented in Figure 4. Please note that the voltage drop during acceleration is the designing figure, see the green part in Fig4. In both cases conventional vehicles with 8 substations and energy storage vehicles with only 6 substations the voltage drop is in the same range.

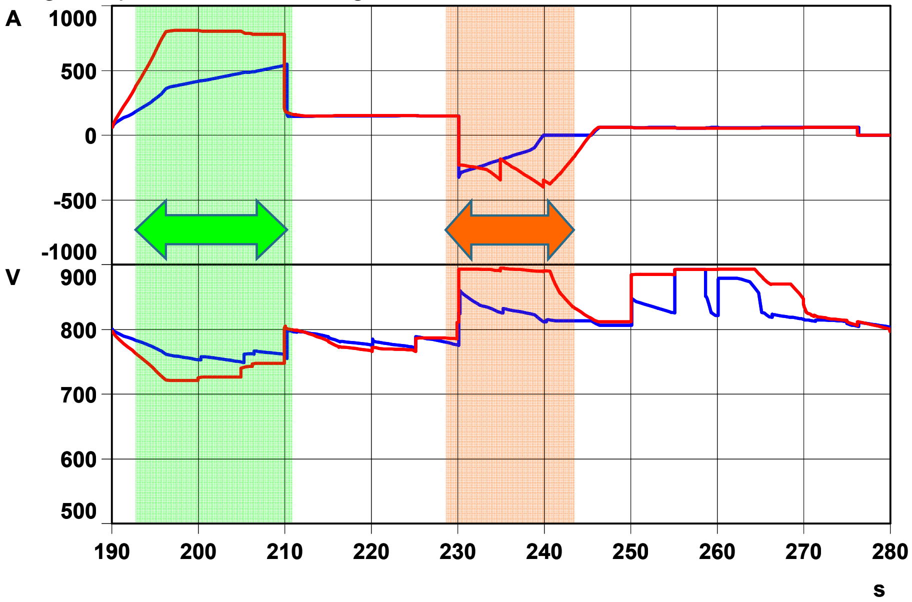


Bild 4. Line currents and voltages for trains, starting at the same time at “Station 14”.
Red: casa a (trains without ES, 8 substations)
Blue: casa b (trains with ES devices, 6 substations)

The comparison of the catenary voltage curves (measured on the vehicle pantograph) for corresponding trains without and with energy storage (s. Fig 4) shows even some advantages of the solution b) with energy storage systems and only 6 substations, may be a further reduction of substations is possible. Especially the impedance voltage drop between the source in a substation and the present vehicle location is in case b) lower. This feature is very important because it results in a higher available power or lower load currents.

The trains with ES systems have better recovery abilities as well, see time between 230 and 240sec in Fig4. Since quite a big part of the trains braking power is used for charging the energy storage, the relatively low amount of the surplus energy usually can be regenerated, utilized by other trains in the system.
In case a) the amount of energy offered by braking trains is very often higher than the present demand of other consumers in the catenary system. In such cases a part of the braking energy is wasted in the brake resistors.

The recovery of the braking energy in the own energy storage is very effective, because a big part of it will be reused locally and doesn’t need to be supplied to sometimes far away consumers.
It results in reduced losses in the catenary system.

With this simulation it could be proven that it is possible to reduce the number of substations by using vehicles with energy storage. This is a very important feature since the costs for substations are very high. Sometimes, especially in downtown areas, there are even problems to find an appropriate location for an additional substation.

Please note that the Return of Investment (RoI) for a new energy storage system is quite interesting. For the example of 6 instead of 8 substations and 21vehicles the RoI was below 2 years.

The RoI is very interesting from an overall point of view, but sometimes struggling with the Bid process. Infrastructure and vehicles are often handled by different departments and quite often in different stages of the project. To make use of all benefits of on board energy storage requires flexibility of all involved parties.

Catenary Free Operation

Another advantage of the on board energy storage system is the possibility to move the vehicle without external power supply. This can be used in special cases as operation during power loss but also for the so called Catenary Free Operation.

Even with limited installed energy storage of e.g. 2*650Wh, which is optimized for the energy saving effect of a 30m tram, several hundred meters could be bridged by just using the energy stored in the on board storage. In an experiment with the prototype LRV in Mannheim the train with only 1kWh installed energy covered successfully a 500m distance without power supply from the catenary. The maximal train speed was about 26 km/h. The fact, that only one bogie of the experimental vehicle in Mannheim was equipped with an energy saver makes the performance even more impressing.
This feature with limited installed energy storage allows the vehicle:

- To evacuate the track (especially tunnels) after breakdowns of the catenary power supply
- Independent movements within depots or workshops

Catenary Free Operation of an LRV is an increasing market demand. The main aspired benefit is possibility to reduce overhead wires for esthetical reasons. There are typically 2 different interests:

- Short track sections without catenary (e.g. Old Town sections or track fragments in front of historical buildings – where the building authorities doesn't allow the installation of overhead lines)
  This demand can be fulfilled by appropriate dimensioning of the on board storage. In most cases 2*1,7kWh installed energy on a 30m vehicle are enough. Please note that it was possible to run some 500m with the prototype vehicle which has just 1kWh installed energy
- Inner city without catenary or several sections without catenary.
  This demand can be served by on board storage and recharging in stopping stations. E.g. several sections of e.g. 500m between stops

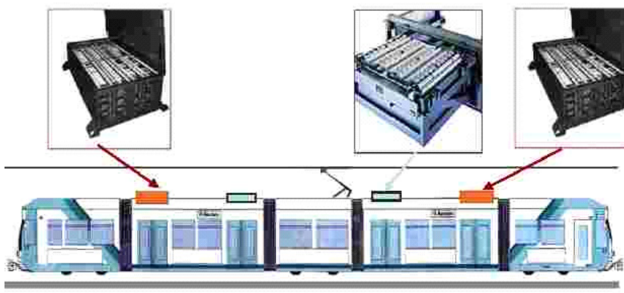


Fig. 5: left: Recharging station with "overhead busbar"
right: Availability through redundant storages, 2 MITRAC Energy Saver and vehicle battery

Recharging in the stations.
Recharging of the on board storage could be done during stops in the stations. The stopping stations should be able to deliver a power of at least 600kW. The time to recharge an energy portion of 3kWh into an on board energy storage is just 20 seconds, assuming 600kW and an efficiency of 85%. This fits very well to a 30m long tram, where the installed energy is 3,4kWh (2*1,7kWh). Please note that during the braking into the station the on board energy storage is already charged quite a bit, so that only the remaining part has to be recharged by energy from outside of the vehicle. Even in a 20 second stop there is enough time to optimize the recharging procedure to e.g. reduced overall losses. One possible realization of a recharging station could be an overhead busbar. The normal pantograph is able to handle currents up to 1kA in standstill by using the bigger contact surface of a busbar instead of an overhead wire. In this case the 600kW could be delivered from a simple recharging station by just adding an

overhead busbar fed by the standard substations. LRV under catenary also have a power demand of about 600kW during acceleration.

Availability of the vehicle in Catenary Free Sections
The availability of the vehicle in a catenary free section is mainly solved by redundancy of the energy storage system. A 30m long vehicle contains typically 2 independent on-board MITRAC Energy Saver as well as the vehicle battery. The following operation situations are possible:

- One failed MITRAC Energy Saver. In most of the application cases the remaining MITRAC Energy Saver can still run the vehicle through the catenary free sections by reduced performance, e.g the Aircon should be switched off and the speed might be reduced
- Two failed MITRAC Energy Saver. Even in this case the vehicle can run some 3…5 km in an emergency mode without help from outside, by using the vehicle battery. Of course the performance is very limited, Auxiliaries have to be switched off as much as possible and the vehicle speed is restricted to a few km/h, e.g. with a step up chopper from battery to dc-link to about 4km/h. The vehicle battery has quite significant energy stored, typically more than 8kWh, which should be enough for 3...5 km with limited performance. Please note that this emergency mode will nearly never happen and therefore the battery can be stressed to its maximum. For more details and a comparison battery and UltraCaps see [5]

Metro Application with MITRAC Energy Saver

The principle of the on-board energy storage system for metro applications is very similar to the already described system for Light Rail Vehicle (LRV). For details see [6,7, 16]

The energy storage of brake energy on board of vehicles delivers several further advantages over and above the energy saving.

- Reduced power demand from the line – the Energy Saver delivers additional power – could result in Metro systems with less substations (less voltage drop allows bigger distance between substations), could avoid upgrades of infrastructure or could enable more or more powerful vehicles in an existing network
- Booster Effect: The additional power from the Energy Saver could also be used to “boost” the vehicle when the line current is limited. Assuming e.g. 30% power from the Energy Saver could result in 30% higher power keeping the same line current. This results in 30% higher tractive effort in the region between base speed and a speed when the storage is empty of e.g. 90km/h, depending on the size of the Energy Saver
- Rescue in tunnel, becomes possible in case of e.g. a power loss. In this case the vehicle could move to the next station by using the energy stored in the Energy Saver. Typical distance achieved is about 1000 to 1500 m from standstill to stop in a flat area, depending e.g. on the size of the Energy Saver. The principal has been demonstrated by the LRV prototype vehicle
- Feeding gaps in the 3rd rail system due to track switches or isolation between different sections in the track, could be bridged by the stored energy in the Energy Saver even without reducing the traction power
- Vehicle movement in a depot or workshop without 3rd rail becomes possible

Diesel-Electric Multiple Unit with Energy Storage

There are two main reasons for using the *MITRAC* Energy Saver on board the Diesel-Electric Multiple Units:

1. The Booster Effect:
   The *MITRAC* Energy Saver enhances the vehicle performance by providing additional power for acceleration
2. Energy Saving:
   The *MITRAC* Energy Saver stores braking energy and reuses it during acceleration

It is possible to use both mentioned effects simultaneously.

Fig 6: Principle scheme of a diesel electric vehicle equipped with *MITRAC* Energy Saver

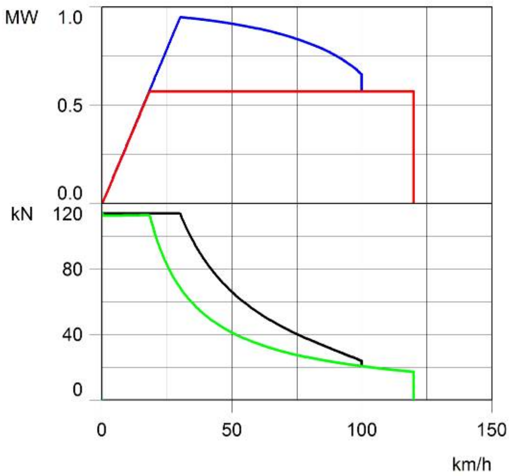
To illustrate the impact of the *MITRAC* Energy Saver on the vehicle performance, the following two versions of a typical three-car DEMU will be analyzed and compared:

- DEMU with two diesel power packs (2*315kW) and without *MITRAC* Energy Saver
- As above but with an additional 4,5 kWh *MITRAC* Energy Saver

The average weight of this train is about 100 t.

Booster effect

The main job of the *MITRAC* Energy Saver is to store the braking energy and to use it afterward for supporting the vehicle acceleration.
The additional power from the *MITRAC* Energy Saver increases the vehicle tractive power and thus allows significantly higher train accelerations.
In this way the energy saver compensates the disadvantage of the usually limited power of the diesel engines.



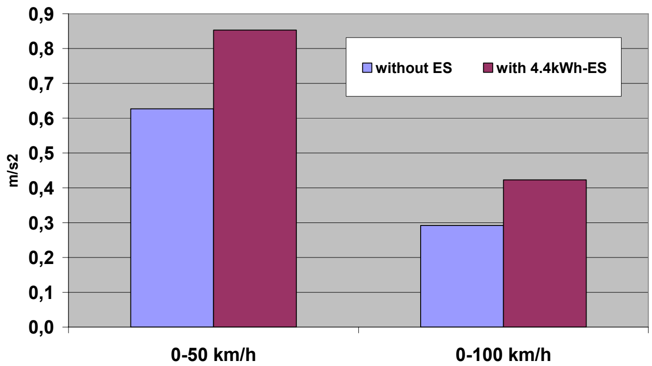


Fig. 7: Left: Tractive power & effort curves with and without 4,5kWh Energy Saver
Right: Average acceleration values from 0 to 50km/h and from 0 to 100km/h

The “booster” effect of the energy storage can be very well recognized in Fig. 7.
The blue curve - tractive power of the train with energy storage – lies in the speed range between 20km/h and 100km/h well over the red curve representing the same quantity of the vehicle with only diesel engines.
A similar relation is valid for the tractive effort curves in the bottom part of the diagram.
The comparison of the average acceleration values 0…50km/h and 0…100km/h for both train versions confirms the booster effect of the *MITRAC* Energy Saver (right part of Fig.7).

Energy savings and emission reduction

In the previous sections a special attention was paid to reduction of the running times.
However it’s possible to use the booster effect thanks to additional energy from the energy storage in another way – to optimize the energy saving by allowing the same runtime, thus allowing for extended coasting.

The red curve in Fig. 8 showing a short coasting sector before braking (4% of the running time) represents the speed of a train without energy storage.

The acceleration ability of the train with ES (blue curve) is much better. For this vehicle it's possible to extend the costing sector to 38% and still to achieve the same running time as the train without *MITRAC* ES.

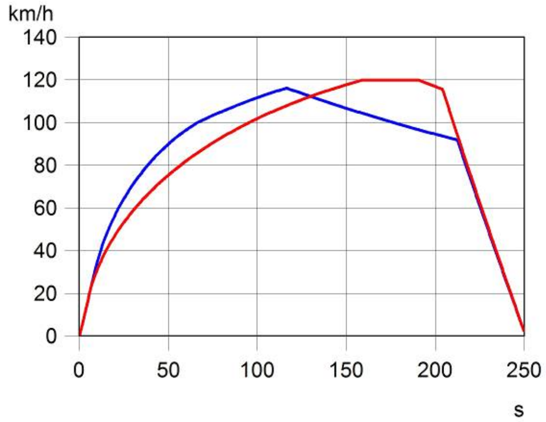


Fig. 8: Runtime simulations with and without Energy Saver.
Relative fuel saving of the train with ES (blue curve): 28%

The energy consumption of the vehicle with energy storage on the 6km track is about 9kWh or 28% lower than that of the train without ES.
At first glance it's amazing, that the absolute energy saving is much higher than the installed energy (4.5 kWh) of the energy storage.
A rather valuable conclusion from the simulation results listed in Table 2 is the possibility to swap the 4.7% time saving for additional 18% energy saving, leading to remarkable 28% total energy savings.

6 km	Savings from energy storage	
4,5 kWh	Energy optimised	time optimised
Runtime Savings	0%	4,7%
Energy Savings	28%	10%

Table 1: Conversion of *MITRAC* Energy Saver benefits

Thanks to a long coasting not only high energy savings but also emission reductions of at least the same order are achievable.
The emissions savings might be in the future at least as interesting as the energy savings.
The rules of "emission trading" are heavily discussed at the moment.
Additionally several railway operators took up the topic "reduction of emissions" in their strategic plans, e.g. the German railways DB announced a further 15% reduction of carbon dioxide until 2020.

The possible relative time savings thanks to "booster effect" are not as spectacular as the possible energy and fuel savings (see Table 2). However the financial benefits of time savings must be also relevant for the customers since very often high performance vehicles will be asked for.

Influence factors on the energy saving

The biggest influence factors on the achieved energy saving are the distance between station, the vehicle type, or more concrete the regeneration capabilities of the vehicle.

The shorter the distance between stations the more often the brake energy can be reused. If the top speed of the vehicle is in the same range, the energy saving effect due to reused energy remains independent of the distance, but the trains energy consumption is increased with distance between stops, therefore the relative energy saving is decreased with the stopping distance.

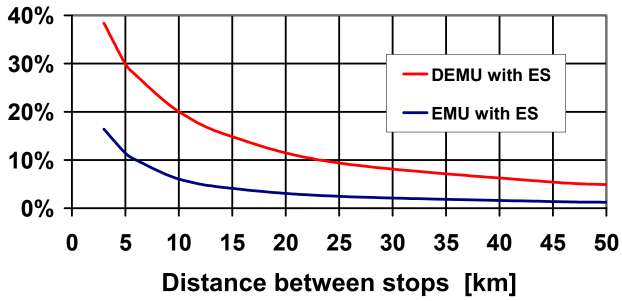


Fig. 9: Energy savings of the energy storage in function of the stopping distance
for a Diesel Multiple Unit DEMU and a Electric Multiple Unit (EMU) in case of no regeneration

The biggest influence on energy saving effect is the distance between stops. Secondary effect on energy saving is gradients. Especially uphill, the energy storage gets empty at reduced distance and the diesel engines become the only remaining power source, this leads to reduced coasting effect and reduced energy savings. Gradients play also an important role in the dimensioning of the energy storage. On uphill tracks the braking energy is reduced. Assuming that the energy storage is dimensioned that at least in the majority of cases the energy storage gets fully recharged by braking the train, the maximum gradient sets with its available braking energy the limit for the energy storage size.

The energy saving effect is considerable bigger on a Diesel Electric Multiple Unit (DEMU) compared to an Electrical Multiple Unit (EMU). The main difference is that the EMU typically is more powerful and the diesel engines do not limit the available power. Therefore the booster effect is not relevant for EMUs, since there is enough power available from the line. As a consequence the energy saving effect due higher acceleration and coasting can only improve the energy saving in DEMUs. EMUs can only reuse the braking energy, which is otherwise wasted in the brake resistors. The potential energy savings of EMUs is therefore considerable below the potential of DEMUs. For EMUs the regeneration also effects the energy saving, the better the regeneration the less interesting the energy storage is. Therefore LRVs and metros with short stopping distances were focused on, but not on Main Line applications where the stopping distances are quite big and the regeneration could be quite good, e.g. in AC fed main lines.

Benefits of energy storage for DMUs (Diesel Multiple Units)

Main advantages of using the *MITRAC* Energy Saver for DMUs:

- Reduced energy consumption which leads to a reduction of operation costs.
- Reduced emissions (especially CO_2).
- Better acceleration due to the booster effect, therefore shorter traveling time – as diesel power packs are big and heavy, the power of a vehicle is limited due to that. The relative light Energy Saver leads to a clear power increase.
- High power flexibility with low weight influence – with the right choice of the storage size, the power of the vehicle can easily be adapted to the specific application.
- 4 part train with 2 diesel engines and middle car with Energy Saver – with the additional power the same acceleration as a 3 part train can be achieved.
- 2 part train with 1 diesel engine and Energy Saver – the Energy Saver replaces one power pack and lowers the energy consumption and weight.
- The stored energy can also be used to travel short distances without diesel power. A 4.5 kWh Energy Saver gives the possibility to run up to 2,5 km on a flat track with 20 km/h, when the auxiliaries are switched off. This could lead to competitive advantages in areas where emissions should be avoided, e.g. in stations or in tunnels. Anyhow it should be noted that using the stored energy for this function will reduce the energy saving effect. In this case only the stored energy can be reused, but since the additional power from the energy storage is not added to the diesel engine power, considerable higher acceleration is not achieved and therefore the energy saving benefits from coasting are not gained any more.

Return on investment

In the case of the modeled three car DMU the initial investment in a MITRAC Energy Saver would be recovered in 2 to 4 years, depending on the way it is used. This estimate assumes that diesel costs between 0,6 and 0,95€/litre, and that passengers value their time saved by higher acceleration at 5€ per hour per passenger. As energy costs rise, the benefits of on train energy storage also go up.

Storage Technology

To select the best suited storage technology the requirements form the application must be known. In Fig.10 an overview on the requirements from applications already described in this paper is given, as well as the requirements for a mild hybrid car, as one example from automotive area. The important application requirements are proposed size of the energy storage, which is normally derived from the average available braking energy. For the Catenary Free LRV this is of course depending on the requirements of the catenary free section, such as length and gradient of the section. Another requirement which has to be considered is the power during braking, where the storage must be designed for, to reuse most of the braking energy. For Metros and LRVs the power during braking is relatively high and drives the selection of technology, especially when the peak power is taken into account. Another value to be considered is the expected load cycles over the lifetime of the energy storage, which will be a limit mainly for batteries. A load cycle is given by charging and recharging the storage, which happens before and after each station, but also when there is a temporary stop or a speed limitation. Examples for additional load cycles between stations are traffic lights, pedestrians crossing, speed limits in curves or during maintenance work on the track. Note that also a speed limit is influencing the load cycles considerably, since the kinetic energy goes with the square of the speed. To reflect the real occurring load cycles a factor between load cycles and start stop cycles is introduced, for LRVs this factor is higher, e.g. 1,7, since in city areas several unplanned stops can happen.

Batteries:

The main limitation for batteries for use in railway applications is the required load cycles, when aiming at energy saving due to brake energy storage. One extreme application is within LRV aiming at brake energy storage occurring each load cycle, even when only designed for 5 years 1 Mio load cycles are expected, which is too much for batteries, other storage technologies are preferred. The catenary free LRV, when using the energy storage only in the single catenary free section, is feasible with batteries. Designing the battery for 10 years lifetime this ends in 100’000 load cycles. When using a modern NiMH or Li-Ion traction battery the DoD has to be limited to about 10% (Depth of Discharge – the relation between “usable energy” and installed energy). That means that only 10% of the installed energy can be used. In automotive applications the situation is different, the limited number of load cycles is beneficial for the battery, on one hand the typical lifetime of a car which is between 8 to 12 years is less than the 30 years for railways, on the other hand the expected annual distance is considerable lower.

One relevant application where traction batteries for catenary free LRVs have been chosen is the project in Nice [14]. In this project an LRV is crossing 2 catenary free places of 400m, the power from the energy storage during discharging is limited to 200kW, while charging is only considered with even less power over long time while running under catenary on the rest of the track. The storage system weight is 1450kg. The lifetime is stated to be 5years. Please note that the storage consists of one single battery and not two redundant ones.

For catenary free applications with very tough requirements, as uphill or very long catenary free sections, the battery has the advantage that more energy can be used when allowing a shorter lifetime. Even when not preferred in standard catenary free LRV cases, since it does not allow brake energy storage and energy savings, it might be the only choice to keep the additional weight for the vehicle in acceptable limits.

The influence of upcoming Li-Ion batteries needs to be judged, when first systems in this size will be passing safety tests. The expected weight saving of more than 30% compared to NiMH is at least very interesting for Catenary free LRV applications.

typical values		LRV 30m, 60t Catenary free One section	LRV 30m, 60t brake energy storage	Metro 240t brake energy storage	Diesel 120t brake energy storage	automotive 1t Mild Hybrid
Proposed Energy	kWh	**3,4 … 4,3 kWh**	**1, 4 kWh**	**9 kWh**	**4,4 kWh**	**0,02 kWh**
Braking Energy	kWh	**1…1,2 kWh**	**1…1,2 kWh**	**7,5…12 kWh**	**4…7 kWh**	**0,02…0,09 kWh**
Brake Power (peak)	kW	**600 kW**	**600 kW**	**3'000 kW**	**800 kW**	**20 kW**
Braking time	sec	**10 sec**	**10 sec**	**18 sec**	**38 sec**	**10 sec**
Load Cycles	Cycles /year	**10.000 Cycles/year**	**200.000 Cycles/year**	**165.000 Cycles/year**	**37.500 Cycles/year**	**5.000 Cycles/year**
km/year	km/year	70.000	70.000	110.000	250.000	10.000
station distance	m	8.000	600	1.000	10.000	5.000
Load / stop cycle		1,1	1,7	1,5	1,5	2,5
Batteries		**Possible, but reduced power no redundancy DoD 10...15% @ 8 years lifetime**	**No load cycles too high**	**No load cycles too high**	**No load cycles too high**	**Possible DoD ~20% @ 8 years lifetime**
Flywheels		**Yes but no redundancy safety concerns**	**Yes, but limited power safety concerns**	**No, power limited safety concerns**	**Yes, but limited power safety concerns**	**Not proposed ?**
UltraCaps		**Yes, but energy limited**	**Yes**	**Yes**	**Yes**	**Yes, but not for "pure electric"**

Fig. 10: Application requirements and preferred storage technology

Flywheels

For storage applications on board of railway vehicles high speed flywheels are still under development, see also [15]. Compared to the flywheel versions used in substation the speed was increased to 20'000…25'000 rpm, resulting in considerably increased energy density. The increase of speed is needed to reduce the size of the flywheel system to fit them on the roof of vehicles and leads to additional safety efforts and development work. The "hard" characteristics of the PM motor designed for high speeds required higher efforts within the power electronics. As an example taking a 4 pole motor with 500kW power at 20'000 rpm requires an inverter, which is capable to generate this power at a fundamental frequency of 667 Hz with limited harmonics to reduce motor losses. Adaptations in energy, power or voltage require therefore considerable efforts in developments. The limited power of flywheels under development, which are close to a product, are often too low for brake energy storage. The high speed flywheels seem to have also some open safety issues.

The only noticeable relevant application of flywheels on board of railway vehicles is the field trial in Rotterdam [14]. After some initial test in summer 2006 the status seems to be back to under development.

UltraCaps, SuperCaps or Double Layer Capacitors

For most of the onboard energy storage applications UltraCaps are the best choice. UltraCaps are much better in power capability than other technologies and allow also high load cycles. The expected lifetime even for LRV applications is up to 15 years, with as much as 3 Mio load cycles.

For some applications like the single section catenary free LRV, the energy density might be seen as a limitation, but typically it is compensated by good redundancy and power. Compared to batteries the UltraCaps allow also energy saving and several catenary free sections.

The relevant application of UltraCap based energy storage vehicles is the prototype in Mannheim, which achieved 4 years in revenue service.

Bombardier Transportation is preferring UltraCap based energy storage. Only in a few pure catenary free applications a NiMH Battery was preferred. Anyhow all technologies are followed up very carefully.

Conclusions

Compared to conventional modern Light Rail or Metro vehicles, which are already using regeneration into the line, a train using a propulsion system with onboard energy storage results in further energy savings up to 30% and a reduction of the peak power demand by up to 50%.
With the prototype Light Rail in Mannheim the benefits have been proven in daily passenger operation, the world first application in passenger service, still unique in this application field. With the good experience in 4 years daily passenger operation the new Bombardier *MITRAC* Energy Saver can be considered as a reliable proven technology. The now placed order for energy storage LRVs from RNV for the city of Heidelberg is the best confirmation of the good results achieved in 4 years field experience.
In addition to the energy savings several cost benefits due to reduced power demand on the infrastructure can be taken into account case by case. The example presented in this paper allowed a reduction from 8 to 6 substations on the presented line, thus leading to very good Return of Investment scenario.
Furthermore the on board energy storage allows an autonomous operation. Also without external power supply or even without a catenary or a 3rd rail a short distance operation can be maintained which leads to further system advantages, such as rescue in tunnels but also for the so called Catenary Free Operation. The main aspired benefit is the possibility to avoid overhead wires in some selected areas for esthetical reasons. Even several km long catenary free areas can be served by on board storage and recharging in stopping stations.
The new *MITRAC* Energy Saver is an important contribution for a more sustainable transport system, boosting the already established environmental advantage of public rail transport.
The proven energy savings of 30% by the LRV prototype and the corresponding emission reduction is in line with various local and global energy saving programs set up by e.g. European Union and major railway operators. Therefore the on board energy storage is one of the main future technologies for rail operation.

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