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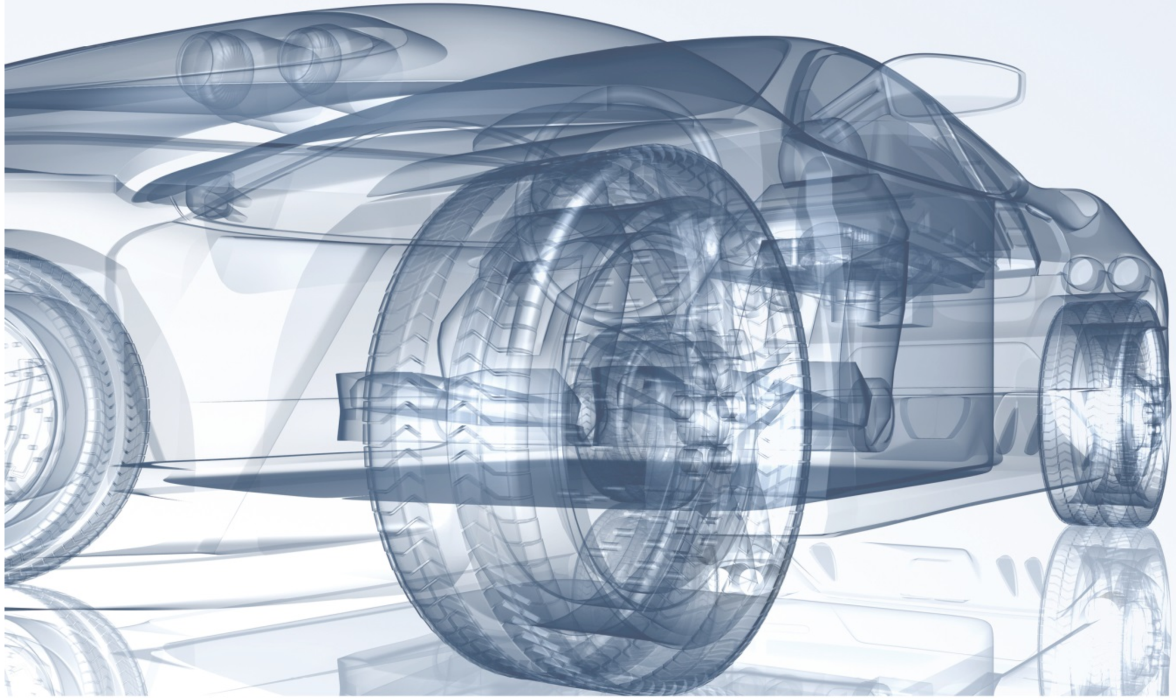

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Evaluation of cyclic battery ageing for railway vehicle application

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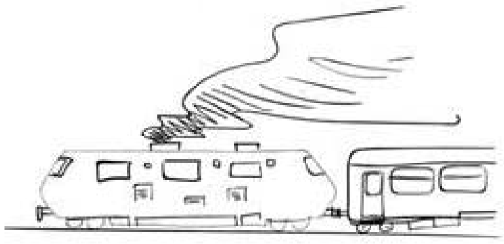
Agenda:

1. Motivation
2. Testing profiles
3. Implementation
4. Results
5. Conclusions
6. Summary

Motivation
EU28: Line electrification and CO_2-emissions from railways



- 46% of railway lines were non electrified in 2012 [1]
- Service on these lines typically provided by diesel traction with significant CO_2-, NO_x and PM emissions
- Example SBB in 2015 [2,3]:
  - Line electrification > 95%, Diesel energy consumption < 4% **but** 31% of total CO_2-emissions
- Internal CO_2 - reduction target of UIC by 2030: -50% (baseline 1990) [4]

➔ Novel concept to fulfill CO_2 requirements: <u>B</u>attery <u>e</u>lectric <u>m</u>ultiple <u>u</u>nit with opportunity charging (BEMU)

[1] International Union of Railways - UIC, “Rail Transport and Environment, Facts & Figures”, 2015
[2] http://www.sbb.ch/sbb-konzern/ueber-die-sbb/zahlen-und-fakten/umwelt/energieverbrauch.html
[3] http://www.sbb.ch/sbb-konzern/ueber-die-sbb/zahlen-und-fakten/umwelt/co2-emissionen.html
[4] International Union of Railways - UIC, “Railway Handbook 2015”, 2015

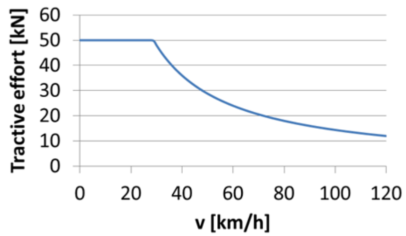
Motivation: Research questions

- What is the effect of the following operation conditions on the energy storage units?
  - frequent charging phases
  - high recuperation power
- What are the differences between various battery chemistries? (Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate (LFP))
- What are appropriate energy storage concepts for BEMU railway vehicles:
  - **B**attery **O**nly (**BO**) – the necessary energy is delivered only by the battery
  - **H**ybrid **E**nergy **S**torage **S**ystem (**HESS**) – combination of battery and double layer capacitor (DLC)
- Ageing characterisation of two batteries types
- Test bench trials for a specific railway application (use case) are performed to represent ~1,500 h of battery operation.

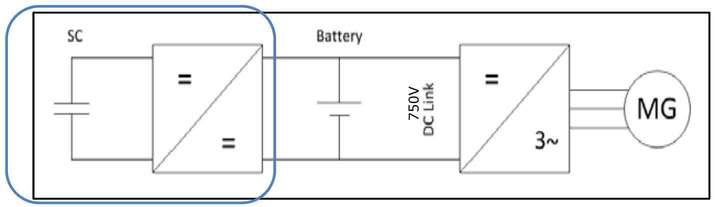
Testing profiles:
Definition of use case: reference vehicle + propulsion system

- Regional single-car DMU Class 650 ("Regioshuttle") with a battery electric propulsion system as a use case for simulation
- Assumed vehicle parameters:

vehicle mass (static)		40,000	kg
vehicle mass (dynamic)		1,300	kg
max. velocity		140	km/h
Power of auxiliaries		~50	kW
max. acceleration		1	m/s²
max. deceleration		0.8	m/s²
max. braking force		80	kN
efficiency traction chain		90	%
driving resistance (Davis)	A	644	N
	C	3,063	N/(m/s)²

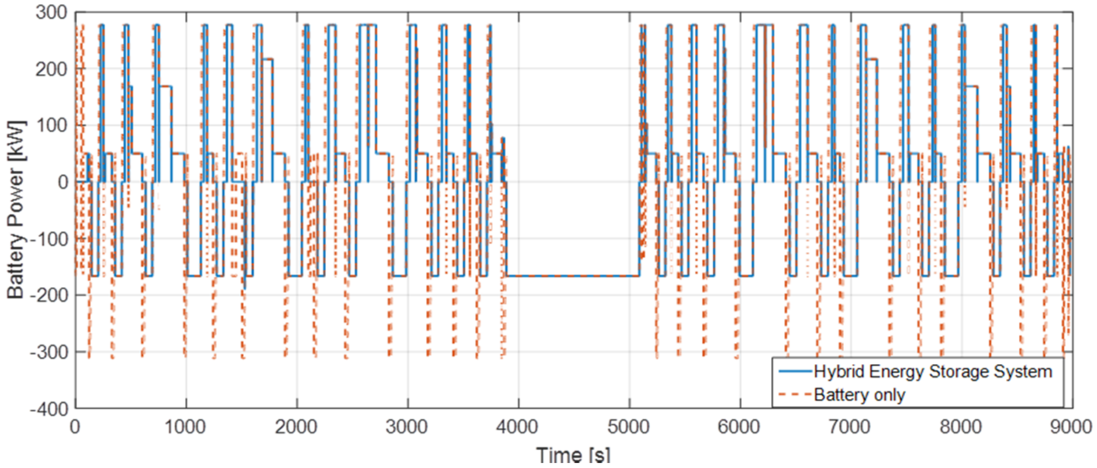


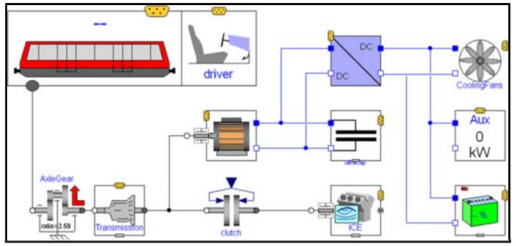
only HESS case



Testing profiles: Definition of track / service profile

- Service profile *Regional* according to TS50591 defines track characteristics and time schedule.
- A round trip is considered (standstill time Station O: 20 min) with a total driven distance of 140 km and a duration of roughly 150 min.
- The vehicle is charged via inductive energy transfer system (IETS) during standstill.
- For this use case (including reference vehicle, electric propulsion system and service profile) power load profiles for the battery system are simulated.





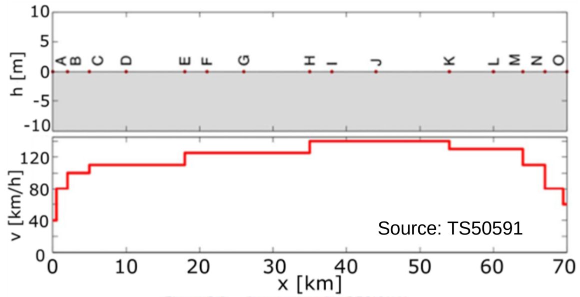


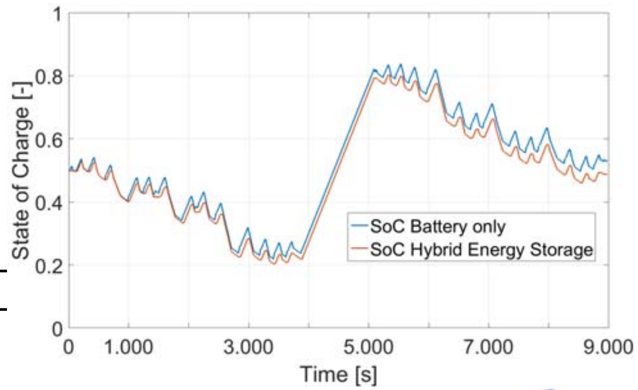
Figure B.2 — Standard profile REGIONAL

Testing profiles: Energy storage characteristics

Source: www.akkuplus.de

Source: data sheet

Parameter	Cell 1 (NMC)	Cell 2 (LFP)
Cathode chemistry	$LiNi_xMn_zCo_yO_2$	$LiFePO_4$
Anode chemistry	LiC_6	LiC_6
Capacity	1.5 Ah	2.5 Ah
Maximum charge voltage	4.2 V	3.6 V
Minimum discharge voltage	2.7 V	2.0 V
Maximum discharge current	16C	48C
Cycle life at 100 % Depth of Discharge (DoD) and 1C	1,000	~5,000
Cell type	Pouch	Cylindrical
Battery system configuration (BO and HESS):		
Number of cells	17,748	11,856
Cell configuration	204 s 87 p	228 s 52 p



Source: www.maxwell.com

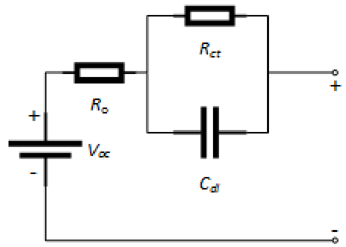
Parameter	DLC
voltage	2.7 V
capacity	3,000 F
SOC range	50 %
Internal resistance	0.4 mΩ
Supercap system configuration:	
Number of cells	1,098
usable energy	2.5 kWh

Implementation: Test method

- Four cells each has been used for the four testing cases:
  - LFP cells with Battery only case and HESS case
  - NMC cells with Battery only case and HESS case
- The test is done in a climatic chamber with 25°C.
- 600 test runs (= 600 power load profiles) have been performed which is equivalent to half a year of service of a vehicle.
- The Start SoC for every test run was 50 %. Every 8 test runs a SoC adjustment was done.
- 7 times the capacity is determined by a 1C discharge and the internal Resistance is estimated by measuring the voltage and current response to a pulse power test at several SoC points.
- Based on the Ah throughput all test runs are equivalent to ~1,200…1,260 (BO case) or ~ 840…900 (HESS case) full charge/discharge cycles.

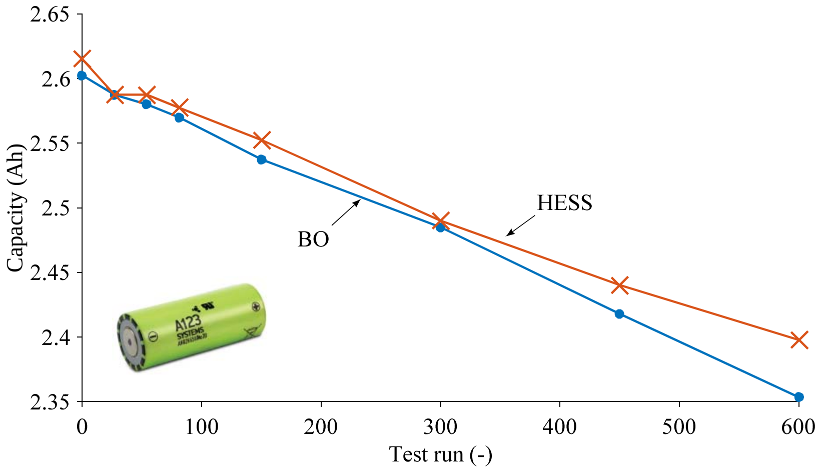
Source: www.akkuplus.de

Source: data sheet

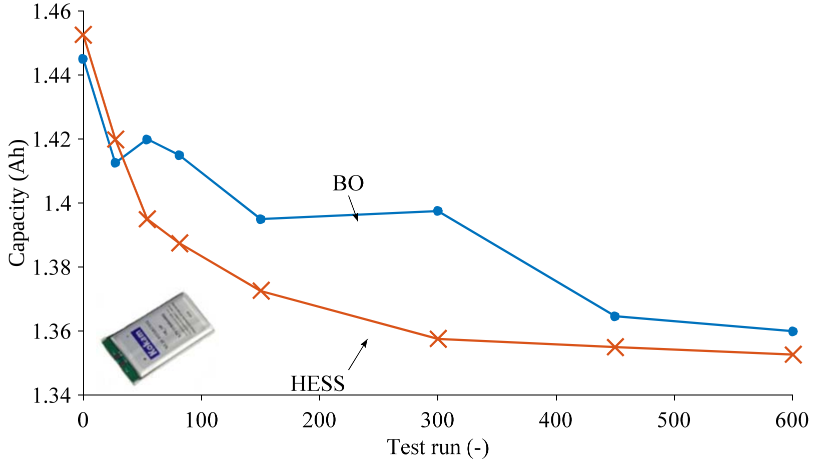


Results: Capacity

- The LFP cells have a linear ageing behaviour. As expected the cells in the HESS case end up with a higher capacity.
- Linearly extrapolated the cells will reach End of Life (80% capacity) after ~ 345 days of service in the BO case and ~ 411 days in the HESS case.

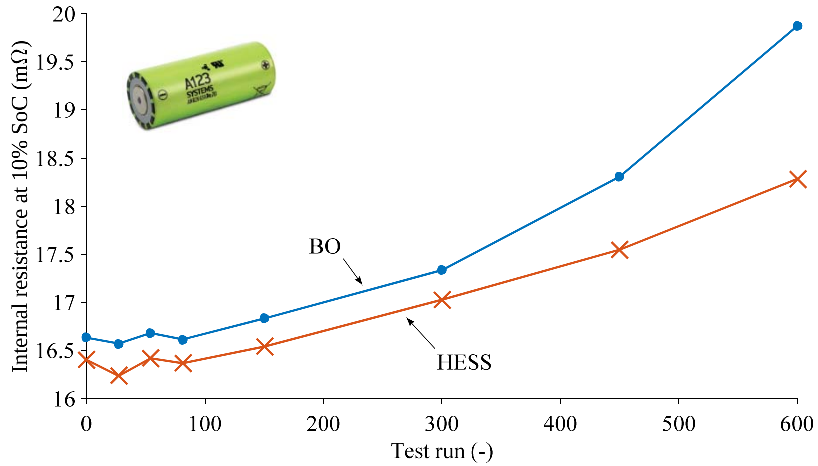


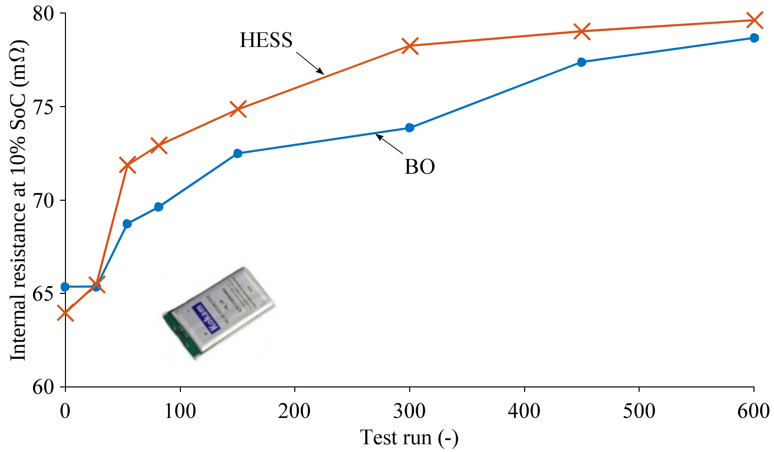
- The NMC cells have a non-linear ageing behaviour. Unexpectedly the cells in the HESS case end up with a lower capacity in comparison to the BO case.
- Linearly extrapolated the cells will reach End of Life (80% capacity) after ~ 565 days of service in the BO case and ~ 490 days in the HESS case.



Results: Internal Resistance

- Higher internal resistances lead to a lower energy efficiency.
- As expected the internal resistance of the LFP cells in the BO case have a steeper gradient than the cells in the HESS case.
- The internal resistance of the NMC cells increases continuously for both cases, but different than for the LFP cells.
- Unexpectedly the BO cells end up with a lower internal resistance than the HESS cells.





Conclusions

- The theory that a HESS is generally useful to enhance the lifetime of the traction battery could not be proven for both tested battery types.
- There is no general ageing behavior for all battery types. It is necessary to have specific ageing models for every battery type.
- The ageing behavior is not easy to predict. In case of the LFP cells it was linear. In case of the NMC cells it was not linear. For the LFP cells the HESS case was better, for the NMC cell the BO case was better.
- The lifetime values of the data sheet are specified for full cycles with a constant current rate These could not be used for a lifetime prediction in a real railway cycle. Based on the datasheet values the LFP cells were supposed to withstand more cycles than they had on the results from the test bench.
- Extrapolating the results, the cells would have a lifetime of 345…565 days in service. This is evidentially not enough for railway applications. These cells are therefore not suitable for this use case with high recuperation energy and high SOC range.

Summary

- A use case was defined consisting reference vehicle, propulsion system and service profile. The use case leads to a power load profile for the battery.
- Two different energy storage concepts (Battery only and HESS) have been investigated.
- Two different cell types (NMC and LFP) have been used for the tests on the test bench.
- On the test bench the cells performed 600 test runs, which are equivalent to ~1,500 hours in service.
- The capacity and the internal resistance were measured during the tests.

- **Further work** will include a comparison of the test results with lifetime predictions of existing battery ageing models to identify suitable approaches for ageing consideration during the design process of advanced railway propulsion systems.

Thank you for your attendance!

Questions?

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