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Accelerated life tests of complete lithium-ion battery systems

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Summary

- Battery design problem
- Battery testing and test results
- From life-cycle tests to a power law relationship
- A numerical application of the power law relationship for battery cost optimisation
- Conclusions



Battery design problem

- We investigate the performances of automotive battery systems made up of lithium-ion batteries
- Lithium (Li) batteries have technical properties and features particularly suitable for these applications in which high energy and power are required in small volumes and weight.
- In electric vehicle applications, unexpected degradation of battery performances has been measured with respect to manufacturers claims on battery lifetime.

Battery design problem

- Many approaches have been proposed in the relevant literature but, due to the large number of factors involved, many difficulties persist to solve the problem of the battery size optimization over a prefixed time horizon of interest.
- There are lots of studies on how different stress influence the battery cell lifetime in automotive applications ,especially in public transport. In this work, we used real world data from tests on two battery packs designed around the same cell.
- As a matter of fact, we compared the ageing results of these batteries subjected to very different C_{rates}



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Battery testing

- Life cycles tests on two complete lithium battery systems using the same elementary cell have been performed in the course of two different projects
- The cells are of the same manufacturer, same capacity and same cathode chemistry, nickel-cobalt-manganese (NMC) in both cases. Each cell has 3.7 V as nominal voltage.
- **Type A** storage system **relates to BEV**: 78 lithium cells series connected in series
- **Type B** storage system **relates to HEV**: 84 lithium cells series connected in series



Type B battery system under test

Battery testing

MAIN CHARACTERISTICS OF THE STORAGE SYSTEMS

Characteristics	<i>Unit</i>	<i>Type A</i>	<i>Type B</i>
Nominal capacity	Ah	40	40
Nominal energy	kWh	11,5	12.4
Nominal voltage	V	288.6	310.8
Maximum voltage	V	327.6	352.8
Minimum voltage	V	249.0	268.8
Maximum C-rate in continuous discharge @ +20°C		5	5
Maximum C-rate in pulse discharge @ +20°C		10	10
Weight (without case, cables and accessories)	kg	89	/
Weight (with case, cables and accessories)	kg	/	124

Battery testing

TEST PROCEDURE FOR TYPE A BATTERY

Macro-cycle composition	Characteristic		
	<i>Procedure</i>	<i>ΔSOC %</i>	<i>Comment</i>
Step n. 1	n. 10 ECE-15	100 → 020	Discharge
Step n. 2	Charge @ 2C	020 → 100	Simulation of fast charge at public station
Step n. 3	n. 10 ECE-15	100 → 020	Discharge
Step n. 4	Standard charge	020 → 100	Simulation of traditional charge at home (14 A)
Step n. 5	n. 13 ECE-15	100 → 000	Discharge
Step n. 6	Standard charge	000 → 100	Simulation of traditional charge at home (14A)
Step n. 7	n. 13 ECE-15	100 → 000	Discharge
Step n. 8	Standard charge	000 → 100	Simulation of traditional charge at home (14A)

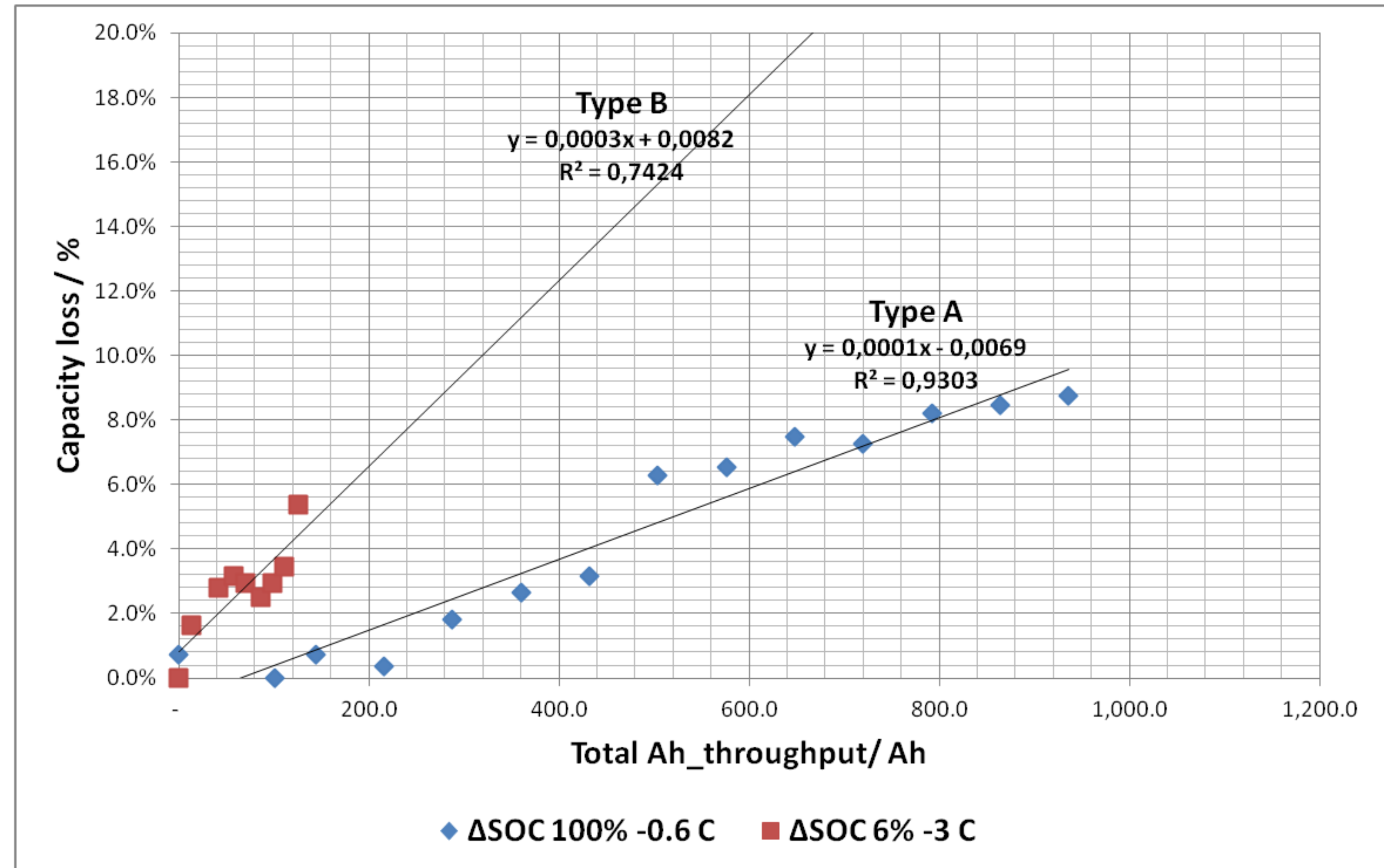
Battery testing

TEST PROCEDURE FOR TYPE B BATTERY

Profile composition	Characteristic		
	Procedure	Step time [s]	ΔSOC %
Step n. 1	Discharge @ 3C	18	80.0 → 78.5
Step n. 2	Discharge @ 1.5C	36	78.5 → 77.0
Step n. 3	Rest	20	77.0 → 77.0
Step n. 4	Discharge @ 3C	18	77.0 → 75.5
Step n. 5	Discharge @ 1.5C	36	75.5 → 74.0
Step n. 6	Rest	19	74.0 → 74.0
Step n. 7	Charge @ 1C	27	74.0 → 74.8
Step n. 8	Charge @ C/2	54	74.8 → 75.5
Step n. 9	Charge @ C/3	180	75.5 → 77.0
Step n. 10	Rest	20	77.0 → 77.0
Step n. 11	Charge @ 1C	27	77.0 → 77.8
Step n. 12	Charge @ C/2	54	77.8 → 78.5
Step n. 13	Charge @ C/3	180	78.5 → 80.0
Step n. 14	Rest	19	80.0 → 80.0

Tests results

Battery capacity is measured in parametric checks after a certain number of repetitions of the profiles versus the total number of repetitions





Tests results

During the life-cycle tests the batteries didn't reach the defined EOL condition (20% capacity loss) → extrapolation

- Type A : a total of 140.000 Ah throughput at EOL was estimated corresponding to a cycle-life of about 1750 charging/discharging phases
- Type B: the estimated value for the Ah throughput at EOL was 36.000 Ah (about 900 charging/discharging phases)



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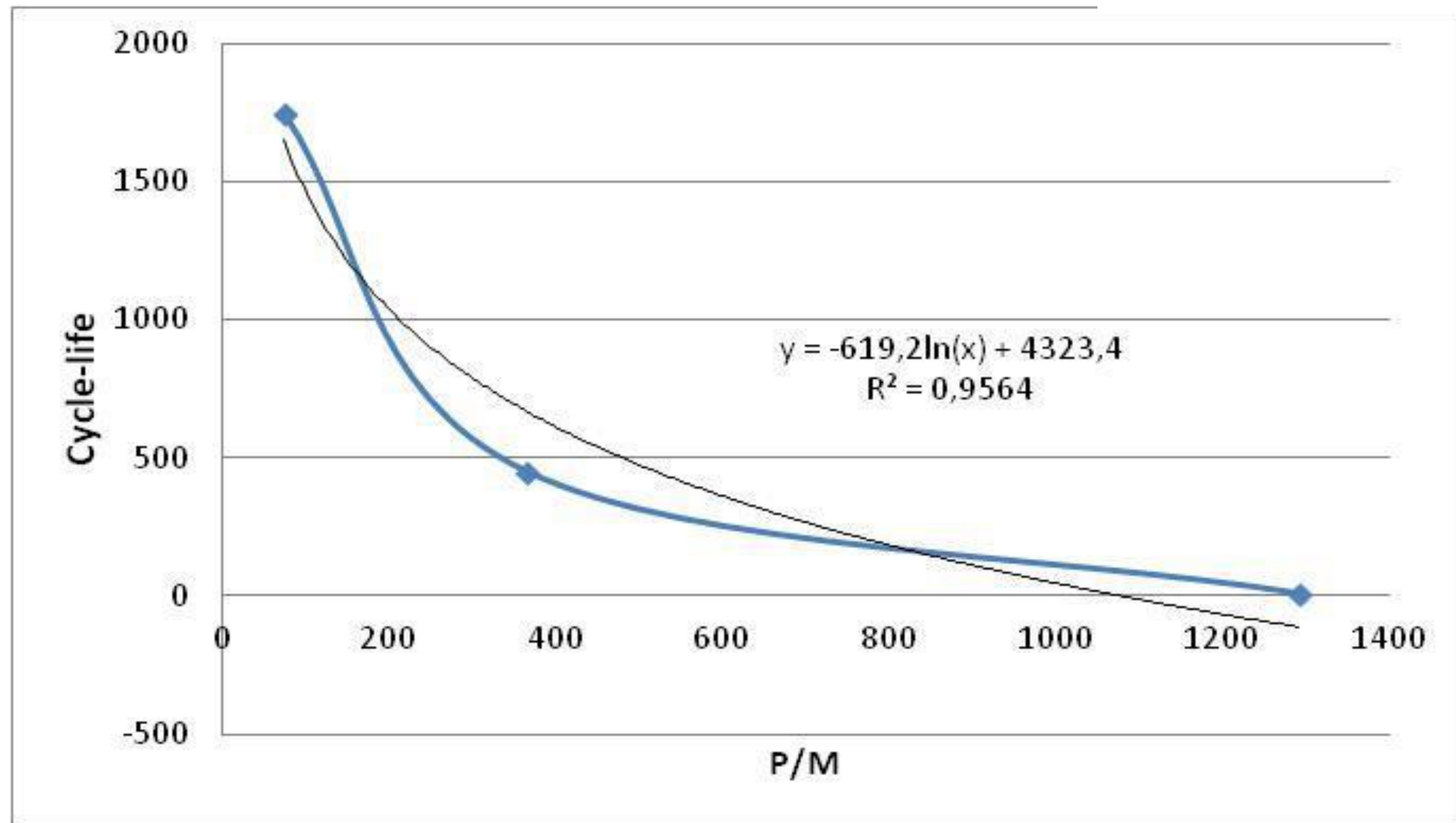
From life-cycle tests to a power law relationship

- Many approaches for battery lifetime prediction have been proposed, but lot of difficulties persist in deriving a quite general model.
- Battery lifetime, or cycle life (CL) depends on many parameters: DOD, design maximum specific power, operating environment, etc.
- Batteries differently stressed show improvements with decrease of required peak-power
 - Type A battery “design” specific power is 75 W/kg
 - Type B battery “design” specific power is 366 W/kg

Battery “design” specific power correspond to the ratio P/M , where P is the battery peak-power and M the battery mass

From life-cycle tests to a power law relationship

“Cycle-life vs. specific power” diagram : log-linear model $N = -a \log\left(\frac{P}{M}\right) + b$



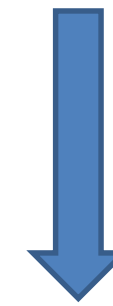


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A numerical application of the power law relationship for battery cost optimisation

- Optimal battery size design over a prefixed time horizon of interest



Find the minimum of the Net Present Value (NPV) of the total investment cost for the battery, I_{batt}

Functional constraints for the battery mass :

- *Maximum power has to be equal or greater than requested power P_{min}*
- *Accumulated energy has to be equal or greater than the requested energy E_{min}*

Reference values for P_{min} and E_{min} must be calculated from the vehicle specifications in terms of acceleration and range.



A numerical application of the power law relationship for battery cost optimisation

Battery initial cost :

$$I_{\text{batt}} = k_M M = k_M \max[P_{\text{min}}/P_s ; E_{\text{min}}/E_s]$$

E_s “specific energy”

P_s “specific power”

k_M cost of the system per kg

$$\text{NPV} = \text{NPV}(I_{\text{batt}}; N) = [NPV]batt\ cost = k_M M \sum_{i=1}^N \left[\frac{1}{(1+r)^{t_i}} \right]$$

N number of battery swap with a timing t_i , and r is the interest rate.

- timing t_i is proportional to the battery life

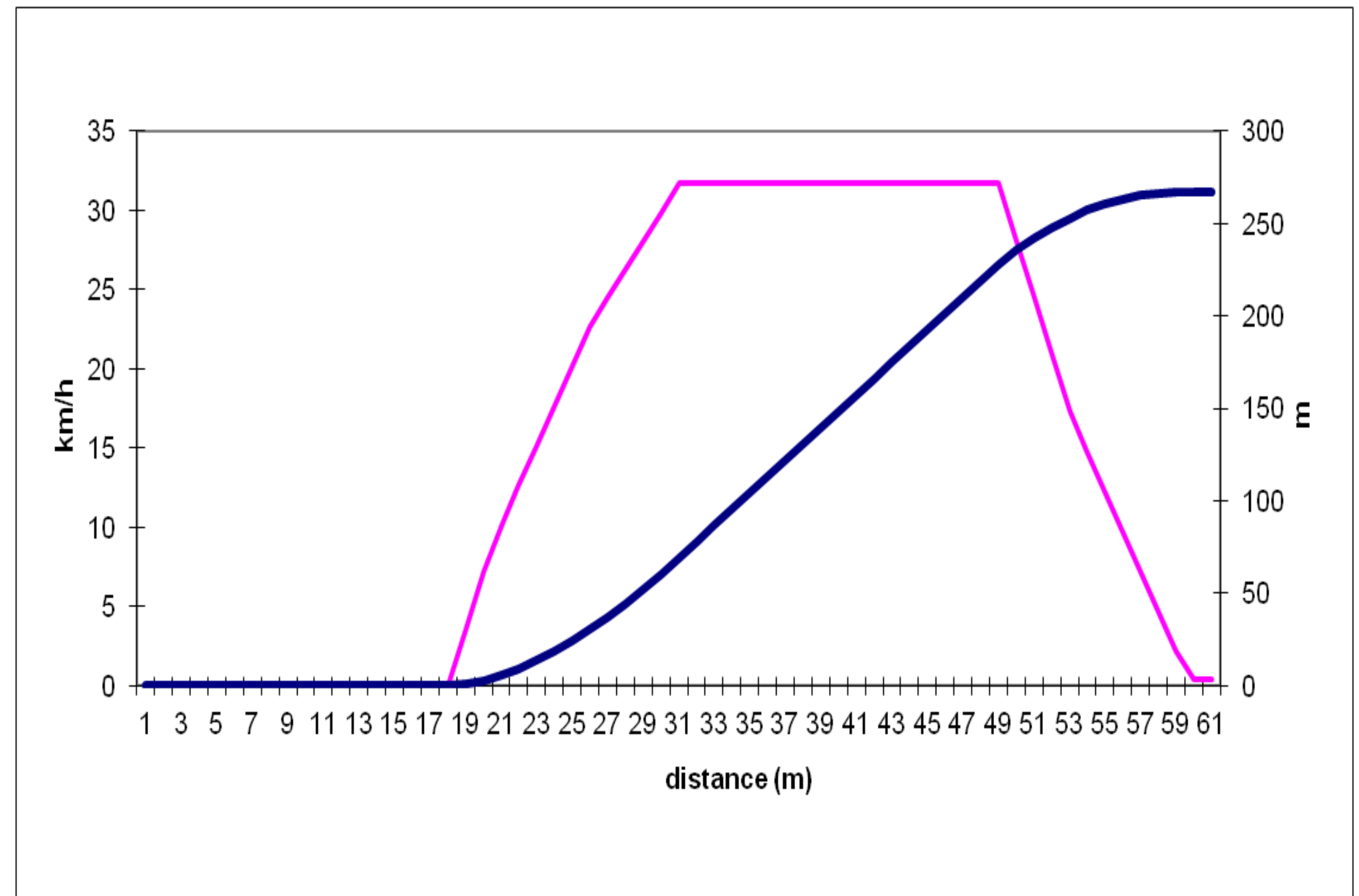
$$[NPM] \text{ batt cost} = R_{bat} M \sum_{i=1}^N \left[\frac{1}{\eta_i} + \eta_i \eta_0 \right]$$



A numerical application of the power law relationship for battery cost optimisation

An application: optimization of the battery size of a Tecnobus Gulliver U520

From technical data, it is possible to calculate the maximum power and the energy consumption on a typical cycle for the bus ECE 32



A numerical application of the power law relationship for battery cost optimisation

An application: a numerical optimization for the battery size of a Tecnobus Gulliver U520

RESULTS FOR A ECE 32 CYCLE

No. <u>Battery</u> <u>modules</u>	M: <u>Battery</u> <u>weight</u> (kg)	Total bus weight (with 5 passengers) (kg)	P/M	<u>Cycle</u> <u>Life</u>
14	266	4516	137	1273
18	342	4592	109	1416
22	418	4668	91	1528
26	494	4744	79	1619

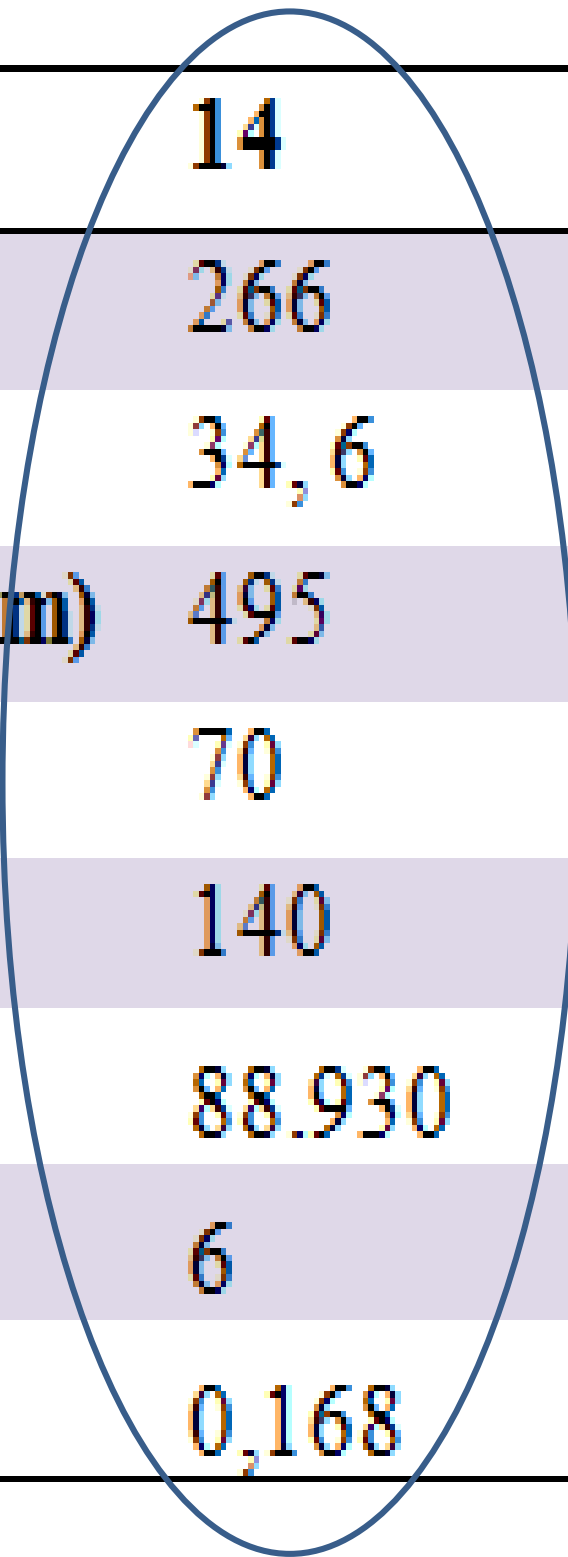
N.B. the design battery parameter P/M is expressed in W/kg



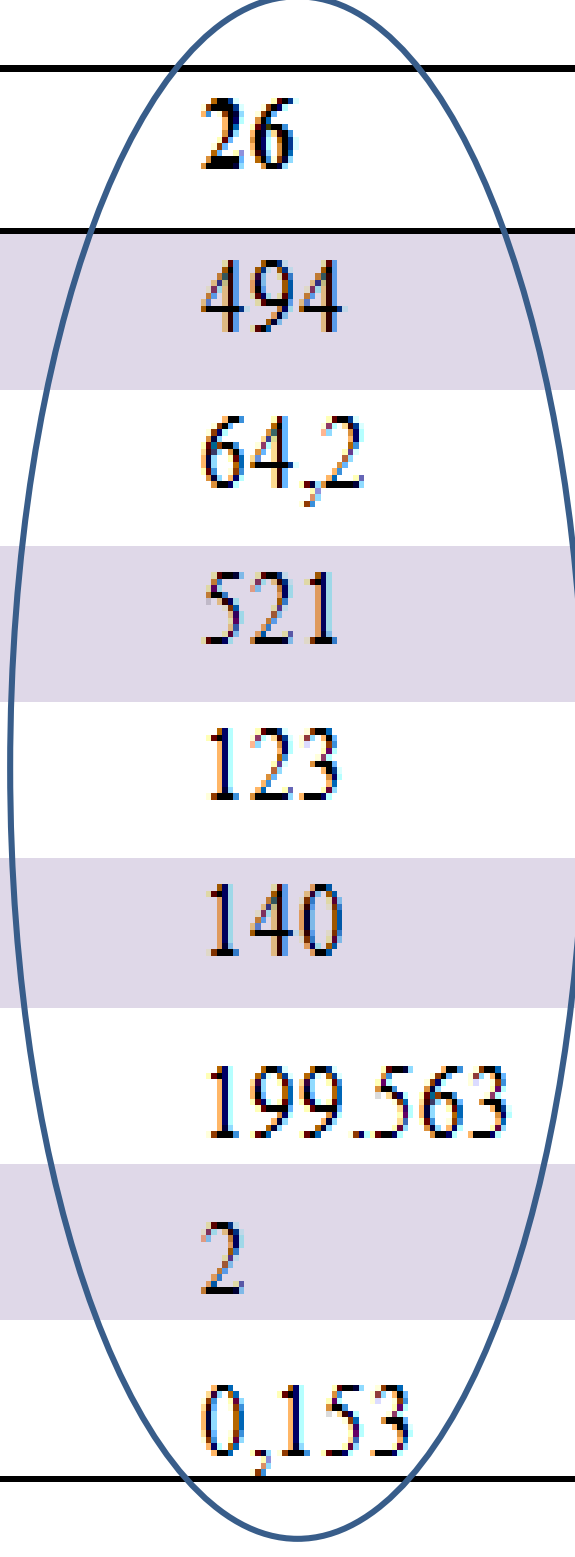
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An application: optimization of the battery size of a Tecnobus Gulliver U520

No. battery modules	14	18	22	26
Battery weight (kg)	266	342	418	494
Energy content (KWh)	34,6	44,5	54,3	64,2
Specific energy consumption (Wh/km)	495	504	513	521
Range in km	70	88	106	123
Daily Covered distance (km)	140	140	140	140
Battery lifetime (km)	88.930	124.911	161.855	199.563
Battery swap	6	4	3	2
Batteries cost per km (Euro)	0,168	0,161	0,156	0,153



Battery n. 1



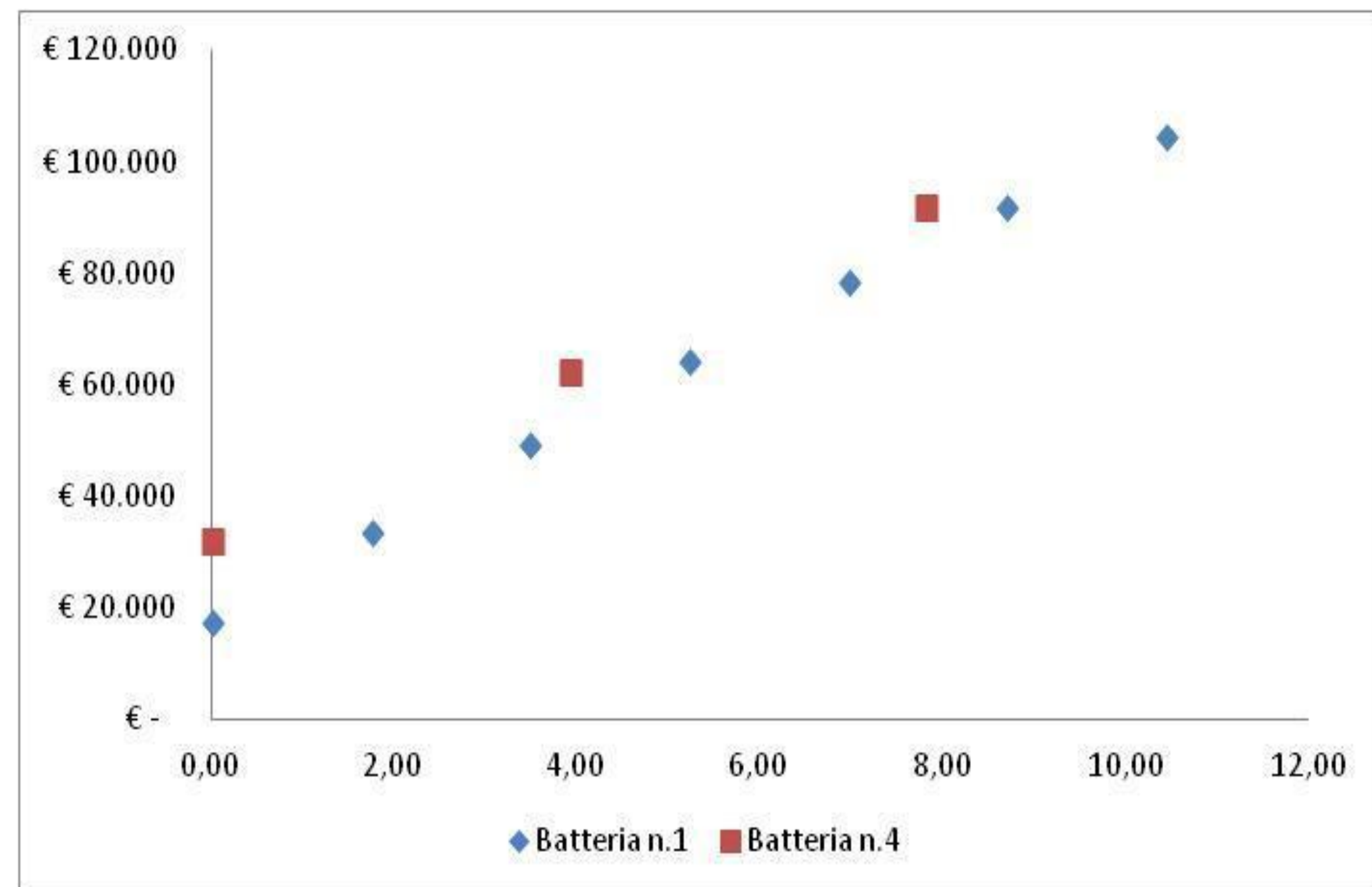
Battery n. 4

A numerical application of the power law relationship for battery cost optimisation

An application: optimization of the battery size of a Tecnobus Gulliver U520

- We calculated the battery cost NPV on the basis of a daily mean distance covered of 140 km
- $k_M = 65 \text{ €/kg}^*$
- $r=0.03$.

* corresponding to 500 €/kWh





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Conclusions

- Testing results of on two battery packs designed around the same cell but subjected to very different C-rates, are reported and discussed with reference to the measured battery ageing.
- A power law relationship, of exponential form, was derived from the experimental results and proposed for predicting the lifetime L of the battery as a function of its mass M and peak power P .
- The total cost of batteries of different sizes for a Tecnobus Gulliver U520 during the bus lifetime have been calculated.
- Increasing battery size increases the initial battery cost but also the battery lifetime  the battery swap frequency decrease, and, as a consequence, total and specific (per km) battery costs decrease



**WAKE
UP
AND**

**THANK YOU FOR
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THANK YOU
FOR
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ANY QUESTIONS?