



EMRailS 2019
Electrical Measurements for Energy
Management in Railway Systems
WORKSHOP
Naples 21 February 2019

Simulation, Design and Monitoring of Energy Storage Systems for Railway Applications



Dr Luca Pugi-Short Bio



LUCA PUGI Born 07-06-1974 Florence Italy

1999-Degree in mechanical engineering in 1999 from the University of Florence, Italy, (Thesis on High Speed Pantograph)

2003-PHD in Applied Mechanics in 2003 from the University of Bologna, Bologna, Italy. (Phd Thesis on HIL Testing of WSP and Odometry Systems)

From 2004 Researcher at University of Florence

Didactical Activities (2016-2018) :

1)Mechatronics Course for Mechanical Engineers at University of Florence

2)Road and Railway Traction Systems for Mechanical, Electrics and Automation Engineers at University of Florence

Research Activities and Interests

Mechatronics, Vehicle Dynamics, Automation and Smart Actuation of Fluid and Electric Systems.

Bibliometric Statistics:

H-Index 19 <http://orcid.org/0000-0001-7385-9471>, (over 170 indexed publications more than 250 publications, over 1000 citations)

AWARDS:

- 1) **2000 “Cesare Bianchi Awards” –CIFI (ITALIAN RAILWAY ENGINEERS ASSOCIATION)** for best experimental thesis with railway topic (active control of railway pantographs).
- 2) **2009 “Mallegori Award” –CIFI (ITALIAN RAILWAY ENGINEERS ASSOCIATION)**
- 3) **2011 “Award-Increasing freight capacities and services”-WCRR 2011 (World Congress for Railway Research)**
- 4) **2015 Don Miller Award 2015 for excellence in system level thermo-fluid design** (Selected/mentioned/runner up, Mentor Graphics) (<http://www.prnewswire.com/news-releases/mentor-graphics-announces-winners-of-don-miller-award-for-thermo-fluid-design-excellence-300173620.html>)
- 5) **2015, The John F Alcock Memorial Prize (Serial 328)**, (award from Railway Industry Association of Great Britain/ IMECHE for a paper concerning Railway Odometry Systems) <http://www.imeche.org/knowledge/industries/railway/prizes-and-awards/alcock-memorial-prize>

Patents:

Six Patents: (three National/ three International)

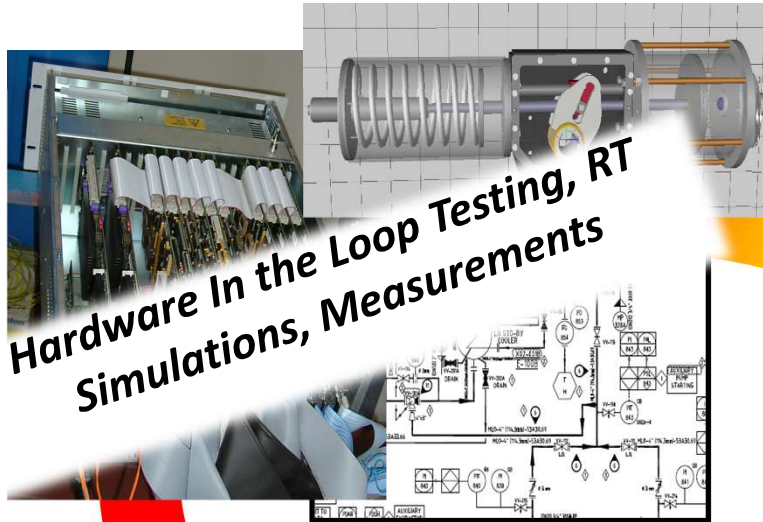
Industrial References (for railway sector):

- **Development of WSP Odometry Test Rig of Trenitalia (Now ITCF)**
- **Development and testing of SCMT algorithm for Trenitalia (various cooperations with other ind. partners)**
- **Consultant for Italcetifer as VIS and CTP for Trenitalia (braking plants/on board subsystems)**
- **Partecipation to real exp. Tests with WSP and Odometry systems (Velim Test Circuit , and other italian lines)**

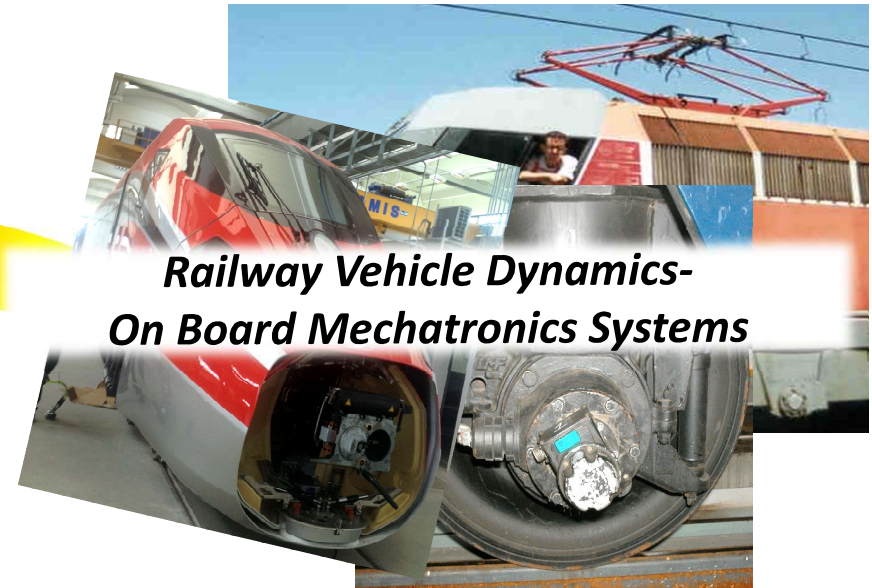


Research and Industrial Back-Ground

**Hardware In the Loop Testing, RT
Simulations, Measurements**



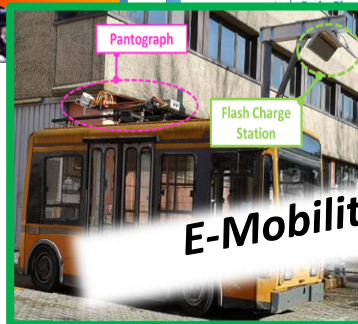
**Railway Vehicle Dynamics-
On Board Mechatronics Systems**



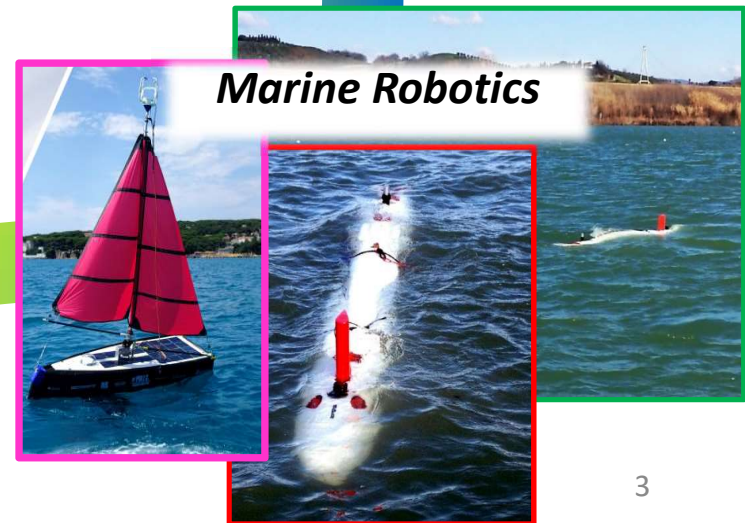
**Suspensions, Impedance
and Vibration Control**



E-Mobility



Marine Robotics



Energy Storages For Railway (examples)

On Board Storage Systems

Backup Units

On Board Regeneration of Electric Braking*

Discontinuous Current Collection (with conventional or wireless current collection)**

Hybrid Traction System (Fuel Cells + Battery)

Full Battery Powered Traction Systems

Stationary Storage Systems

Backup Units

Increased Efficiency of Lines (regeneration/reduced voltage drop etc.)*

*Frilli, A., Meli, E., Nocciolini, D., **Pugi, L.**, Rindi, A.. Energetic optimization of regenerative braking for high speed railway systems (2016) Energy Conversion and Management, 129, pp. 200-215 DOI: 10.1016/j.enconman.2016.10.011

Alessandrini, A., Barbieri, R., Berzi, L., Cignini, F., Genovese, A., Locorotondo, E., Ortenzi, F., Pierini, M., **Pugi, L.; Design of a hybrid storage for road public transportation systems (2019) Mechanisms and Machine Science, 68, pp. 149-157. DOI: 10.1007/978-3-030-03320-0_16

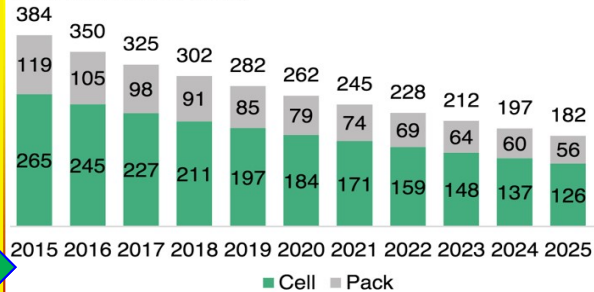
Opportunities from Other Markets:

1°

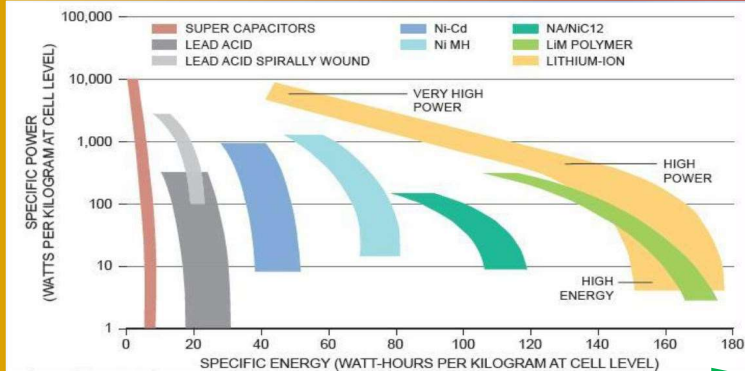
**Large Scale
Production &
Tech. Improv.**

Battery Prices Keep Tumbling

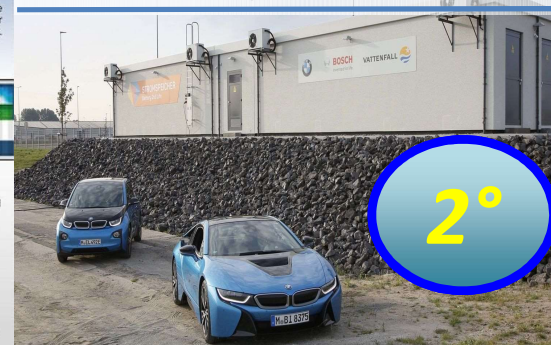
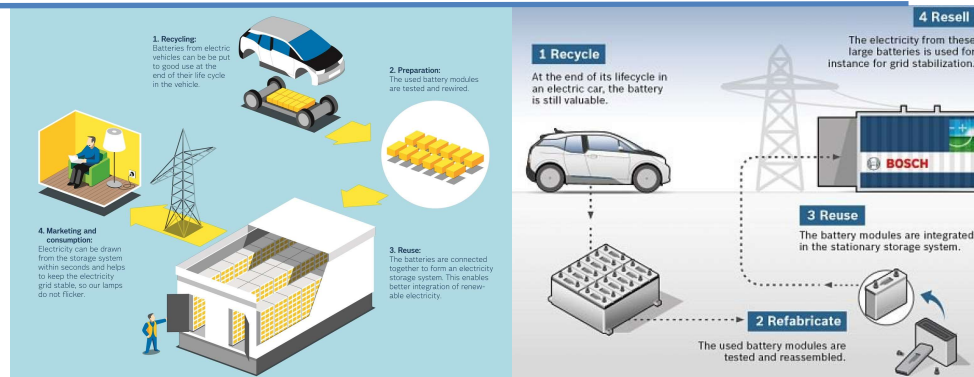
Lithium Ion Forecast (\$/kWh)



Source: Bloomberg New Energy Finance



Second Life Opportunities

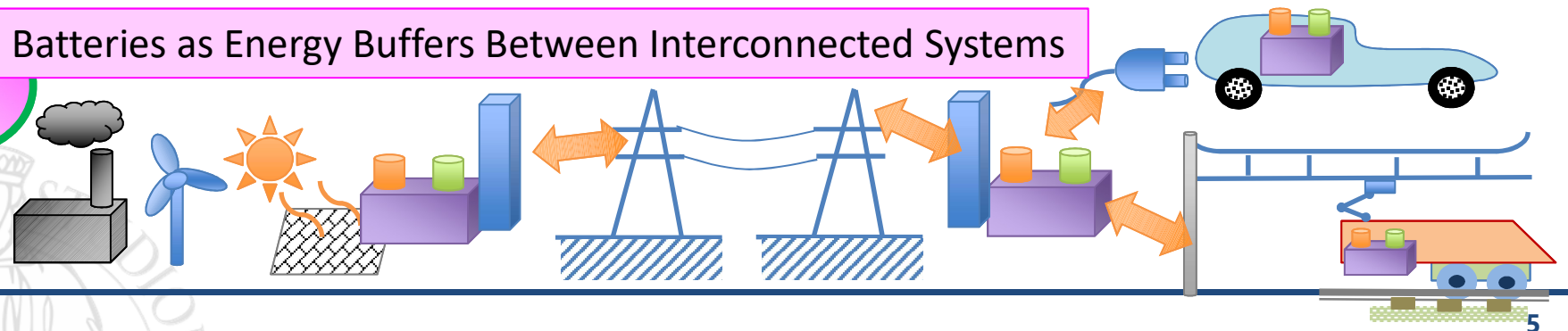


BMW has inaugurated a second-life battery facility at the BMW i3 factory in Leipzig. The phrase "second life" means that after a battery pack's first life as the traction battery in a car, it can be repurposed as an energy storage unit.

2°

Batteries as Energy Buffers Between Interconnected Systems

3°



SOC & SOH Introduction

SOC (State Of Charge) \longrightarrow $SOC = \frac{E}{E_{\max}}$

SOH (State Of Health) $\left\{ \begin{array}{l} \longrightarrow SOH = \frac{E_{\max}}{E_{\text{nom}}} = \frac{C}{C_{\text{nom}}} \longrightarrow \\ \longrightarrow \text{Increase of Internal Resistances and Losses} \end{array} \right.$

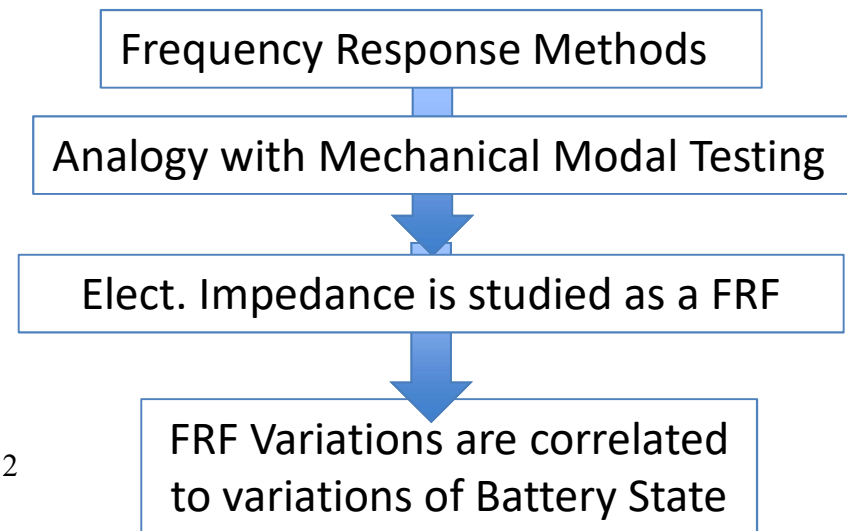
Cycle Aging//Time Aging//
Vib. Induced Aging etc.etc.

Ampere Count Methods

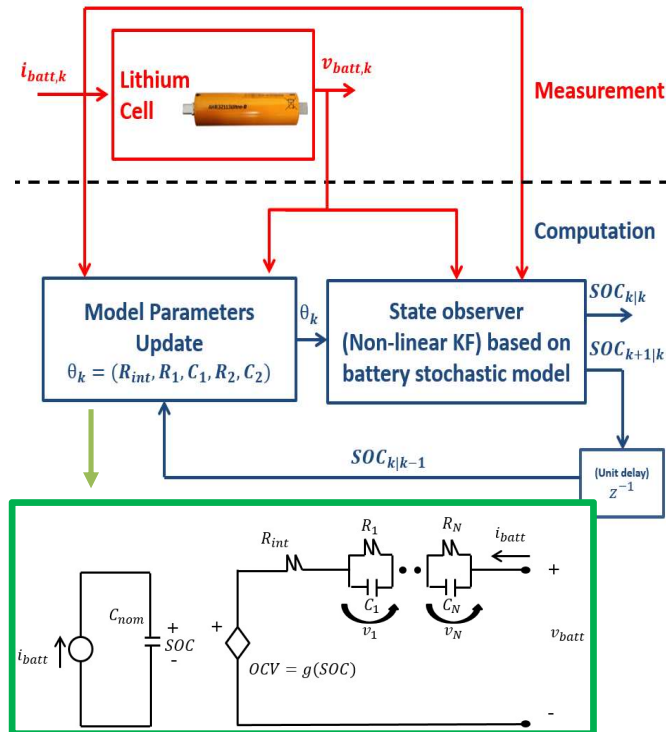
SOC Estimation \longrightarrow $Q = \int Idt \Rightarrow$

SOH Estimation \longrightarrow

$$\left\{ \begin{array}{l} E = \int VIdt; \\ V = V_{oc} + RI; \\ V_{oc} = f(Q); \\ R = g(T); \end{array} \right. \quad \left\{ \begin{array}{l} \frac{\int Idt}{\Delta SOC} \propto C \\ |E_{exc} - E_{\max}| \propto \int RI^2 \end{array} \right.$$



Ampere Count Methods: Example/1



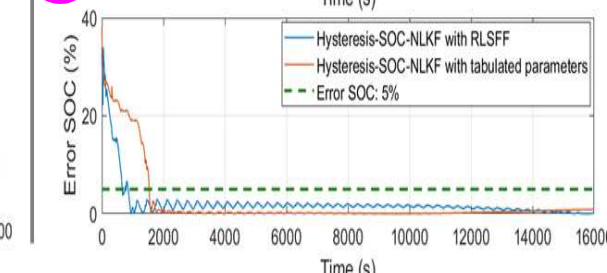
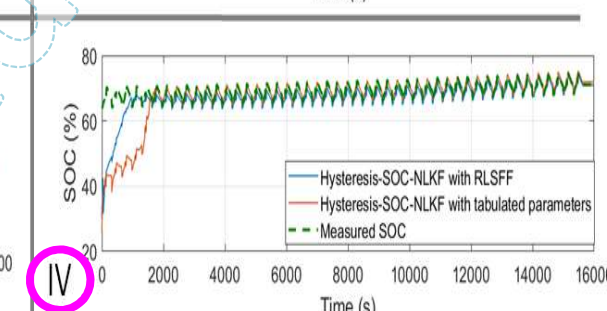
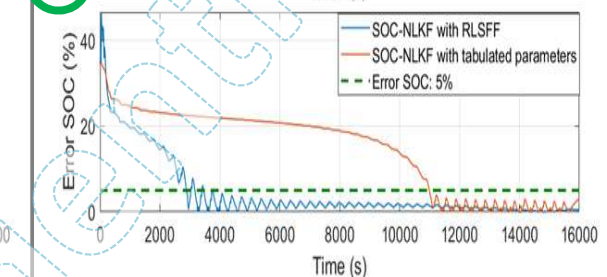
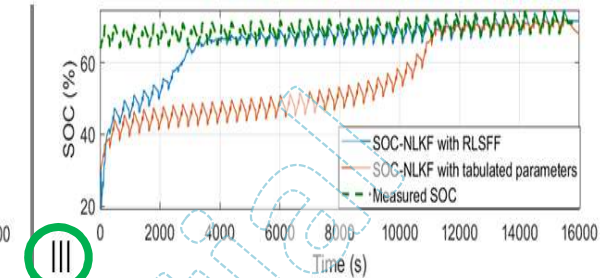
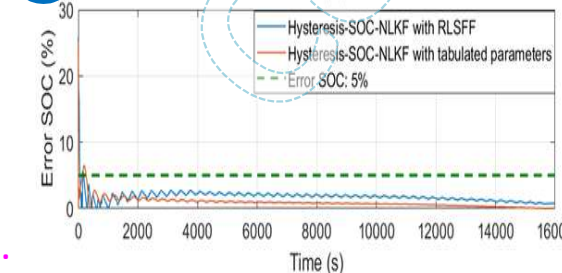
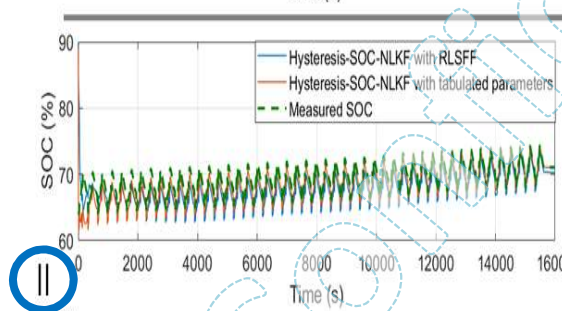
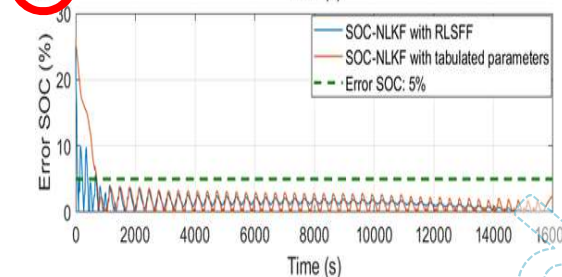
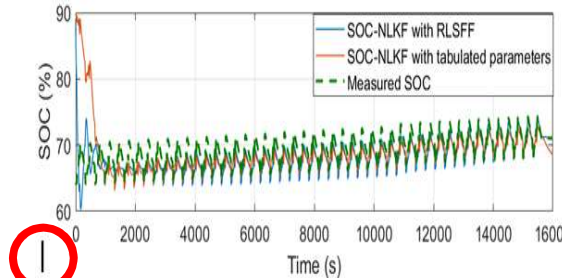
Not only SOC but also internal parameters of Battery Lumped Models are estimated

SOC-NLKFs NO hyst. model (I)

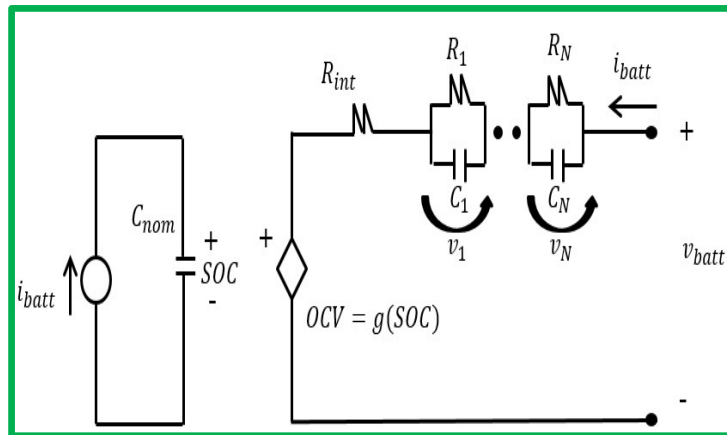
SOC-NLKF hyst. model init. SOC 90% (II)

SOC-NLKFs NO hyst. init. SOC 30%(III)

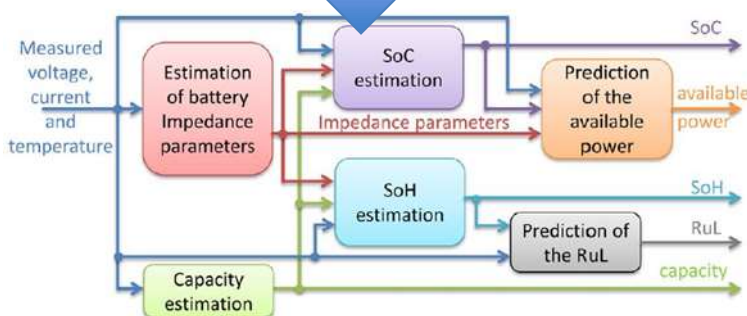
SOC-NLKFs hist model init. SOC 30% (IV).



Multiscale Extension → From SOC to SOH



Diffrent/time/cycle Scaling of similar estimation techniques on the same models



Waag, W.; Fleischer, C.; Sauer, D.U. Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles. J. Power Sources 2014, 258, 321–339.

SOC variations

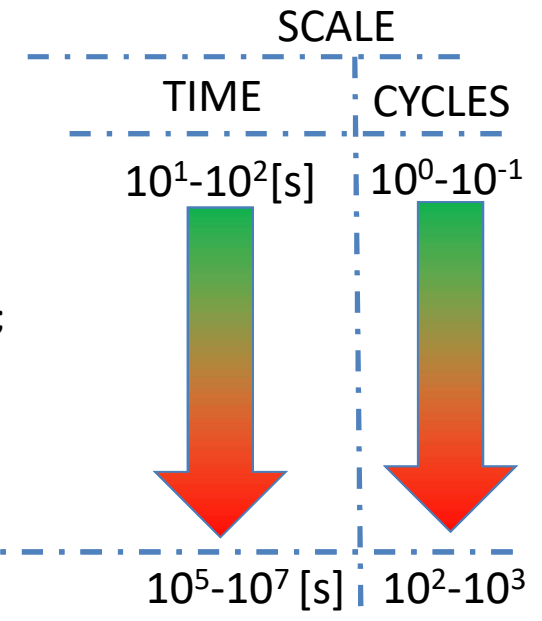
$$R_{int} / R_1 / R_n$$

Mainly influenced by temperature;
Battery Capacity is Approximately
invariant



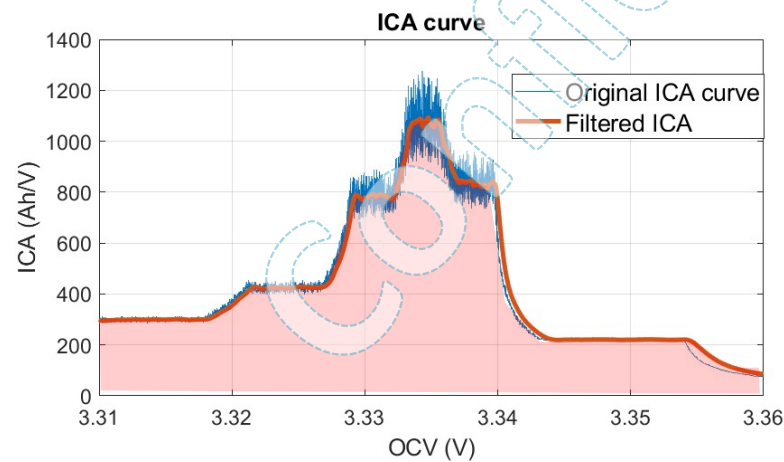
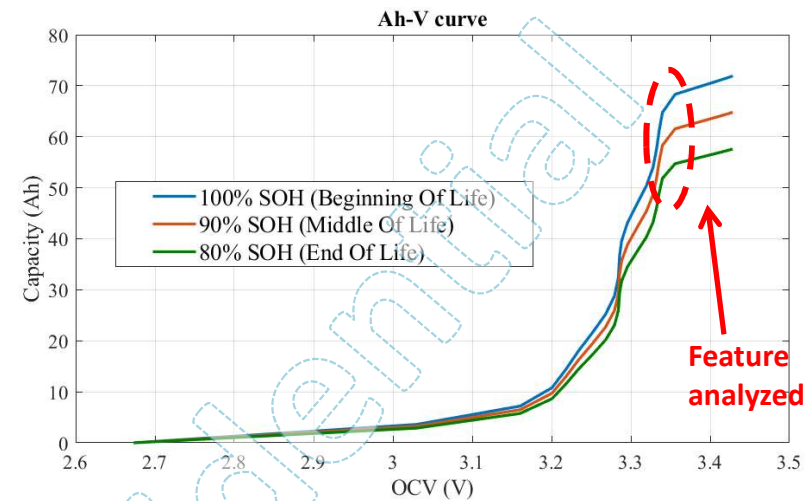
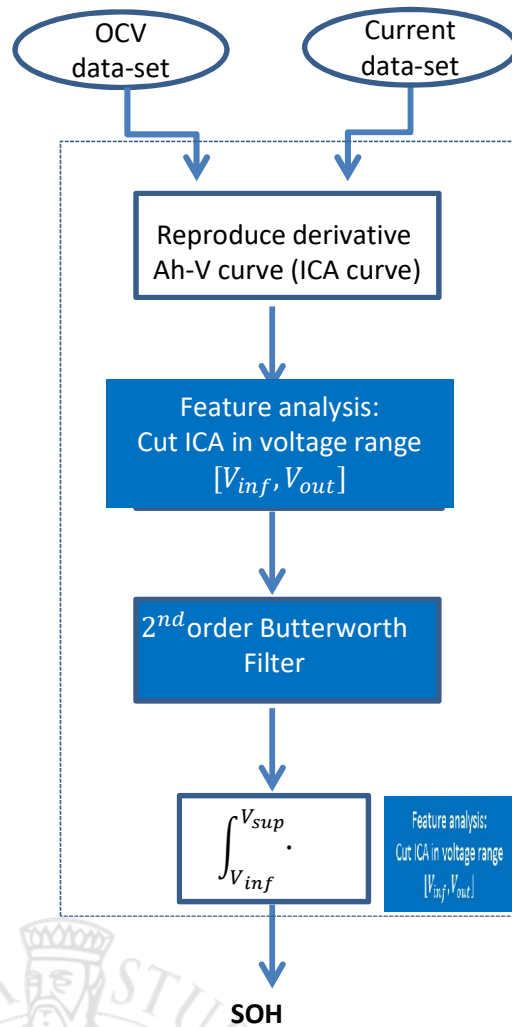
SOH variations

- Slow variations of mean values of storage impedance depends from aging
- Same SOC variations (calculated assuming costant batt. capacity) after hundreds of cycles are associated to different values of the current integral



Ampere Count Methods: Example/3

Specific Features of the Battery OCV curve should be exploited to estimate aging effects.



Key Benefit respect to Ampere Count Method:

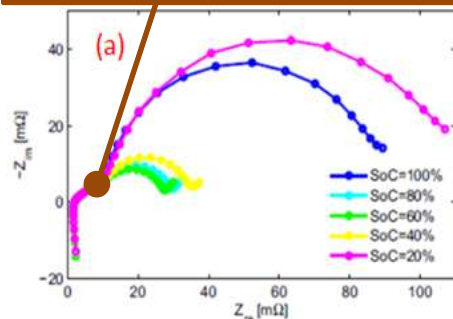
- Faster measurement
- It's not need a significant variation of SOC
- More robust respect to self discharge of batteries
- More robust respect to measurement errors of small currents

Drawbacks respect to Ampere Count Methods:

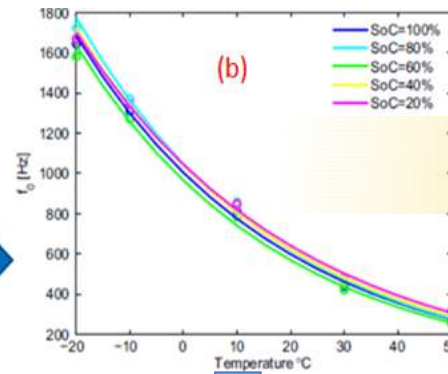
- High frequency dynamics of the storage as to be properly excited (10^2 - 10^3 Hz)
- High frequency acquisition and signal data conditioning
- More demanding in terms of computational resources

Freq. Response Methods: Examples/2

$$\text{Im}(Z(f_0)) = 0$$



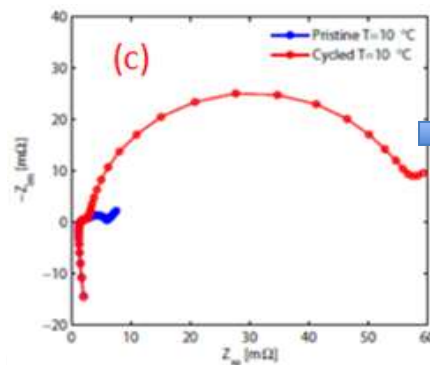
FRF of Z is affected by SOC



f_0 Depends mainly
From T

SOC and Temp. Estimation

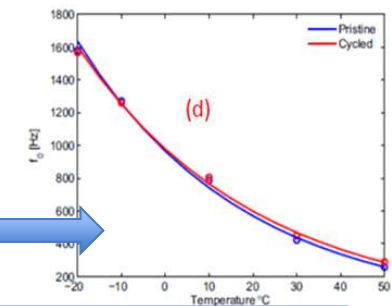
- SOC fluctuations are associated to Variations of freq. Response
- Value of f_0 mainly depends on temperature



SOH degradation is associated to
Variations of freq. Response.

Value of f_0 mainly depends on temperature

SOH and Temp. Estimation



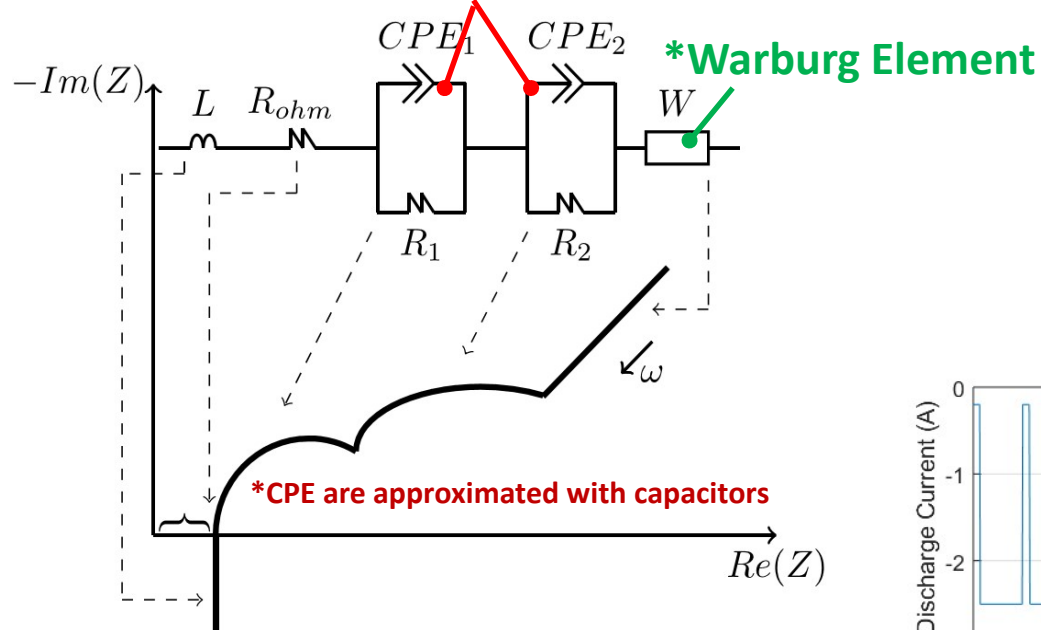
*Ranieri, M., Alberto, D., Piret, H., Cattin, V. Electronic module for the thermal monitoring of a Li-ion battery cell through the electrochemical impedance estimation (2017)

Microelectronics Reliability, 79, pp. 410-415. DOI: 10.1016/j.microrel.2017.06.010

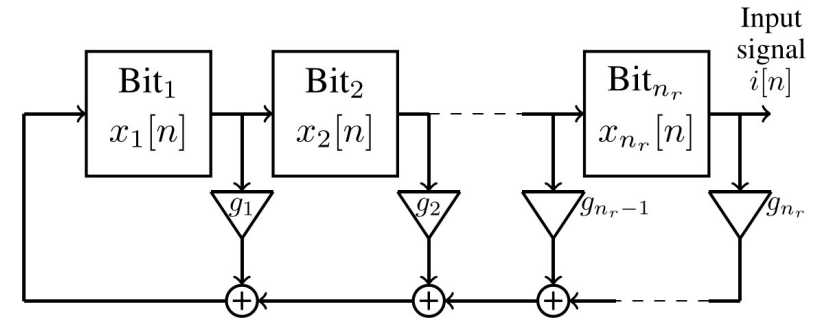
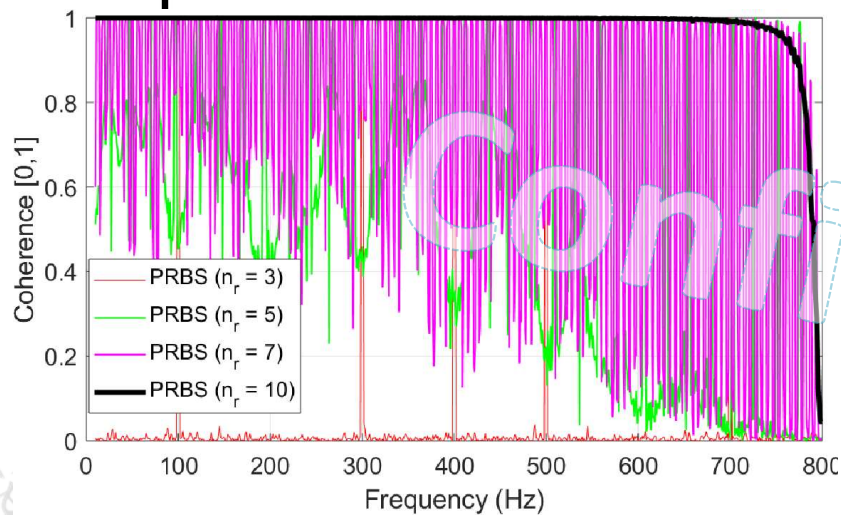
**H.P.G.J. Beelen, L.H.J. Raijmakers, M.C.F. Donkers, P.H.L. Notten, > H.J. Bergveld, "A comparison and accuracy analysis of impedance-based temperature estimation methods for Li-ion batteries," Applied Energy, > vol. 175, pp. 128-140, 2016.

Freq. Response Methods: Examples/3

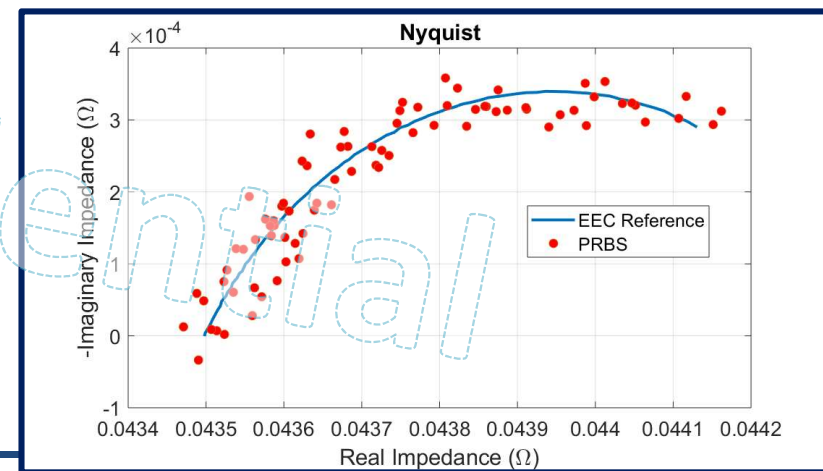
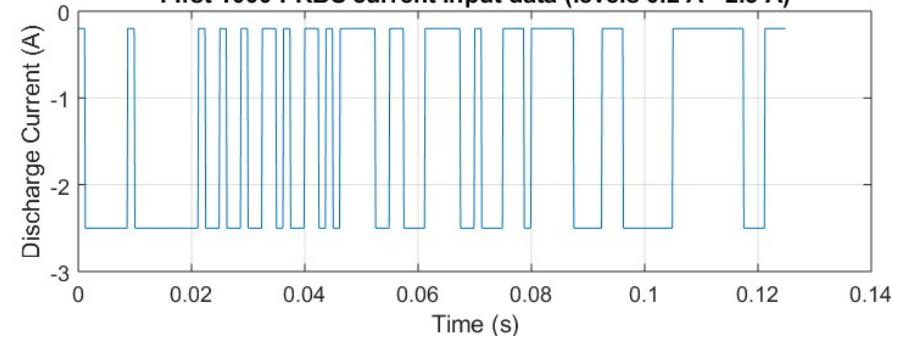
***Constant Phase Elements**



***CPE are approximated with capacitors**

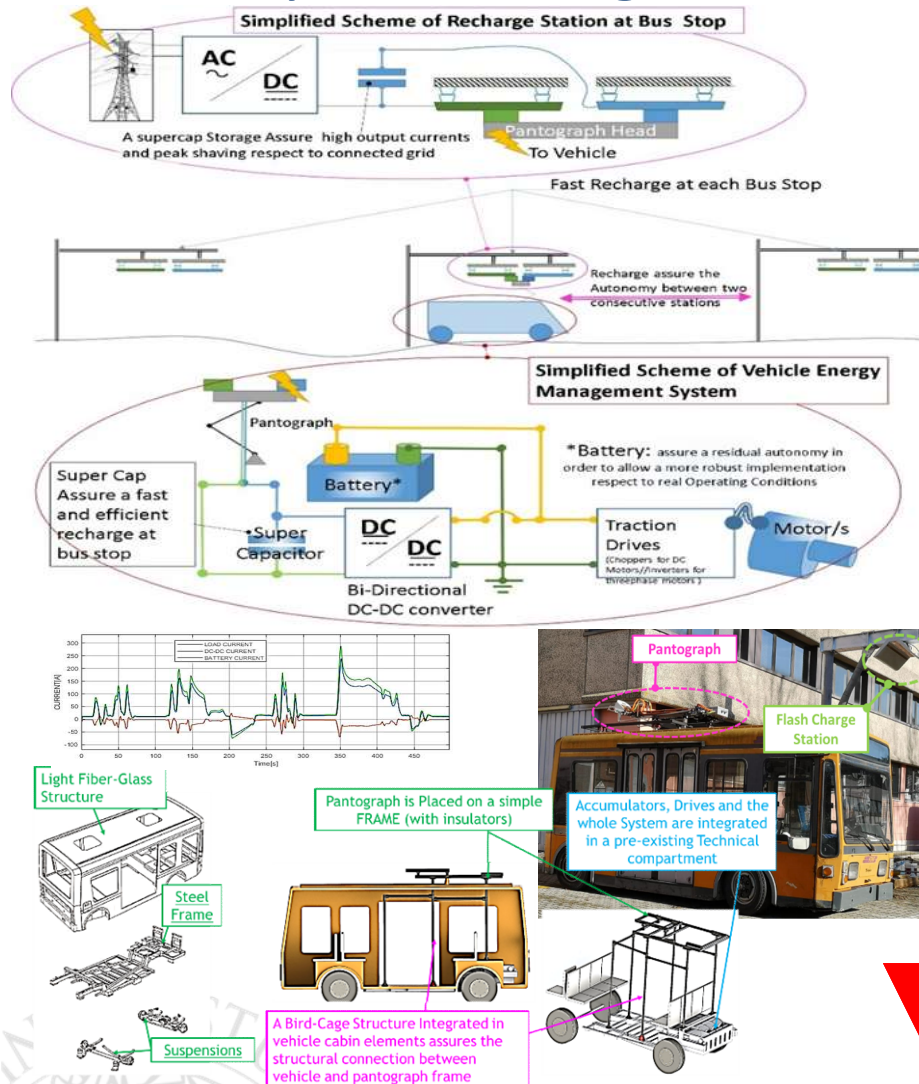


First 1000 PRBS current input data (levels 0.2 A - 2.5 A)



Re-Charge Innovations

Flash Hybrid Charge ENEC

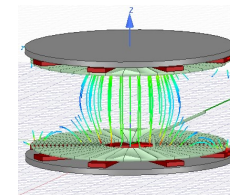


Alessandrini, A., Barbieri, R., Berzi, L., Cignini, F., Genovese, A., Locorotondo, E., Ortenzi, F., Pierini, M., Pugi, L. Design of a hybrid storage for road public transportation systems (2019) Mechanisms and Machine Science, 68, pp. 149-157. DOI: 10.1007/978-3-030-03320-0_16

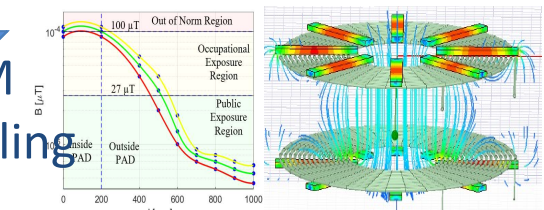


Wireless Power Transmission
Applications:

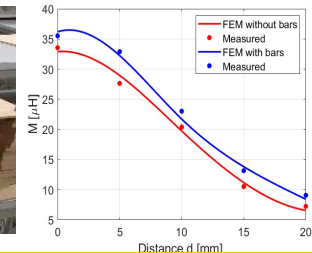
Maglev; Parking; Contact-Less Recharge etc.;



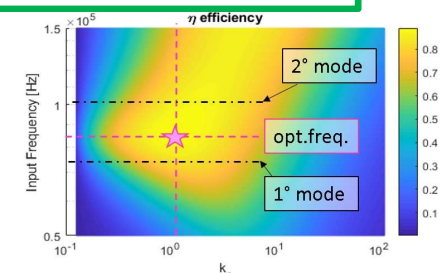
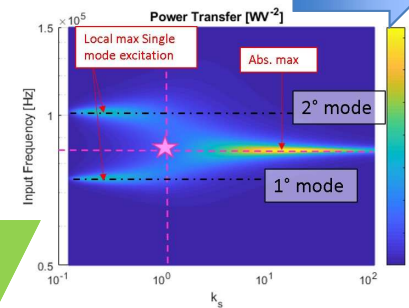
FEM
Modelling



Exp. Validation

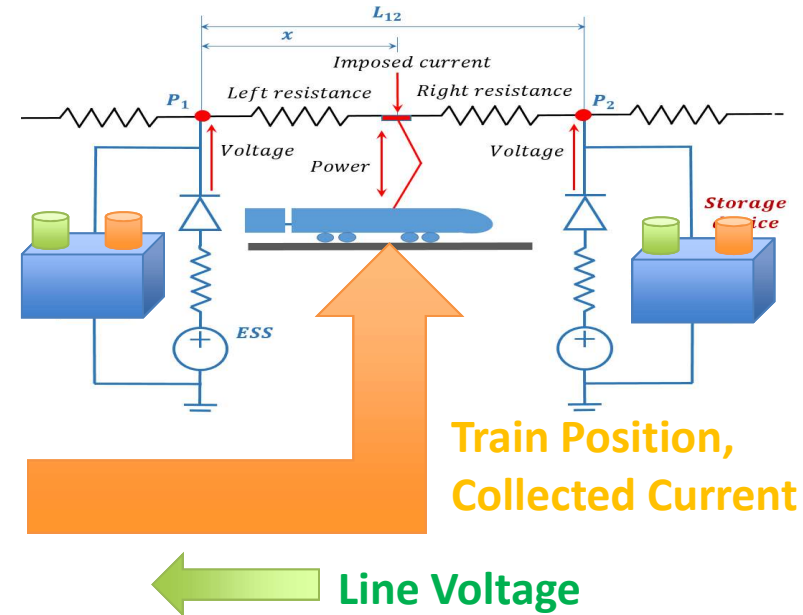
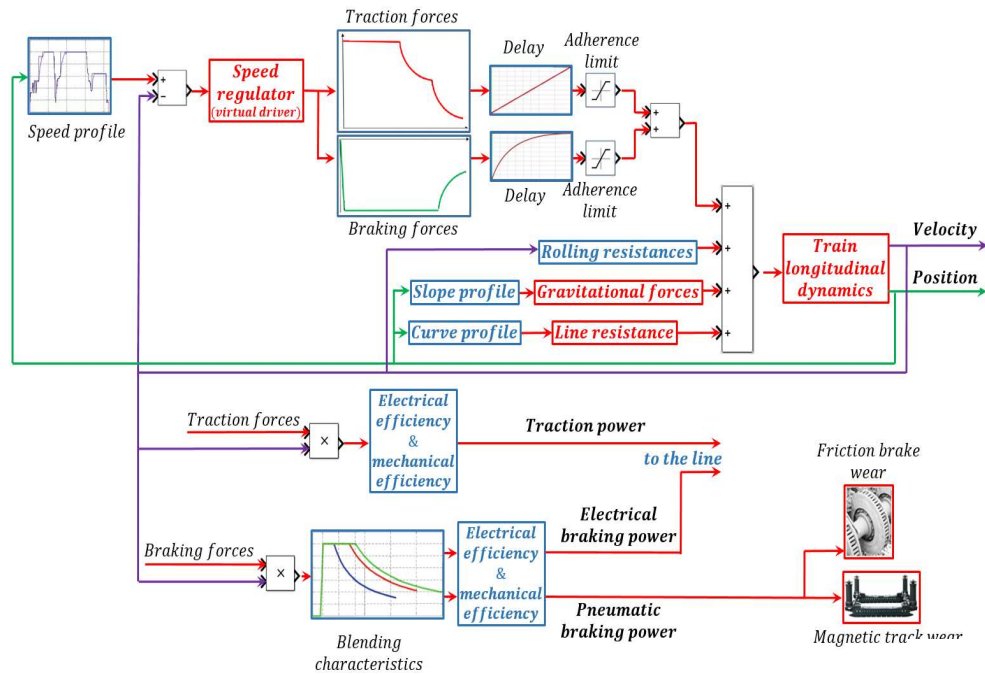


Adv. Modal Opt.

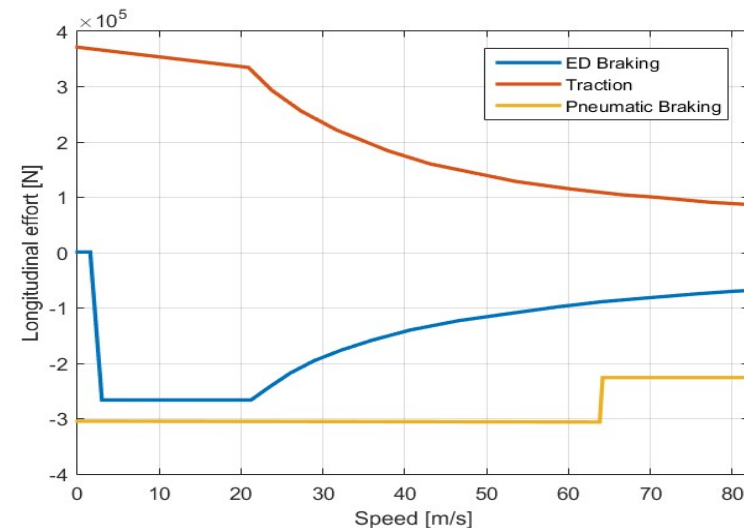
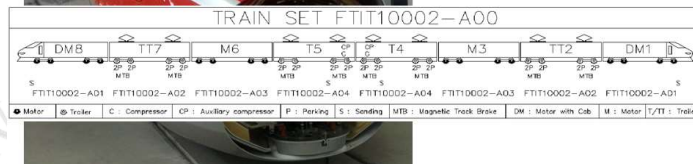


Pugi, L., Reatti, A., Corti, Application of modal analysis methods to the design of wireless power transfer systems (2019) Meccanica, 54 (1-2), pp. 321-331. DOI: 10.1007/s11012-018-00940-x

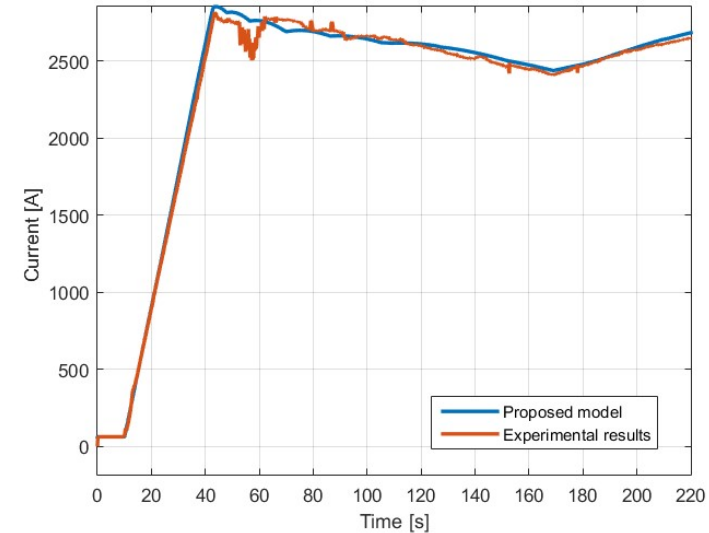
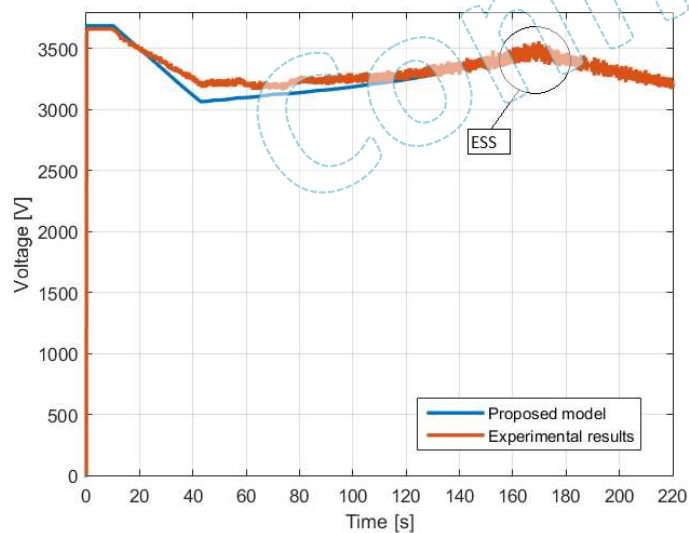
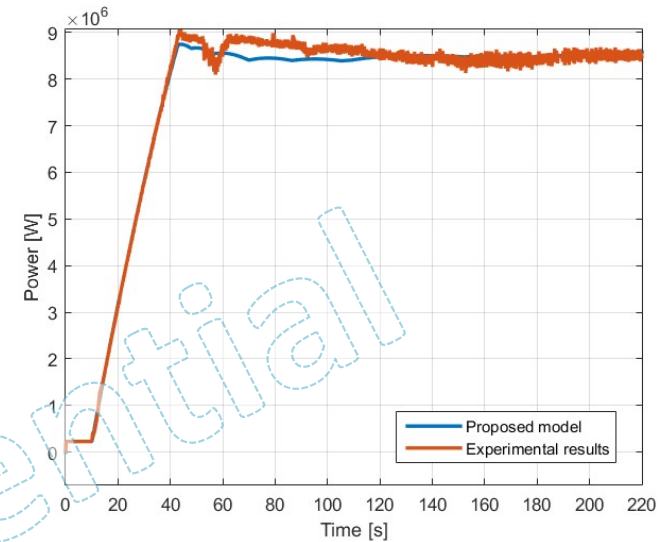
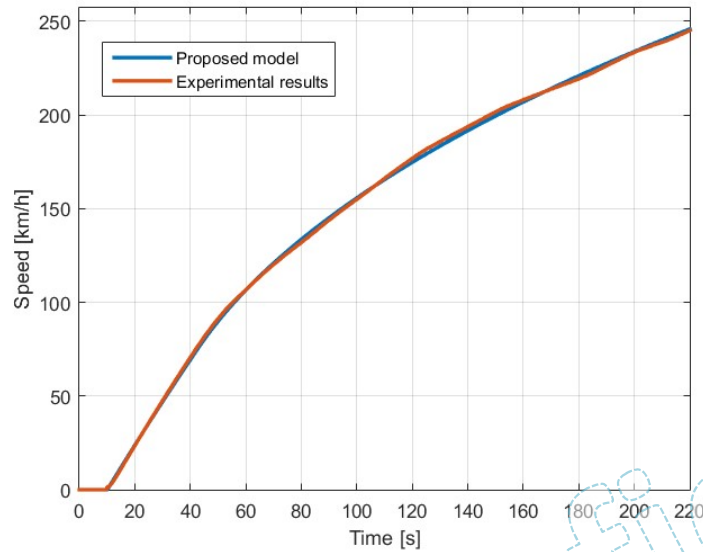
Storage Integration In Railway Systems



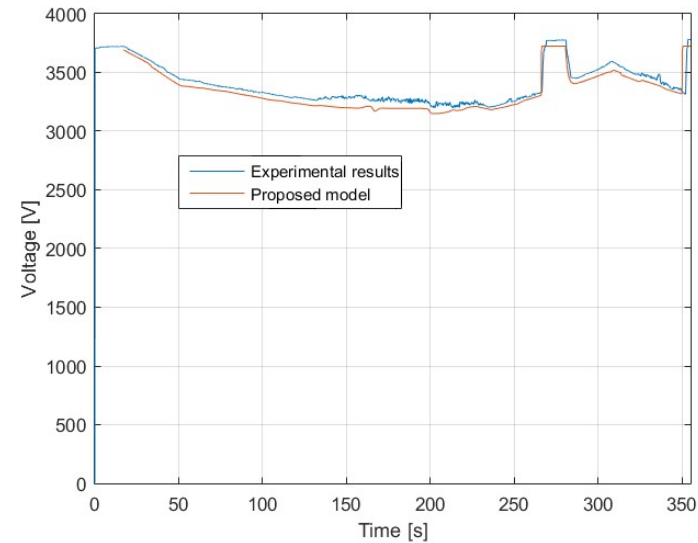
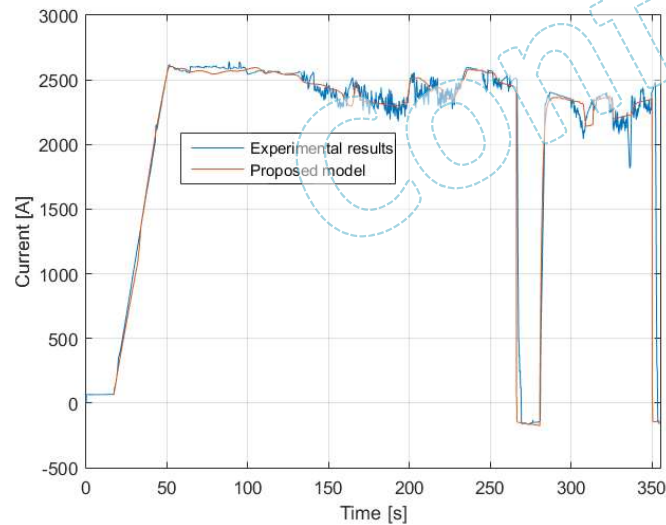
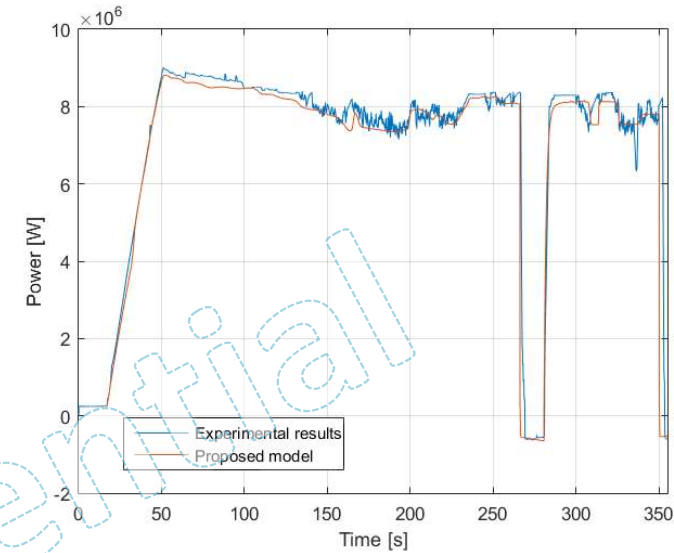
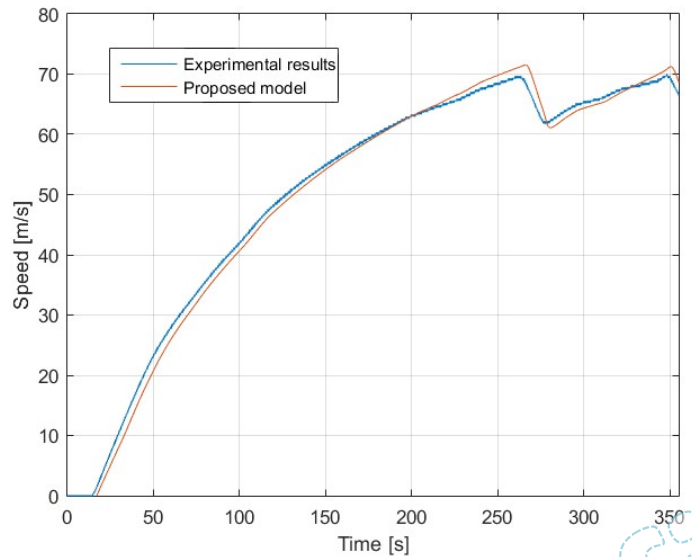
Train mass	495 t
Motorized weight fraction	0.5
Nominal power	9.8 MW
Nominal speed	300 km/h
Brake pad 1	0.1-0.15 cm ³ /MJ
Brake pad 2	0.1-0.21 cm ³ /MJ
Line impedance	0.05 Ω/km
ESS equivalent impedance	0.1 Ω
ESS no-load voltage	3700 V
Mean distance between ESSs	14.7 km
Max. distance between ESSs	76 km
Min. distance between ESSs	12 km



Integration In Railway System: Validation

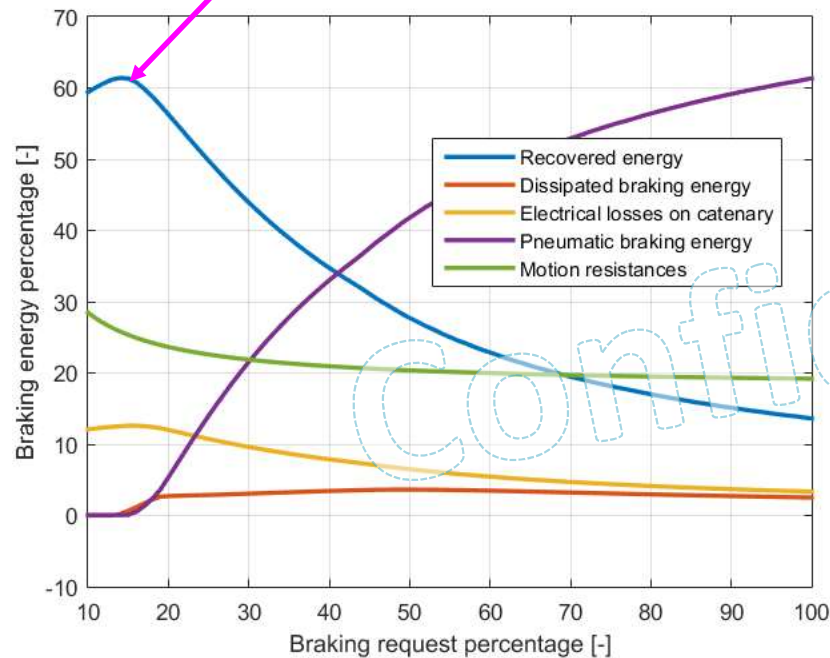


Integration In Railway System: Validation

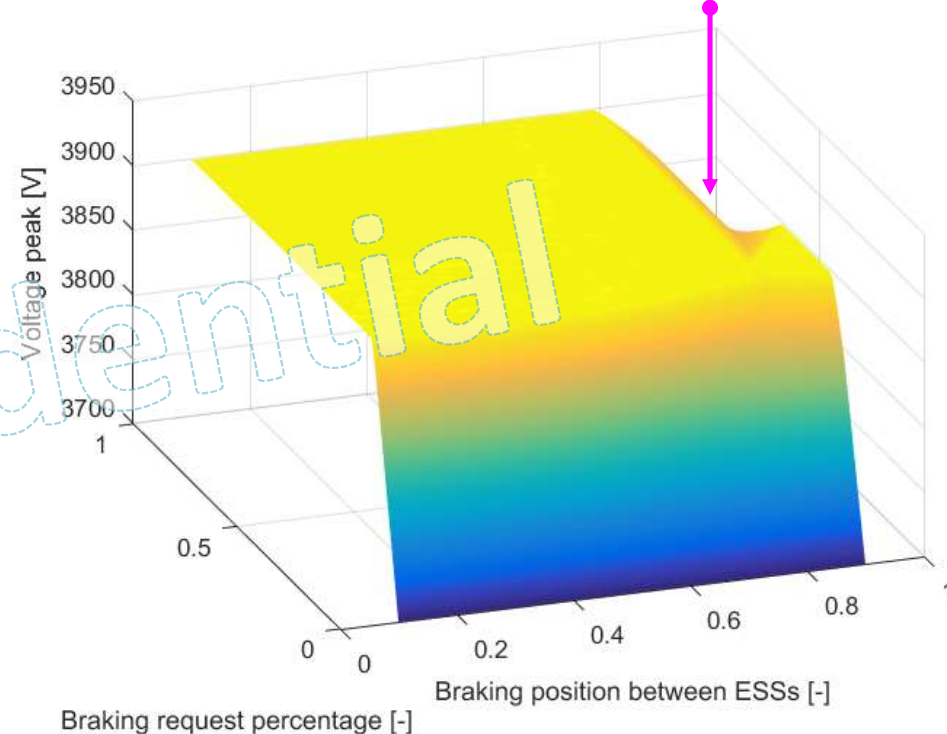


Integration In Railway System: some Results

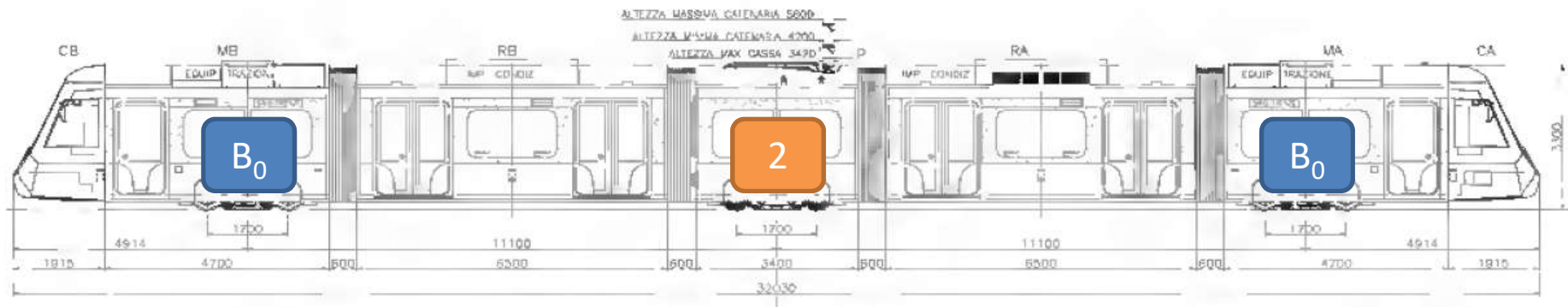
A Smooth Braking is preferable in terms of efficiency



Higher efficiency when brake occurs near a storage



Storage Integration In Tramway Systems

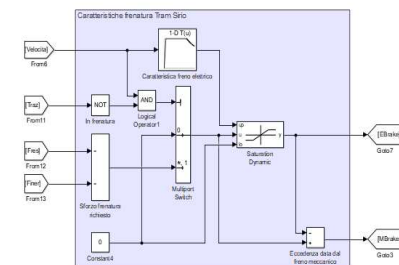
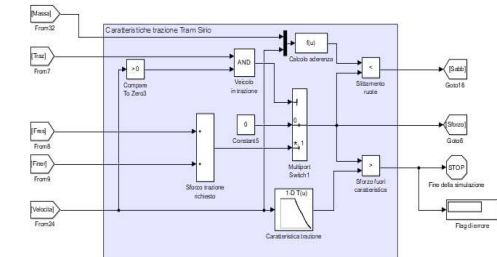
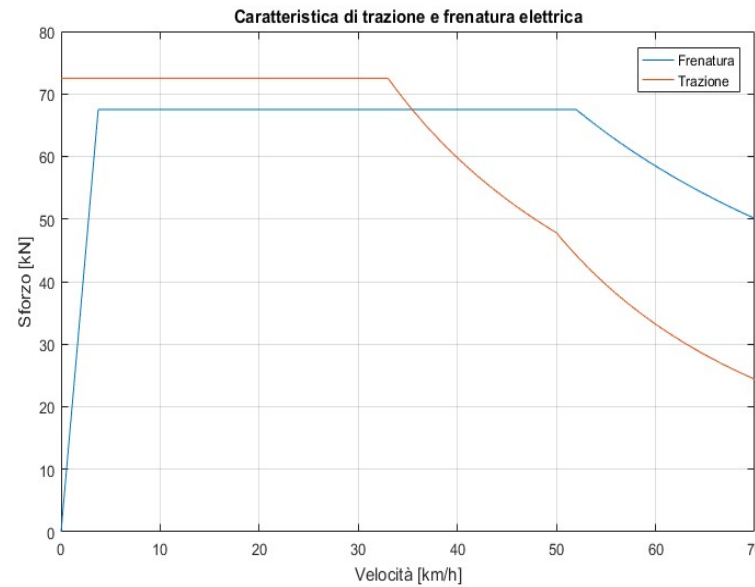
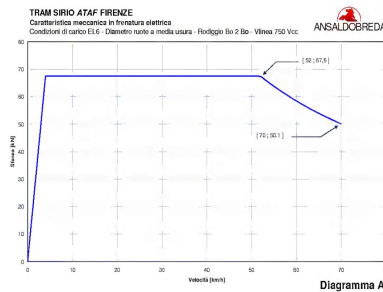
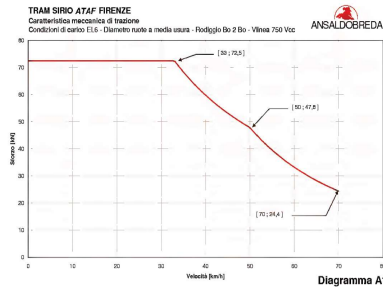


Source: tram Sirio Firenze - descrizione generale del veicolo per il progetto esecutivo della linea 1, AnsaldoBreda, 2007

Length	32030 mm
Width	2400 mm
Height (vehicle with lowered pantograph)	3414 mm
Tare	39.768 t \pm 4%
Max Weight (full loaded)	58.808 t \pm 4%
Axle Load	About 11 t
Un-sprung Mass (/axle)	1.25 t

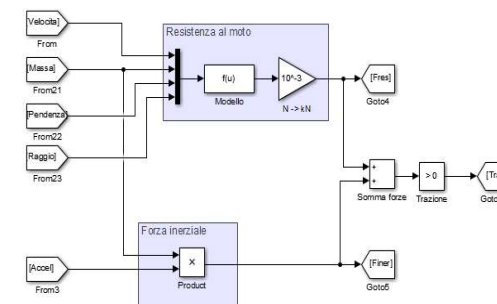
Max Speed	70 km/h
Residual Acceleration	$>0.1 \text{ m/s}^2$
Mean Acceleration 0 – 40 km/h	1 m/s^2
Jerk	1.1 m/s^3
Max Slope	7%
Electric Actuated Pantograph with carbon contact shoes	
Nominal Voltage	750 (+20%, -33%) Vcc
Continuous Collected Current	1200 A
Max Standstill Current	300 A

Storage Integration In Tramway Systems

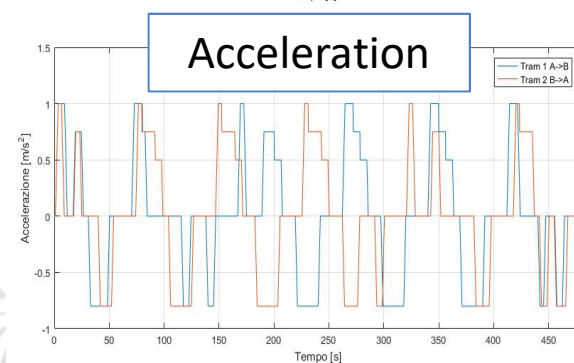
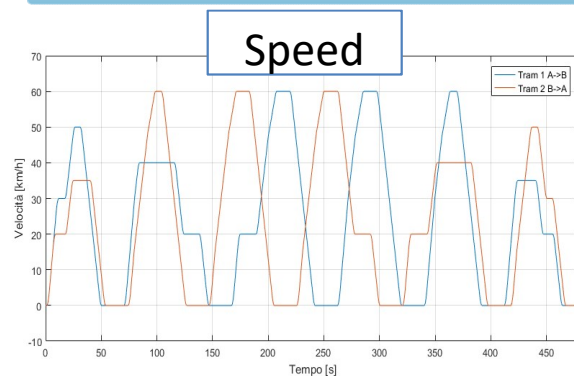
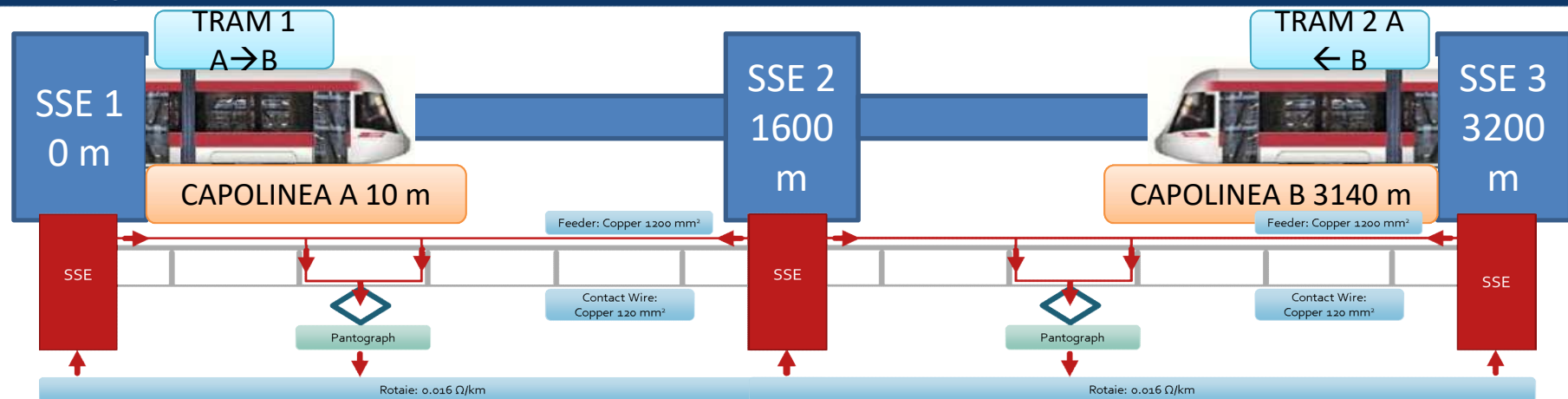


$$F_r = mg \left(p + A + \frac{v^2}{B} \right)$$

$$F_i = ma \quad F_t/F_b$$



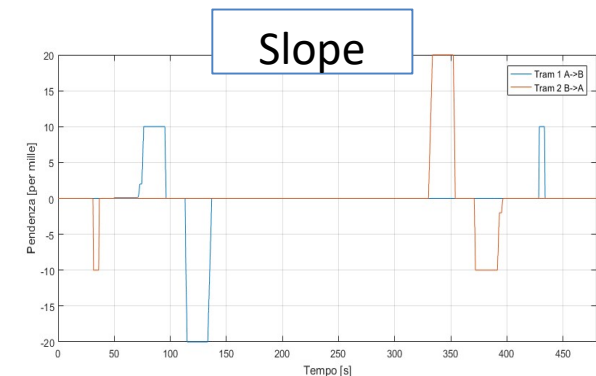
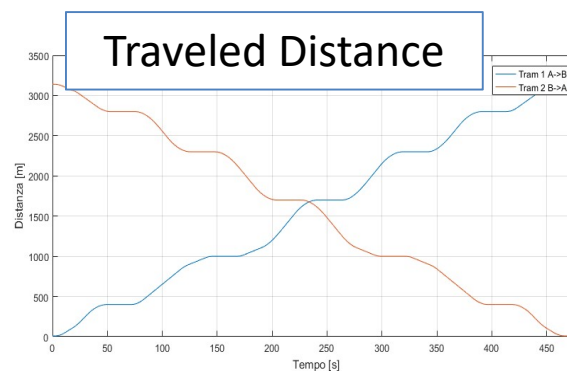
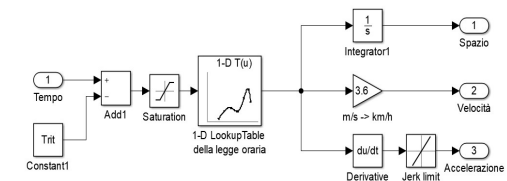
Storage Integration In Tramway Systems



Simulated Line

(Editable excel file)

- 7 Stops (train waits for 20 seconds)
- Max Speed 60 km/h
- Max Jerk 0.4 m/s³
- Commercial Speed ≈ 23.5 km/h
- Max Slope 2%



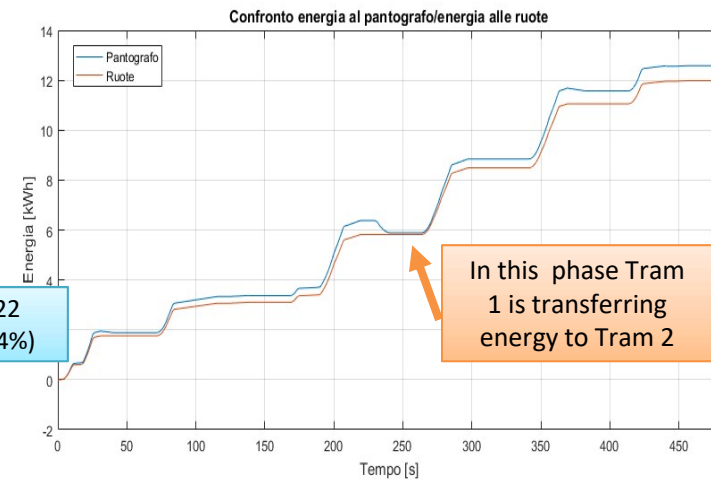
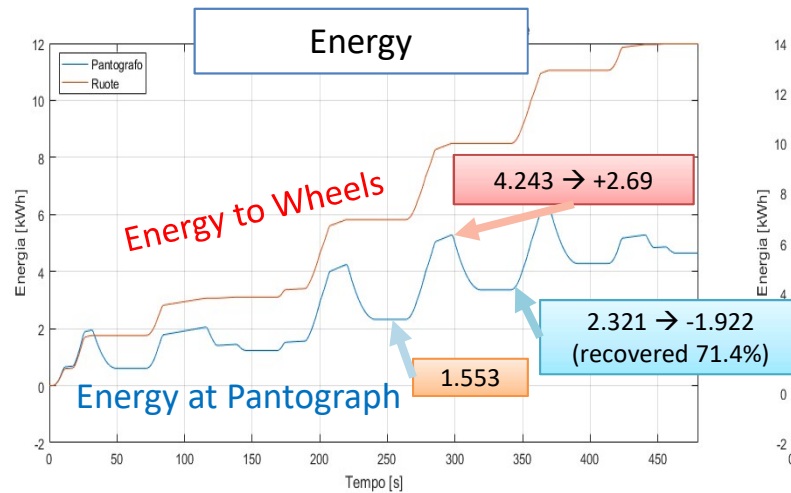
Storage Integration In Tramway Systems

IDEAL BI-DIRECTIONAL SSE

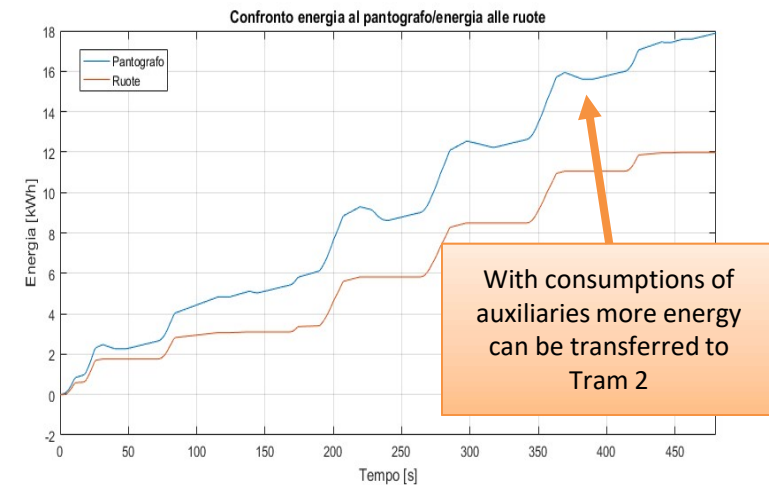
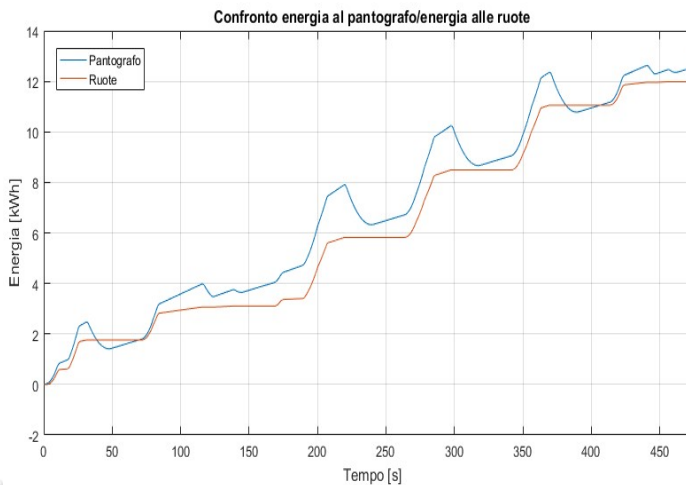
Results for Tram 1

CONVENTIONAL SSE

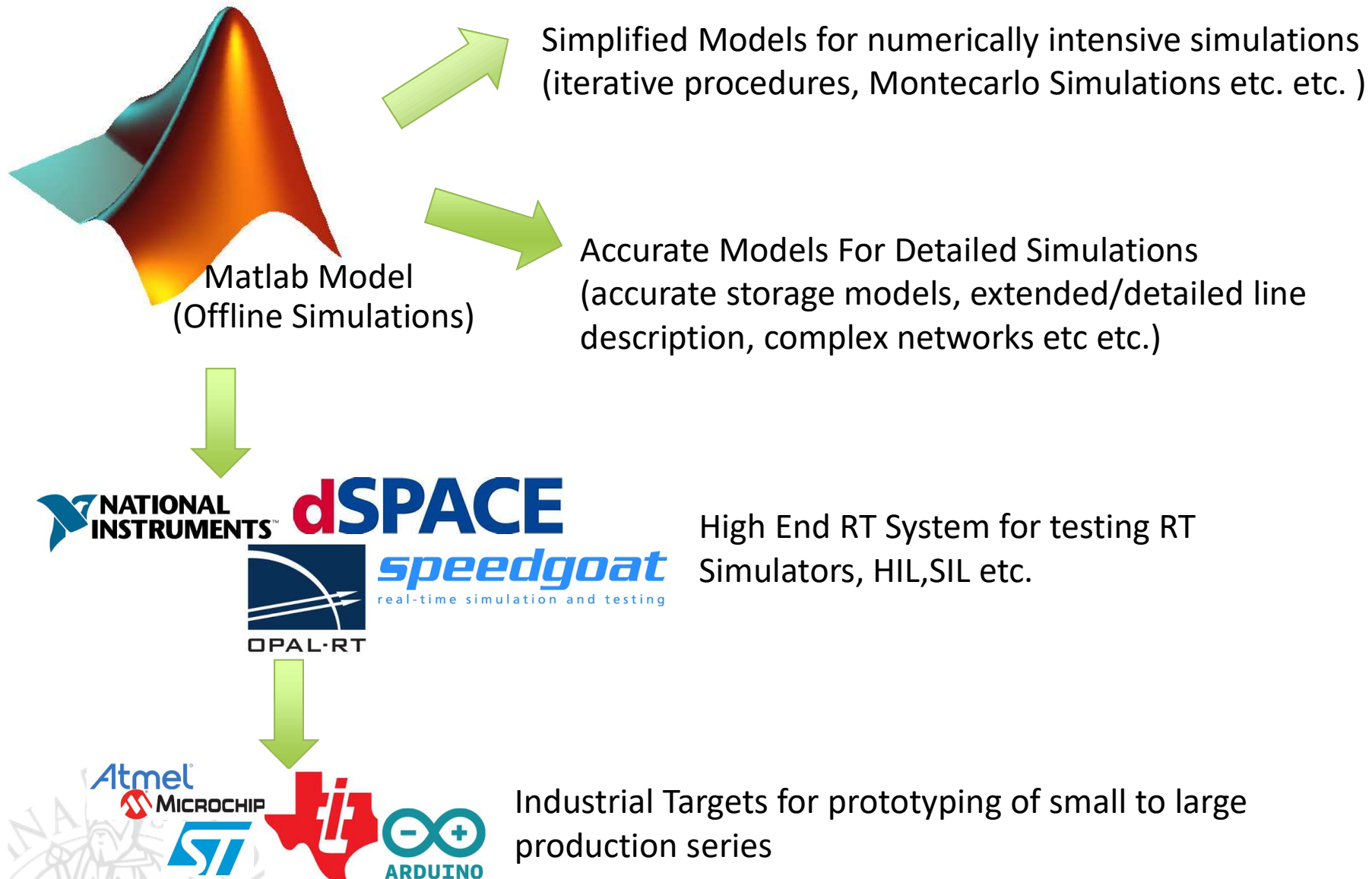
Without
Auxiliaries



With Auxiliaries



MULTI-TARGET IMPLEMENTATION



Conclusions

- ***Energy Storage System are key components for the development of electric transportation systems and smart energy management.***
- ***There is a clear convergence/sinergy between Railway and Other Sectors (Automotive, Smart Grid Management, etc.).***
- ***Integrated multi-phasic and interoperable models should be useful to speed up the application of innovative solutions giving a precious contribution not only to preliminary design optimization but also to diagnostic and maintenance.***



QUESTIONS?

Perhaps Many New
Cooperative
Intuitions.....



...are Better than...
....an Old Idea



We Should Continue in Florence ...

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