Tallinn University of Technology, May 2025

Estonian Doctoral School

“Electric and Hybrid Vehicles & EMR formalism”

……………..

Prof. Alain BOUSCAYROL, Prof. Betty LEMAIRE-SEMAIL

L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Université de Lille · Arts et Métiers Sciences et Technologies · centralelille · JUNIA Grande école d'ingénieurs

MEGEVH
French network on HEV's

(Energy management of Hybrid and Electric Vehicles)

Coordination:
2005-2019 A. Bouscayrol
2019-Present S. Jemai

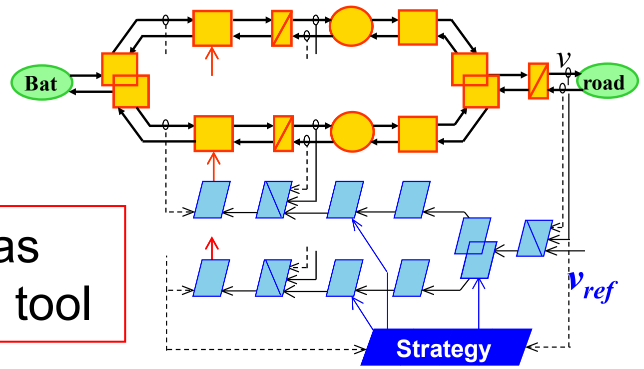
6 projects
4 PhDs in progress
11 PhDs defended

8 industrial partners
10 academic Labs

http://www.megevh.org/

Development of modeling & energy management methods

independently of the kind of vehicle



EMR as common tool

IEEE - Institute of Electrical & Electronics Engineers

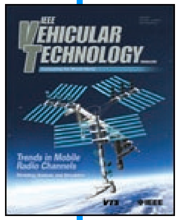
- **Non-profit professional organization** for advancing technological innovation and excellence
- **400,000 members from 160 countries** (30 % students)
- **38 societies on technical interest**

- **Activities**
  - scientific workshop, conferences, publications, standards
  - database *IEEE Xplore*, 3.5 millions documents, etc

IEEE VPPC'24, Washington DC 2024
300 attendees from 28 countries

IEEE – Vehicular Technology Society

- **Technical topics**
  - land, airborne and maritime services
  - mobile communication, vehicle electro-technology
- **2 publications and 4 annual conferences**
- **Distinguished Lecturer Program**



Prof. A. Bouscayrol
- HIL simulation
- EMR formalism
- EVs and HEVs

1 Electric & Hybrid Vehicles

2 EMR of a EV

3 Control of a EV

4 Example of a HEV

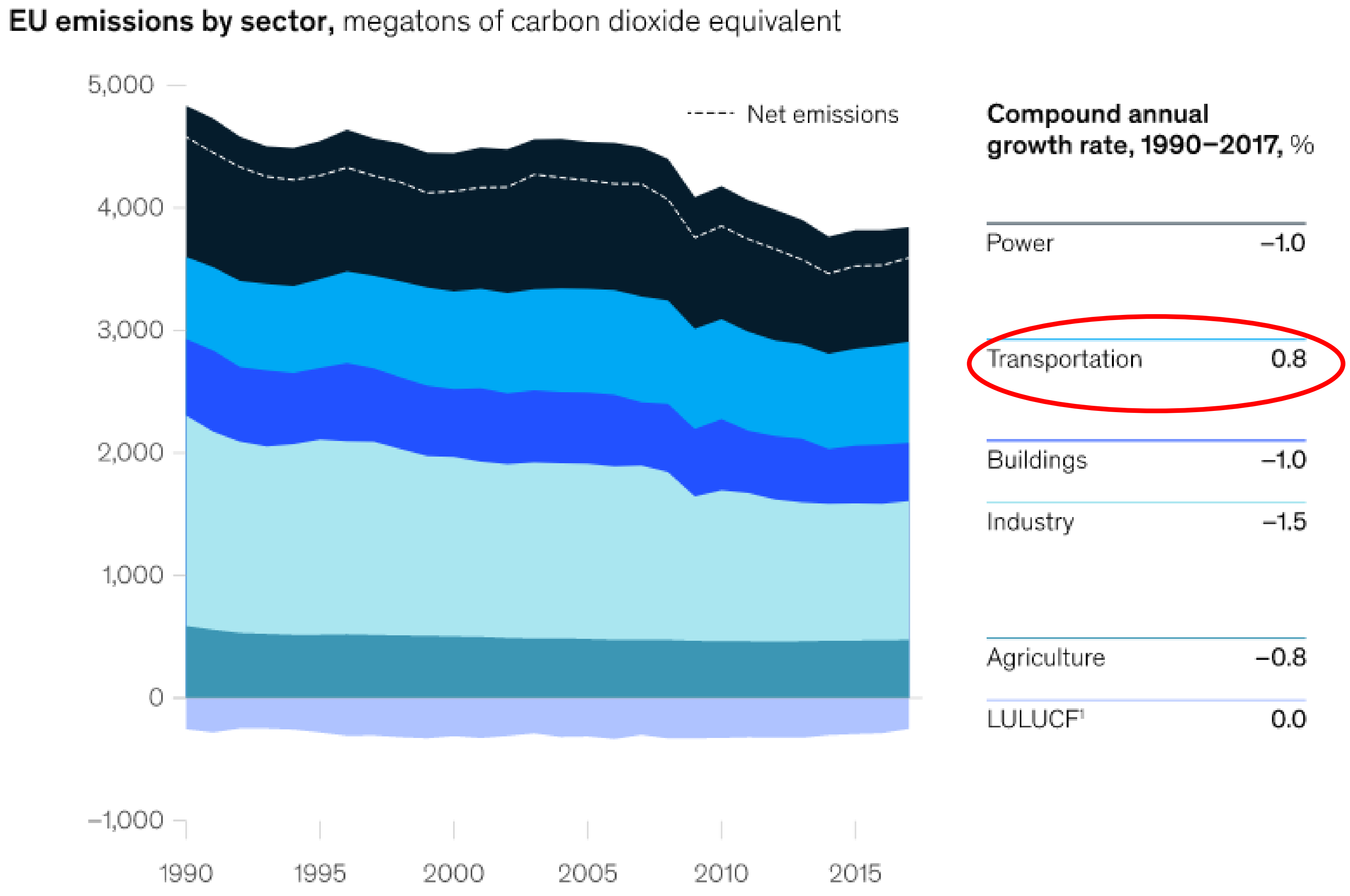
1 **Electric & Hybrid Vehicles**

2 EMR of a EV

3 Control of a EV

4 Example of a HEV

Green Houses Gase in Europe

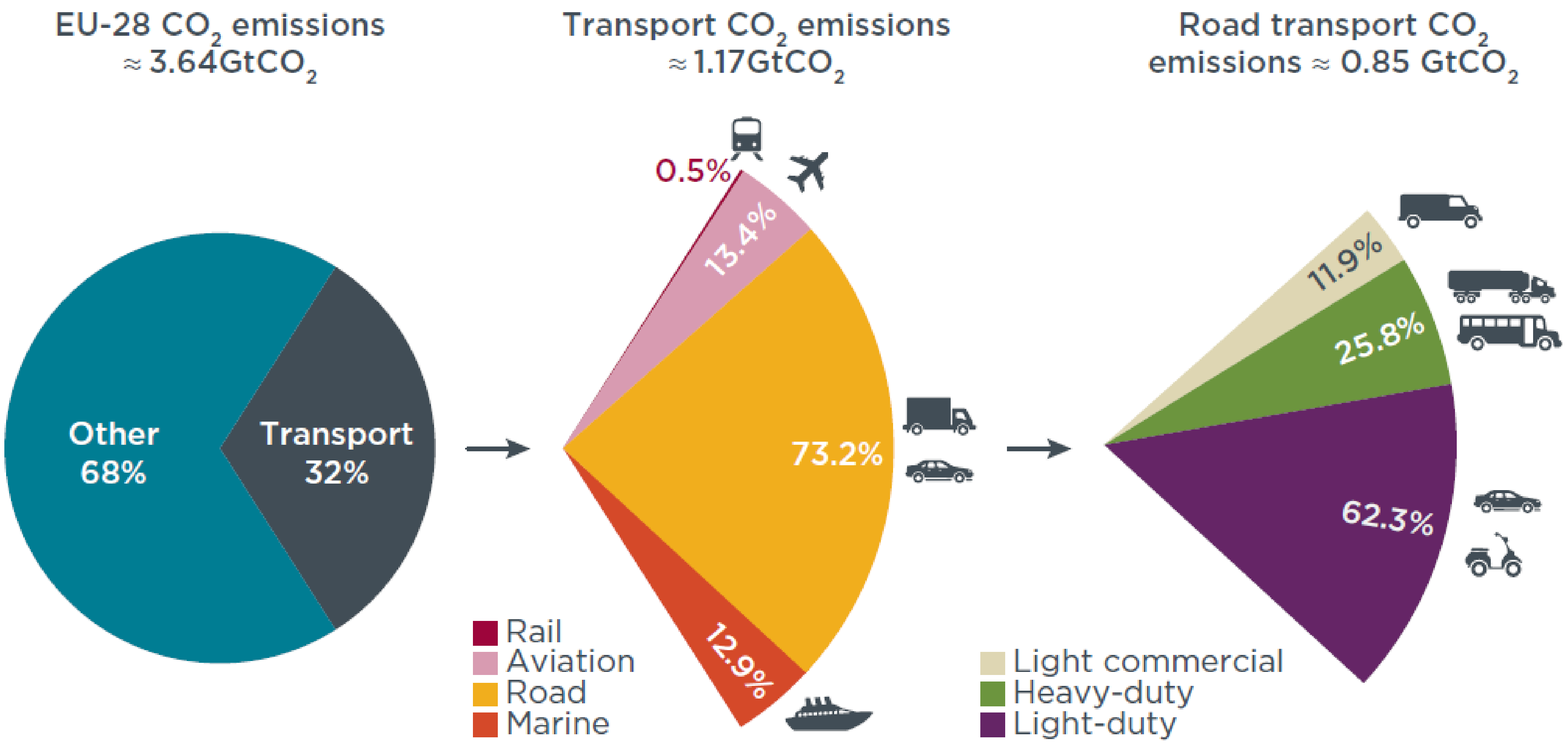


[McKinsey 2020]

The GHG of all sectors are decreasing….

except transportation

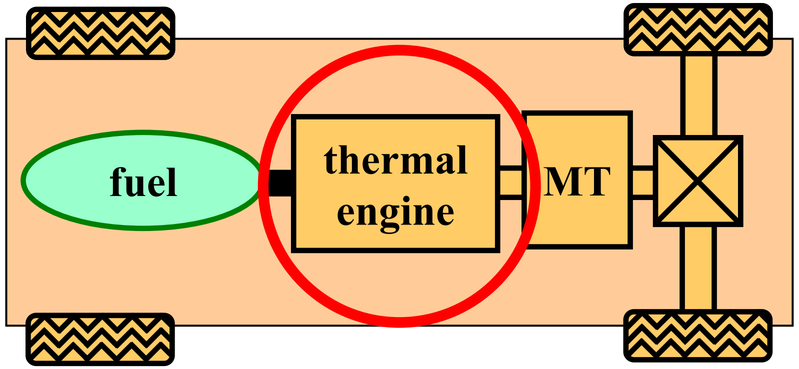
Green Houses Gases in Europe

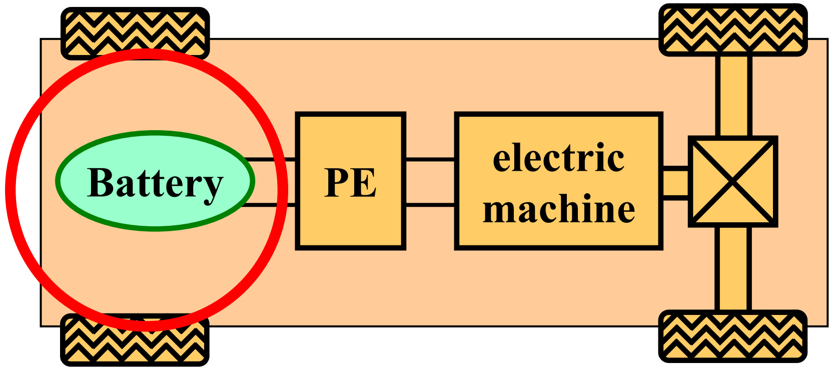


[Rodríguez 2018]

Thermal vehicle

- local pollution
- engine losses > 70%
- driving range > 600 km
- energy charging < 5 min



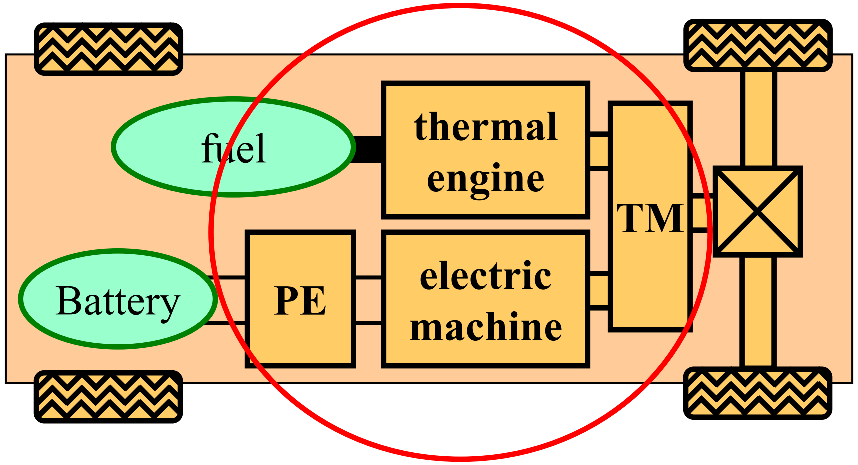


Electric Vehicles

- no local pollution
- e-motor losses < 10%
- driving range < 300 km
- energy charging > 5-10 h

EVs require a new mobility!

MT = Mechanical Transmission
PE = Power Electronics



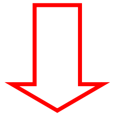
Hybrid vehicle:
- advantage of each technology
- higher cost
- complex control

Toyota Prius 3

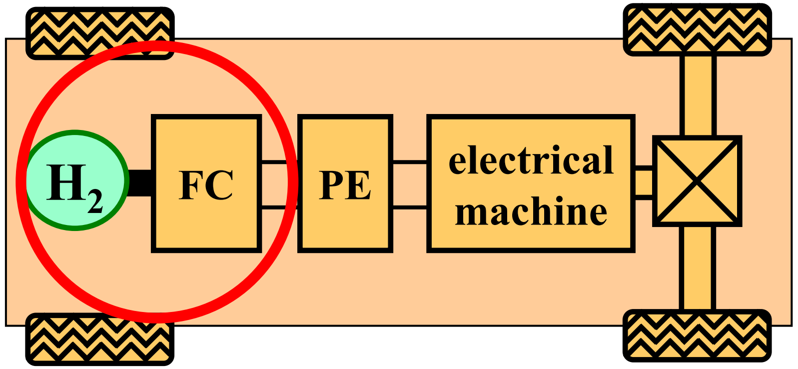
http://www.toyota.com/

Peugeot 3008 HY4

http://www.mpsa.com



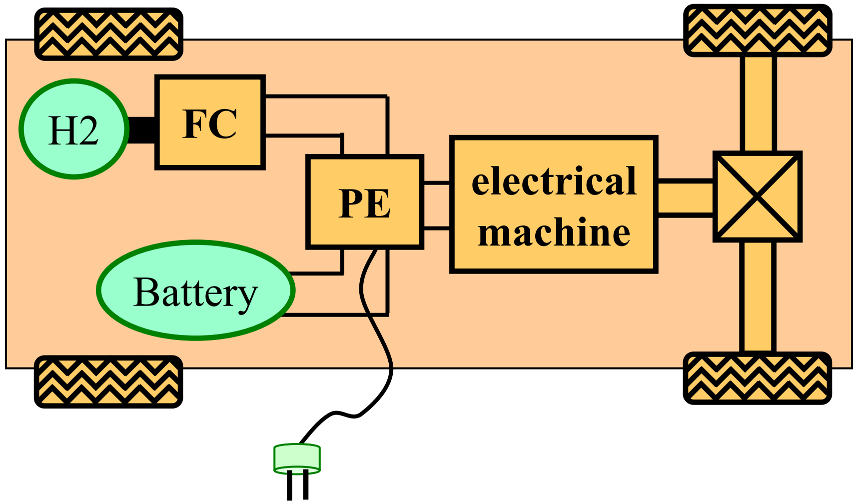
Various configurations:
- different power ratios P_{ICE}/P_{EM}
- different component organization



Fuel cell vehicle :
= EV with battery replaced by a fuel cell and a H2 tank

Honda Clarity FX

http://www.honda.com/



FC vehicle with hybrid storage
= another kind of HEV

Toyota Mirai

http://www.toyota.com/

Other vehicles

E-bike, e-motorbike

Light EVs, Grenobe (France)

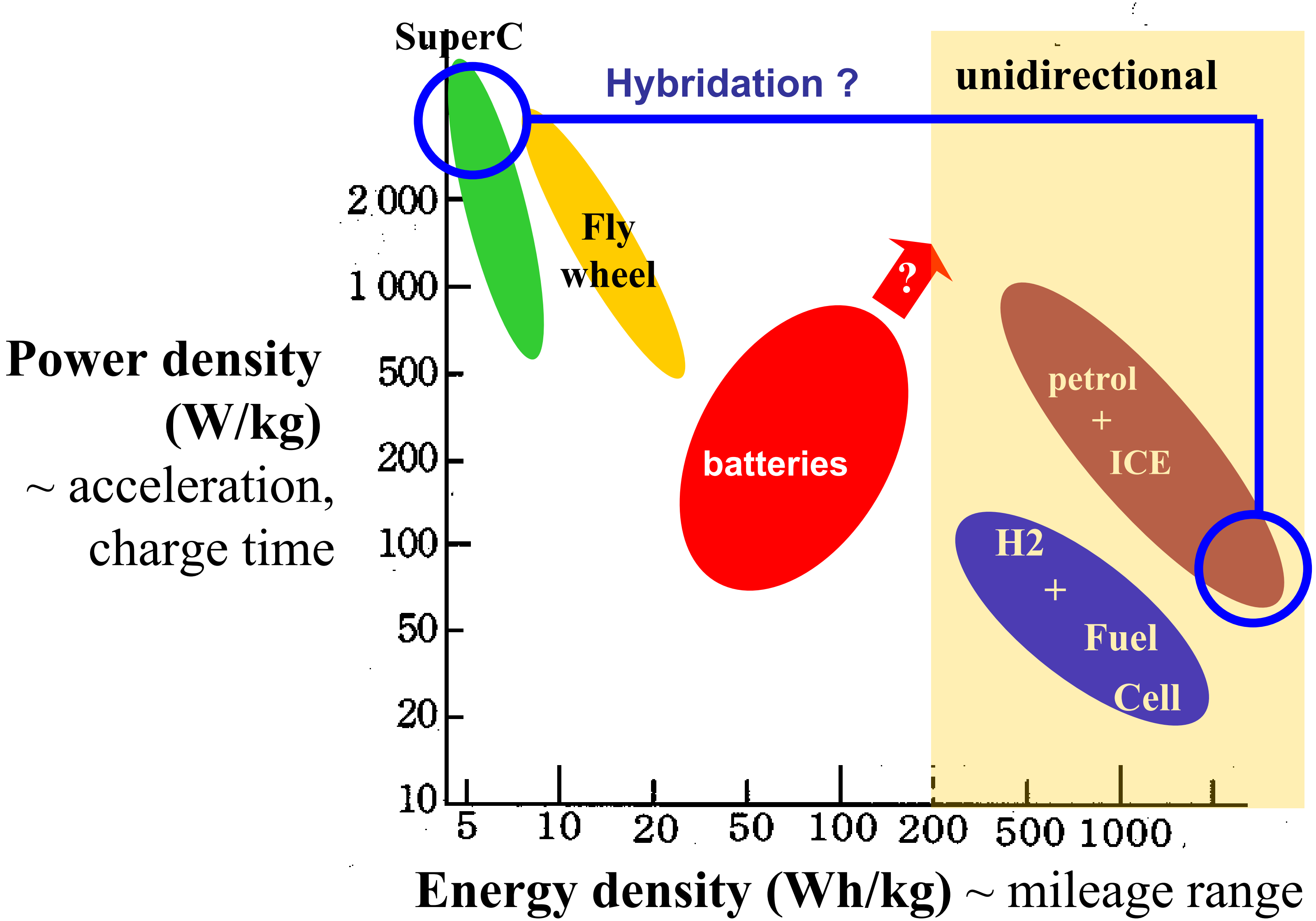
DAF LF Hybrid truck

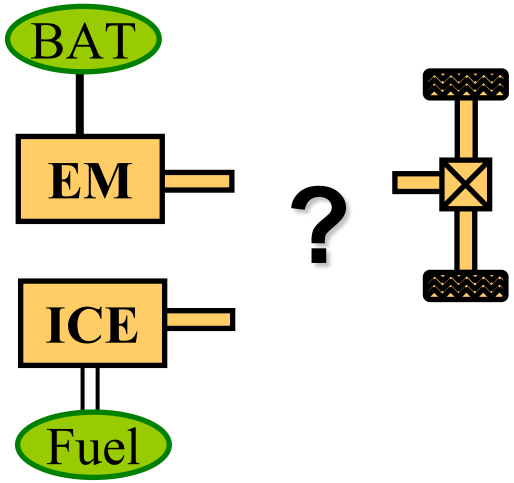
MAGLEV Shangaï

MS Turanor (120 kW)

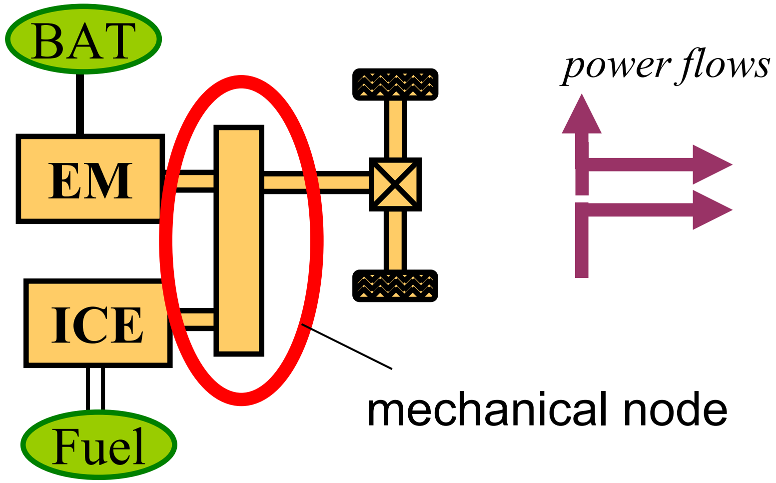
Boeing Dreamliner (1,4 MW)

Solar-impulse (50 kW)

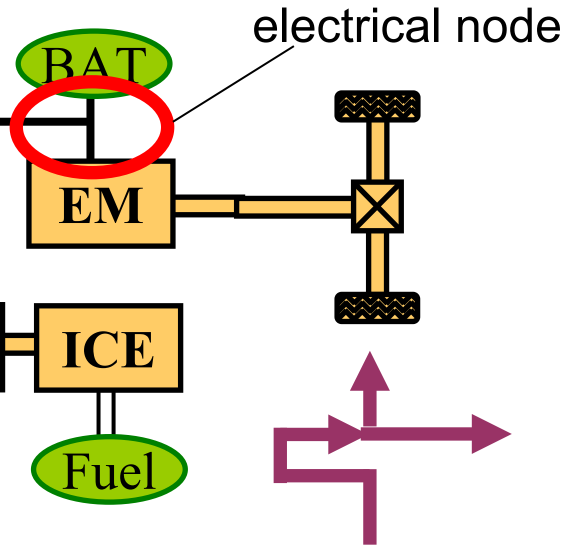

SuperC
Hybridation ?
unidirectional
2 000
1 000
500
200
100
50
20
10
Fly
wheel
?
batteries
petrol
+
ICE
H2
+
Fuel
Cell
Power density
(W/kg)
~ acceleration,
charge time
5
10
20
50
100
200
500
1000
Energy density (Wh/kg) ~ mileage range



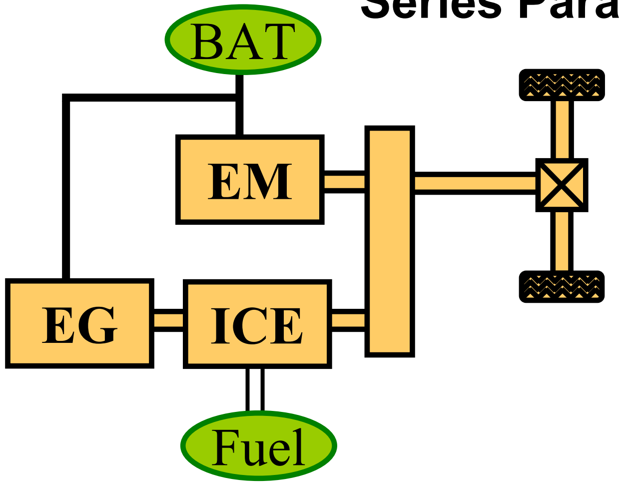
Parallel HEV



Series HEV

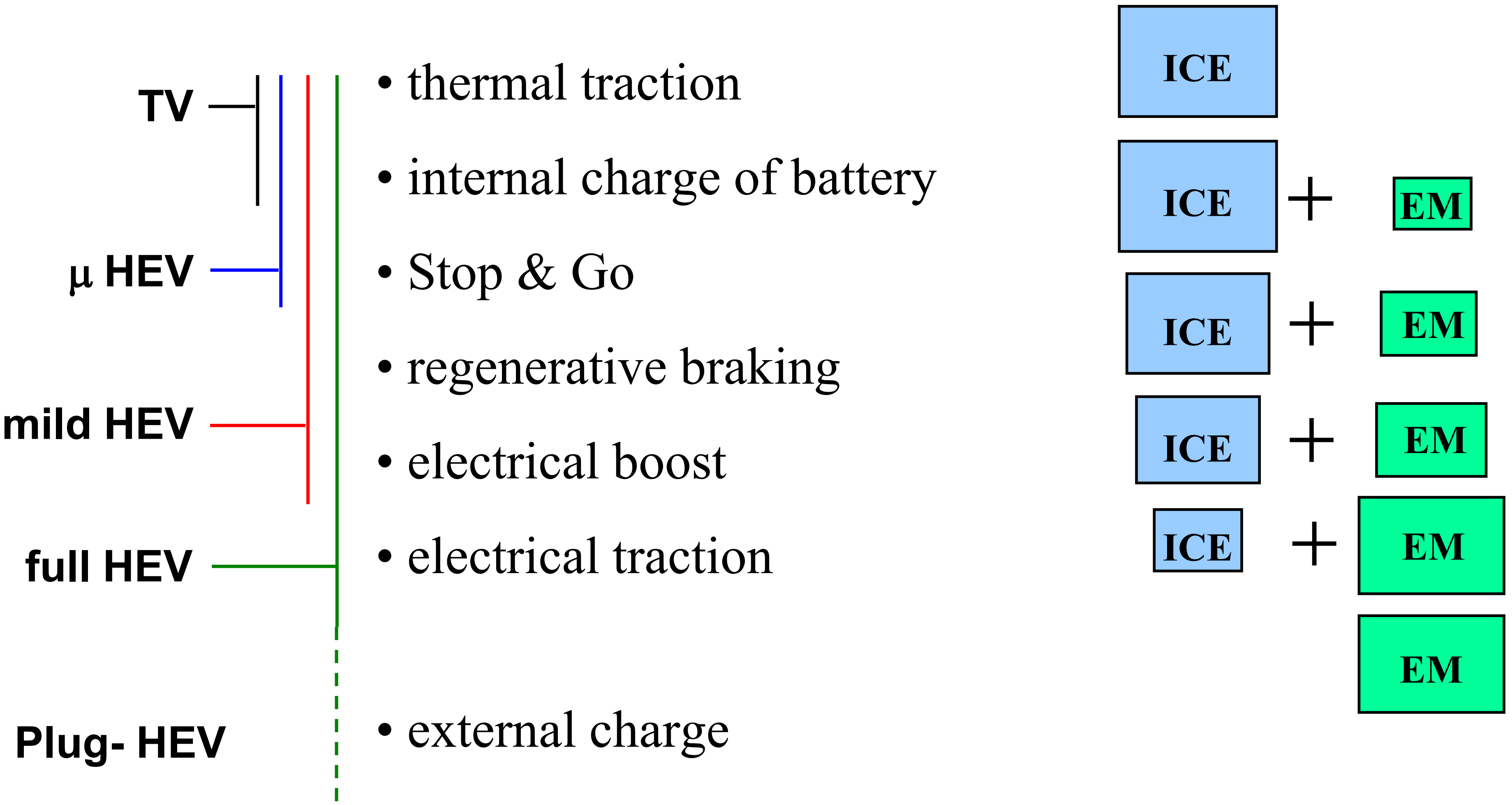


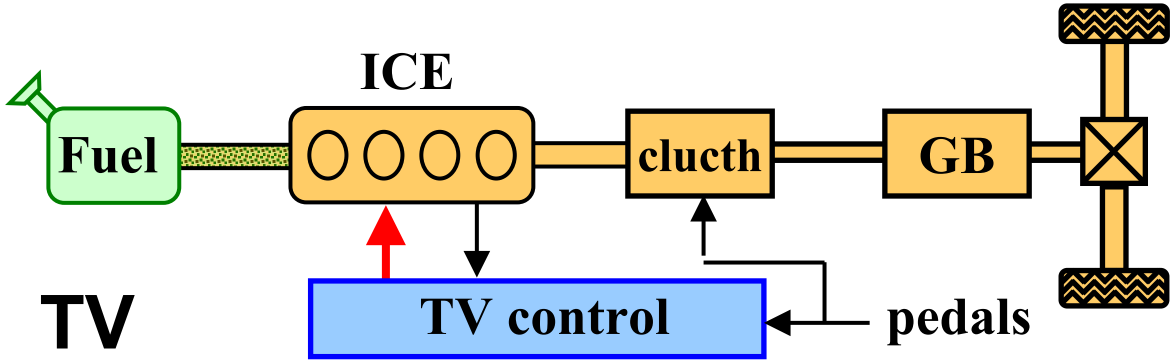
Series Parallel HEV

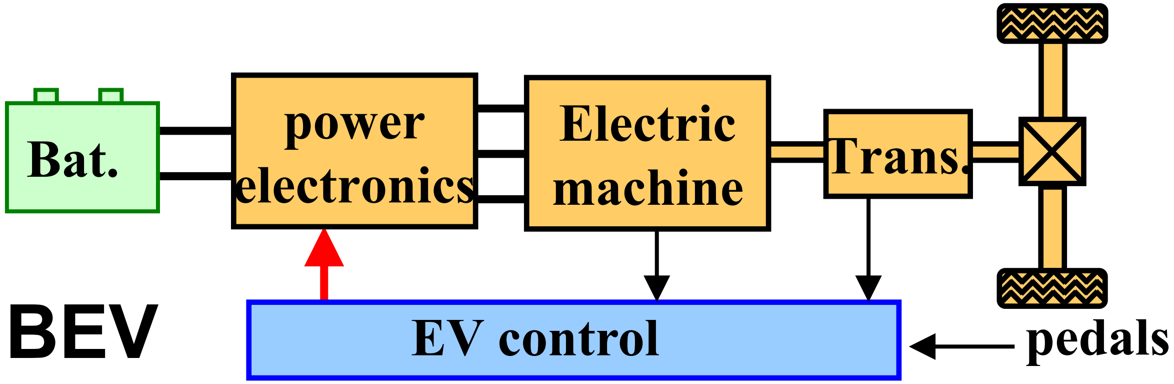


Hybridization rate

(power ratio associated with functionalities)



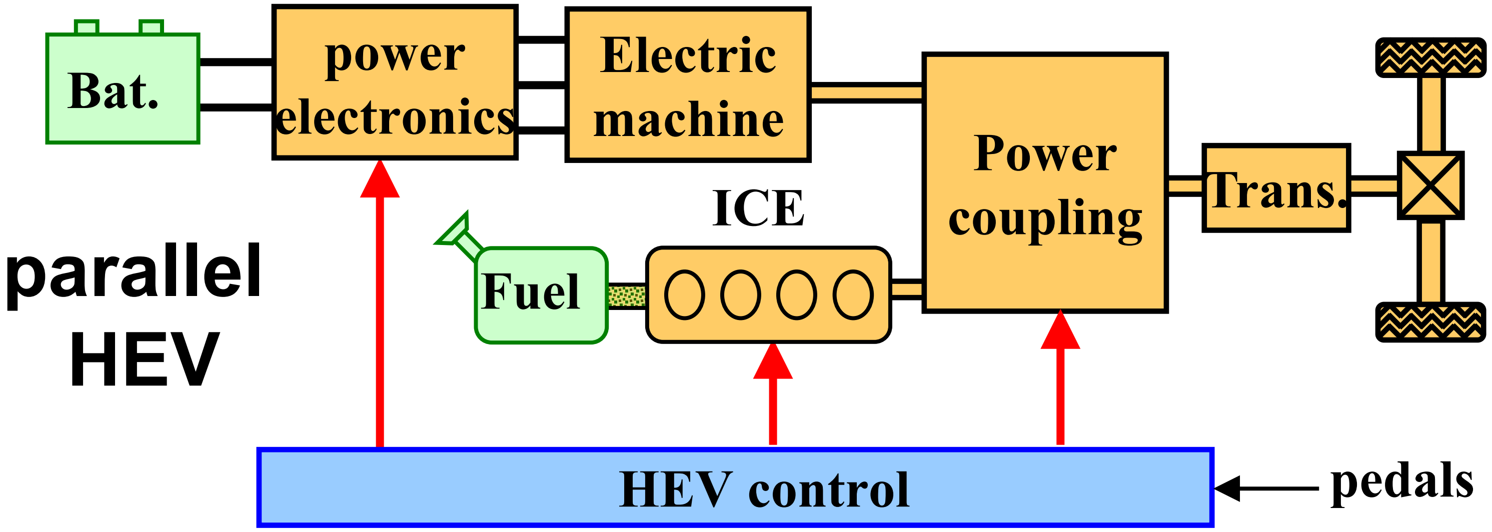




Controls of TVs and BEVs:
mono-objective (no optimization) to ensure the driving cycle

Controls of HEVs:

- multi-objective: ensure driving cycle AND reduce fuel consumption
- various modes: pure electric, (pure thermal, hybrid, etc.)

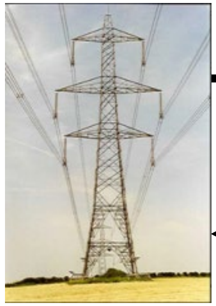


- slow charge at home
  / at work (4-10h?)
  (plug or induction)
- ultra-fast charge at specific
  station (1/2h?)
- battery swap station
  (5-10 min?)

http://france.betterplace.com/

⇩

New technologies and developments? “Smart” charge?
but also
A new way to manage our energy charge?



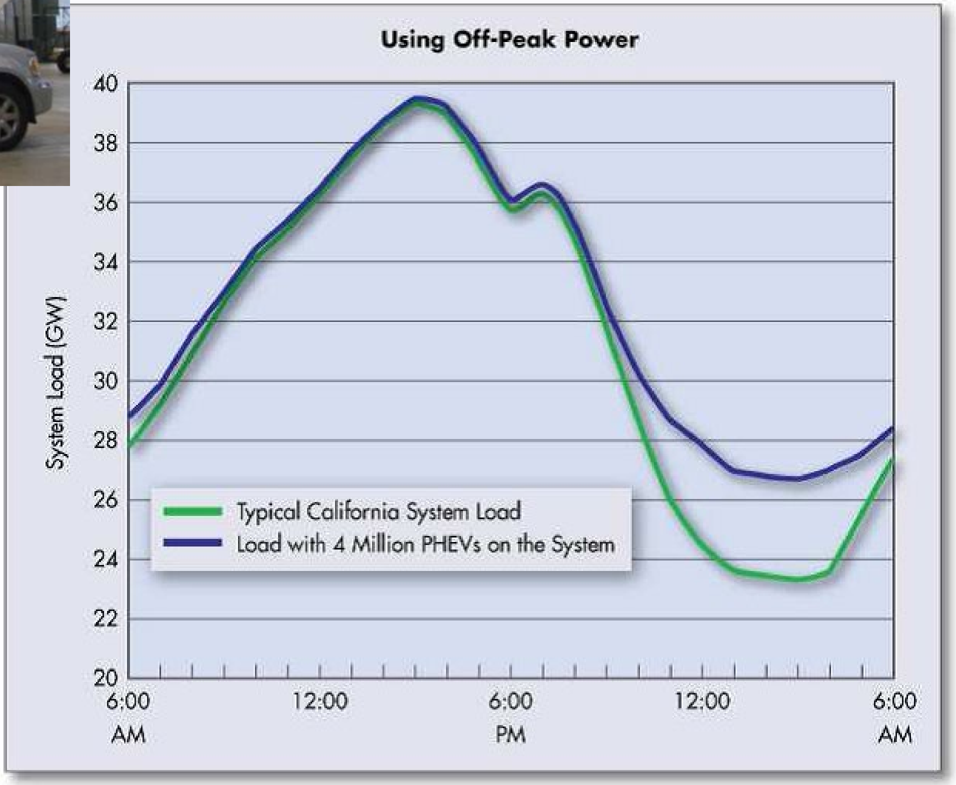
G2V

V2G

(Vehicle to Grid)

New concepts for
grid management?
but also
A new way to manage
our energy prize?

http://my.epri.com



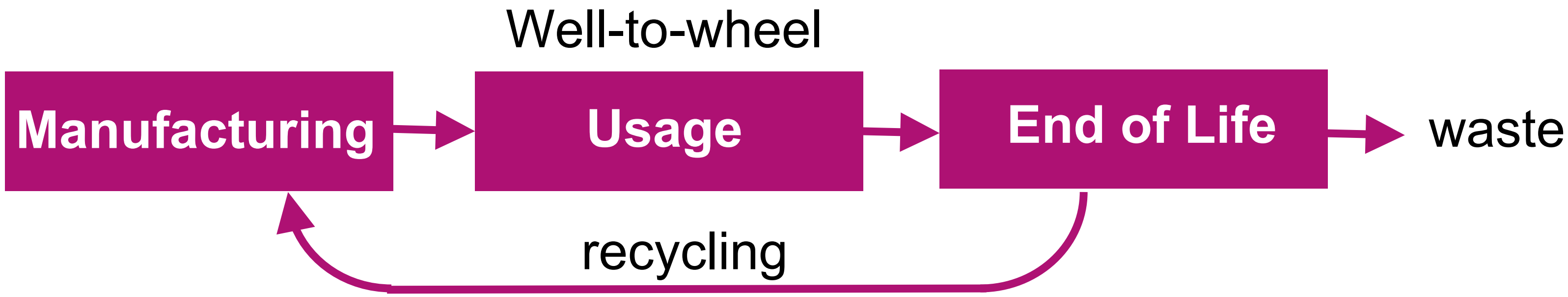
Life Cycle Assessment (LCA):

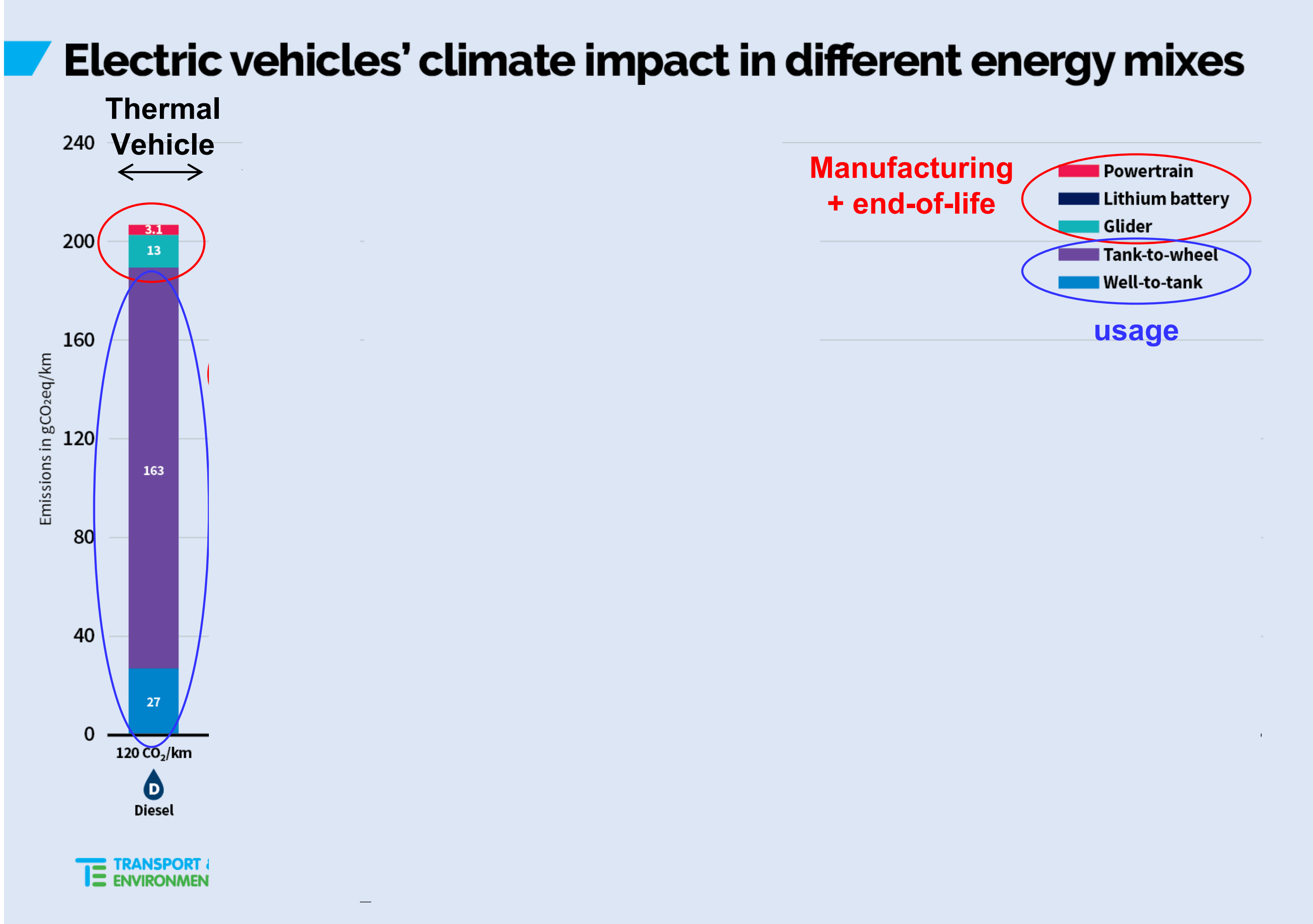
"From cradle-t-o-grave"

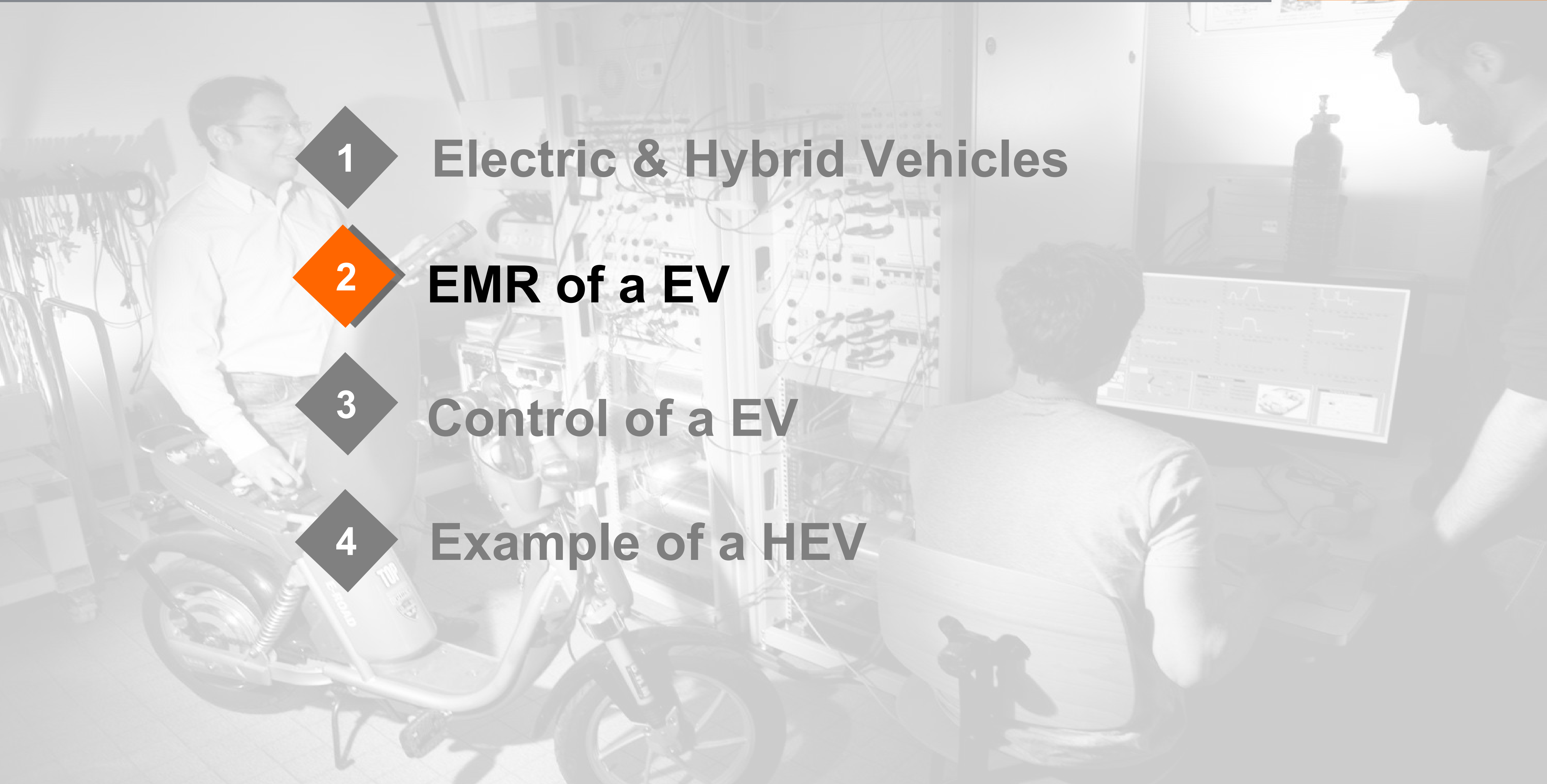
Methodology for estimation of the environmental impacts of a product all along its life time (**pollutant emissions**, water, air toxicity, soil pollution, energy…)

LCA for vehicles

"for fair comparison"




Electric vehicles' climate impact in different energy mixes
Thermal Vehicle
Manufacturing + end-of-life
Powertrain
Lithium battery
Glider
Tank-to-wheel
Well-to-tank
usage
Emissions in gCO₂eq/km
240
200
160
120
80
40
0
3.1
13
163
27
120 CO₂/km
Diesel
TRANSPORT
ENVIRONMEN



1 Electric & Hybrid Vehicles

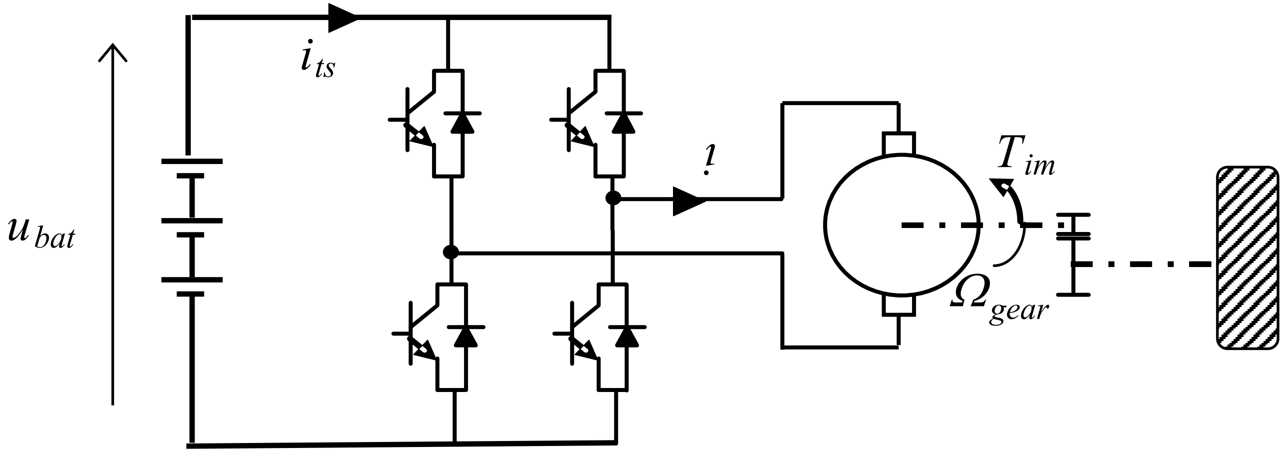
2 **EMR of a EV**

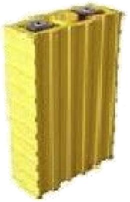
3 Control of a EV

4 Example of a HEV

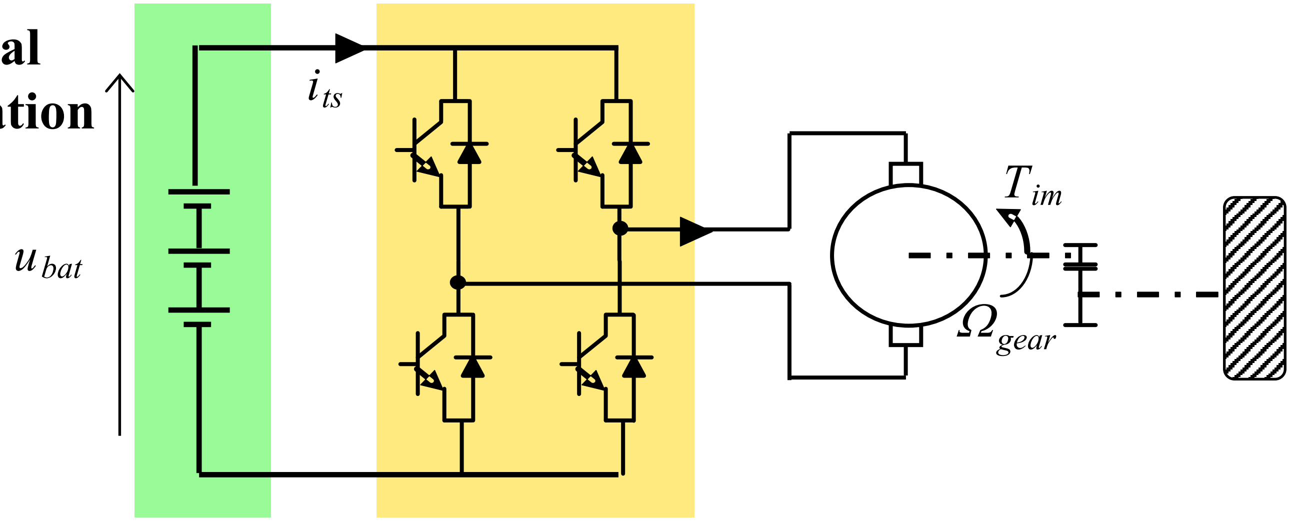
Objective:
control of the traction system in straight lines

Simplifications:
- a permanent magnet DC machine is considered in a first step
- an equivalent wheel is considered (no curve)

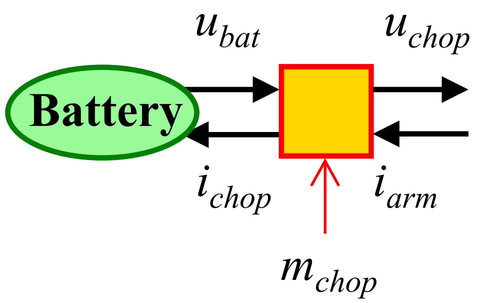




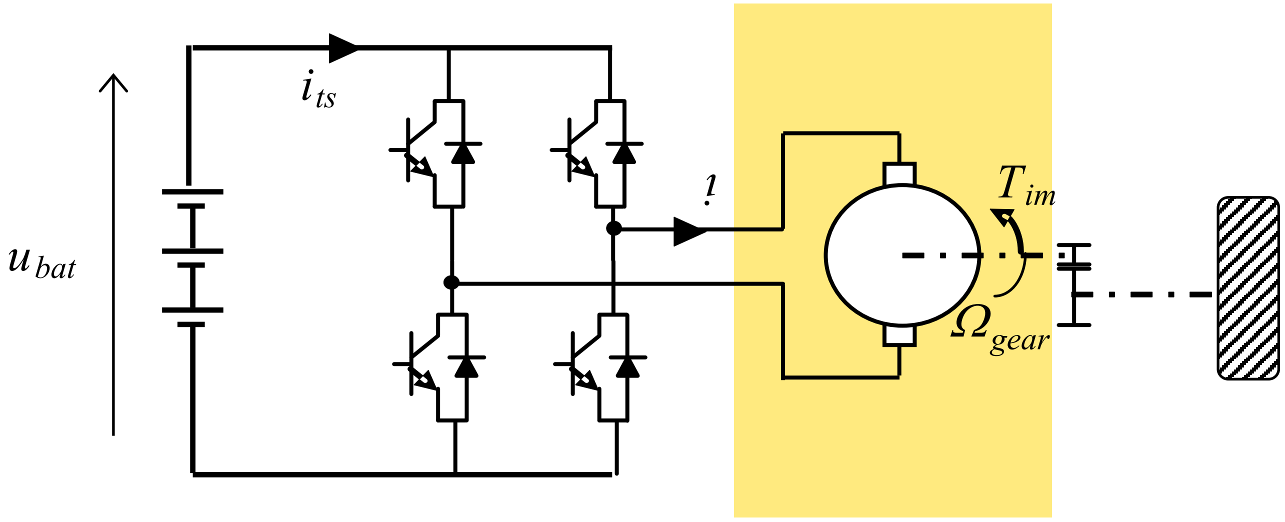
Structural Representation

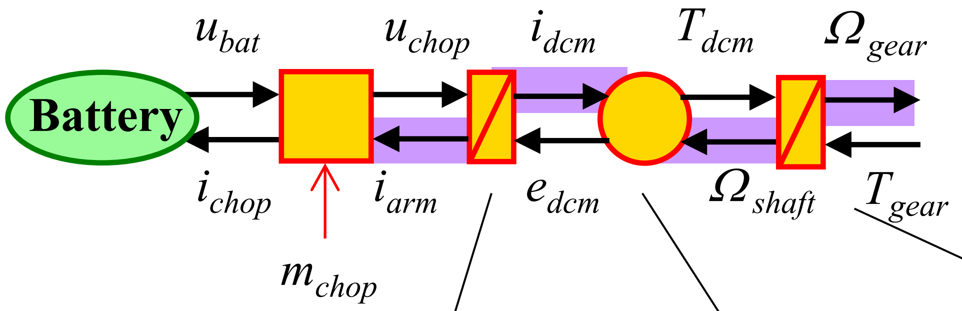


Functional Description



$$\begin{cases} \mathrm{u}_{\mathrm{chop}} = m_{\mathrm{chop}} V_{bat} \\ \mathrm{i}_{\mathrm{chop}} = m_{\mathrm{chop}} i_{arm} \end{cases}$$

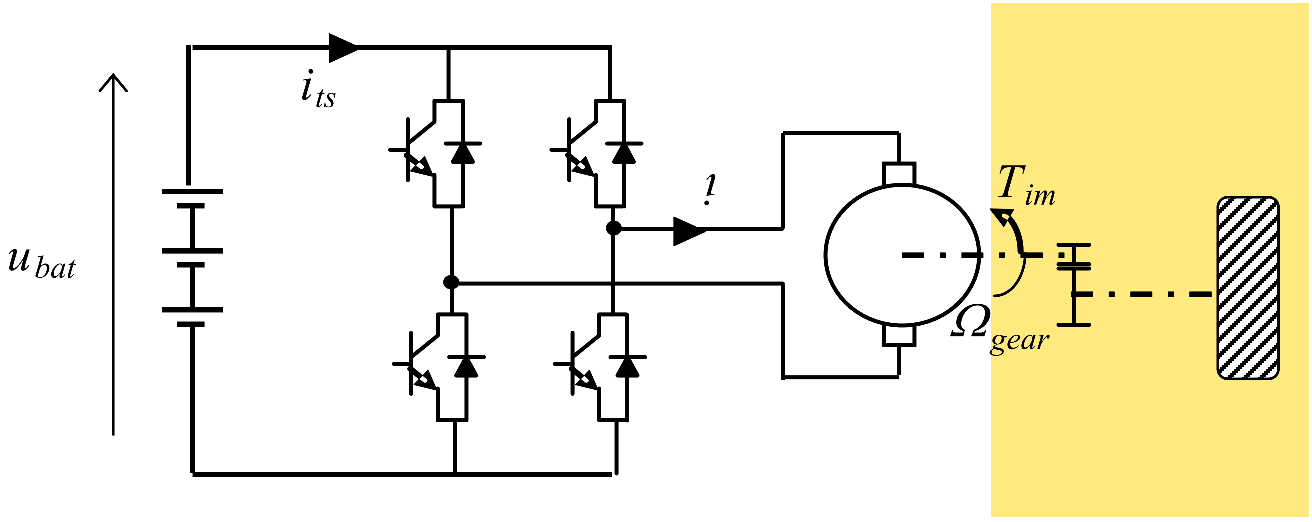


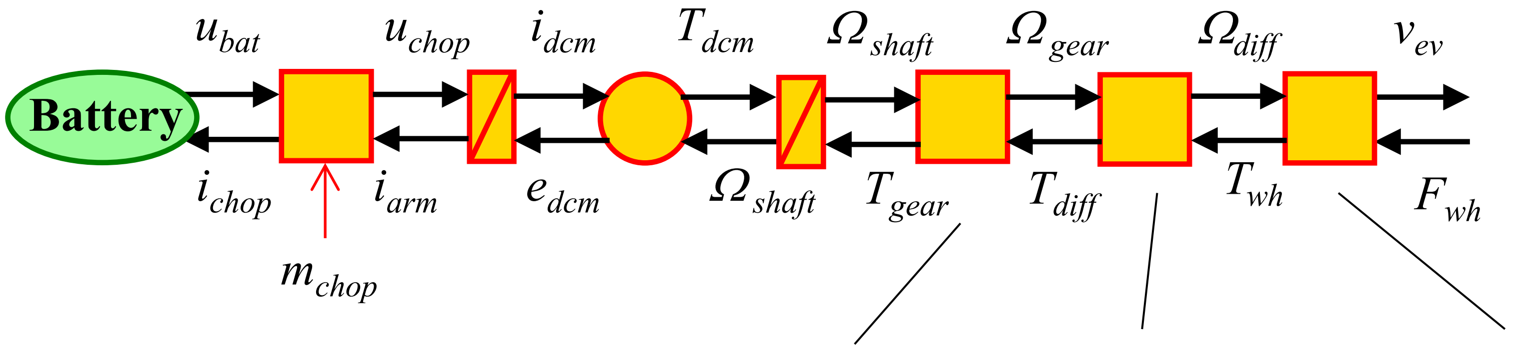


$$L_{arm}\frac{d}{dt}i_{dcm} = u_{chop} - e_{dcm} - R_{arm}i_{dcm}$$

$$\begin{cases} T_{dcm} = k_{dcm}i_{dcm} \\ e_{dcm} = k_{dcm}\Omega_{gear} \end{cases}$$

$$J\frac{d}{dt}\Omega_{gear} = T_{dcm} - T_{gear} - f\Omega_{gear}$$

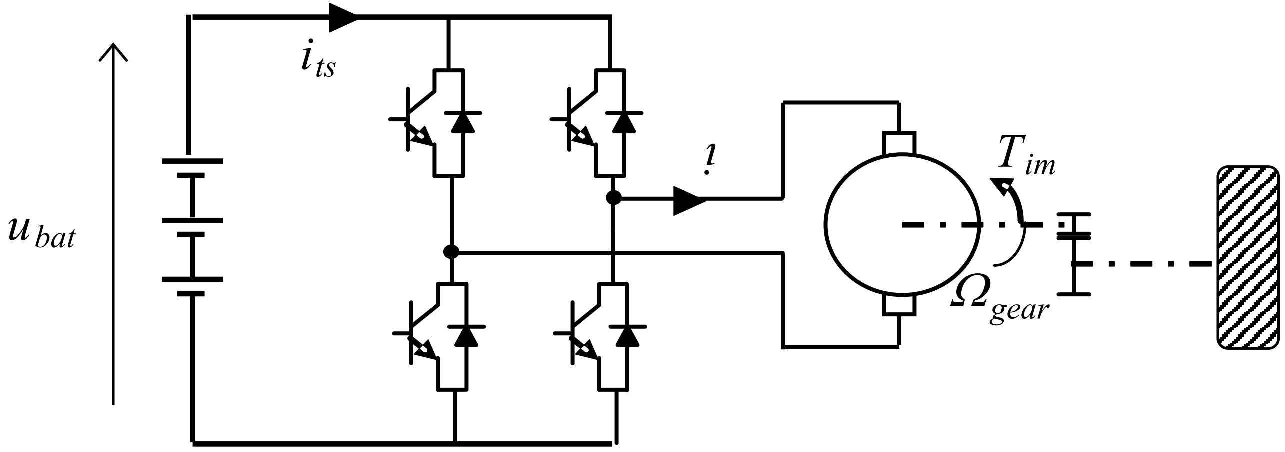


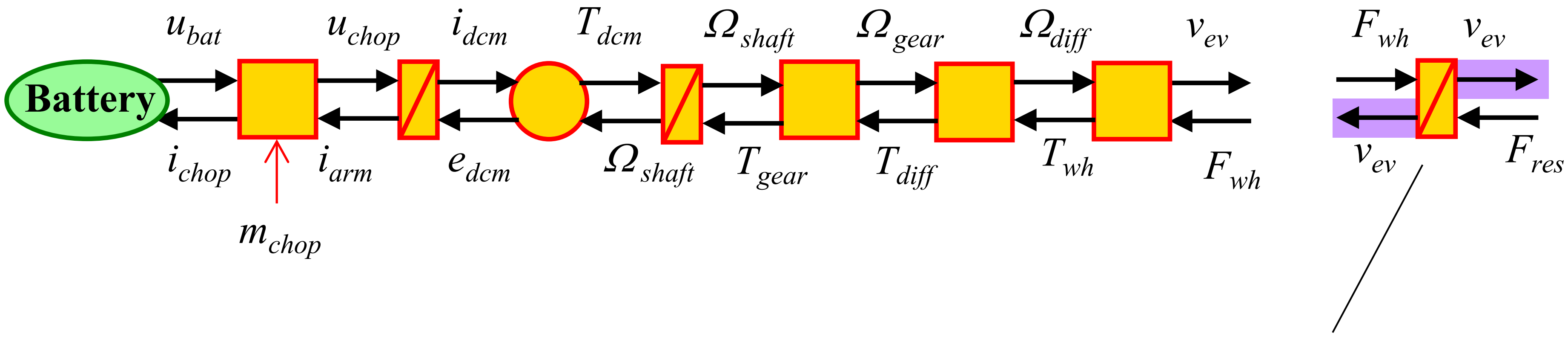


$$\begin{cases} T_{gear} = k_{gear}\, T_{diff} \\ \Omega_{gear} = k_{gear}\, \Omega_{shaft} \end{cases}$$

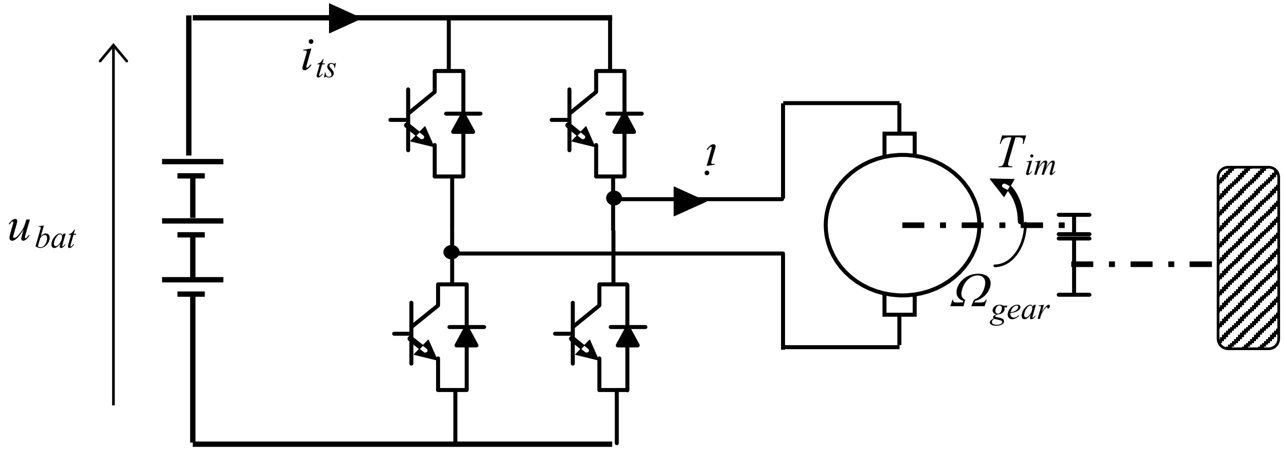
$$\begin{cases} T_{dif} = k_{dif}\, T_{wh} \\ \Omega_{dif} = k_{dif}\, \Omega_{gear} \end{cases}$$

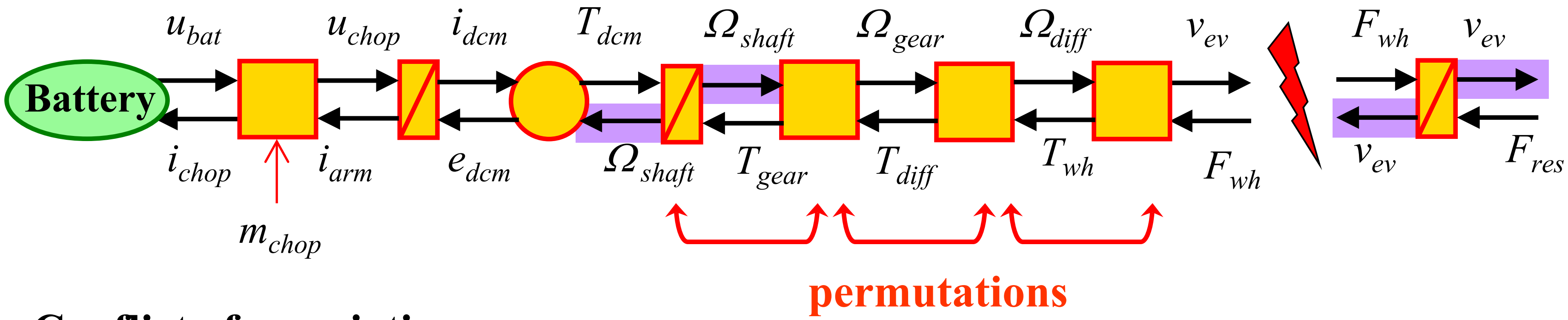
$$\begin{cases} T_{wh} = R_{wh} F_{wh} \\ v_{ev} = R_{wh} \Omega_{diff} \end{cases}$$





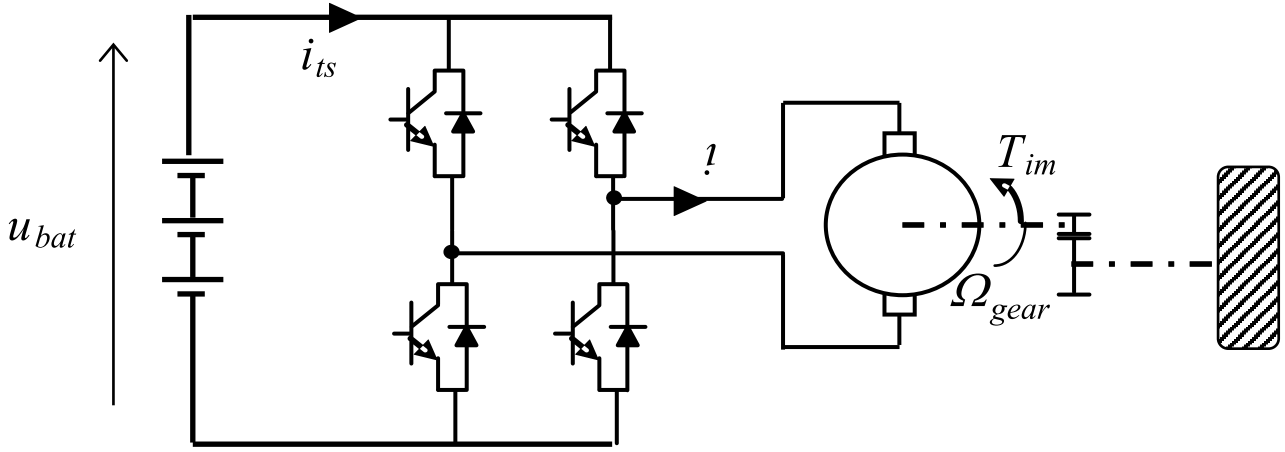
$$M \frac{d}{dt} v_{ev} = F_{tot} - F_{res}$$

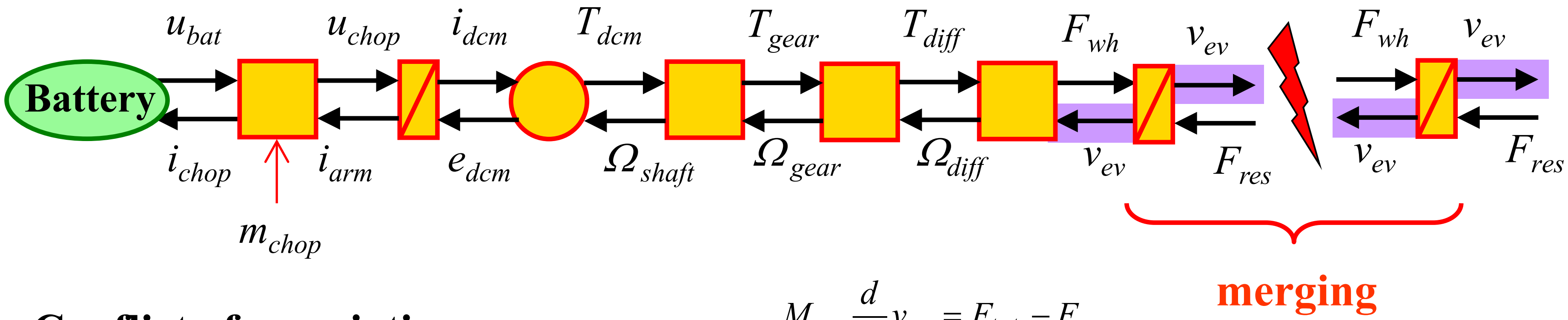




Conflict of association:

Ω_{shaft} and v_{ev} state variables but $v_{ev} = R_{wh} k_{diff} k_{gear} \Omega_{shaft}$

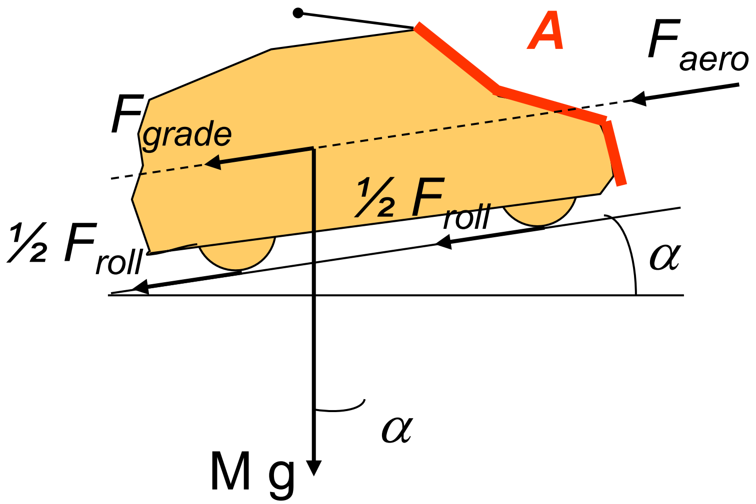


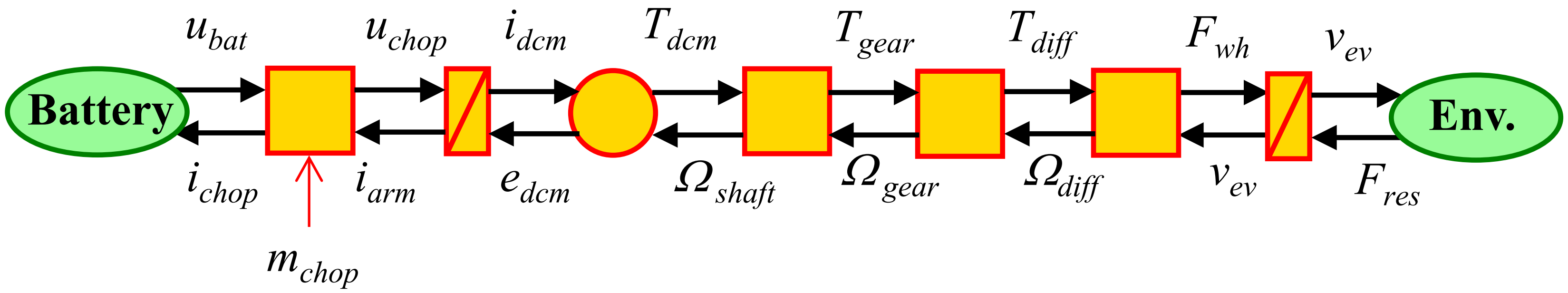


Conflict of association:
a unique state variable is required!

$$M_{eq}\frac{d}{dt}v_{ev} = F_{tot} - F_{res}$$

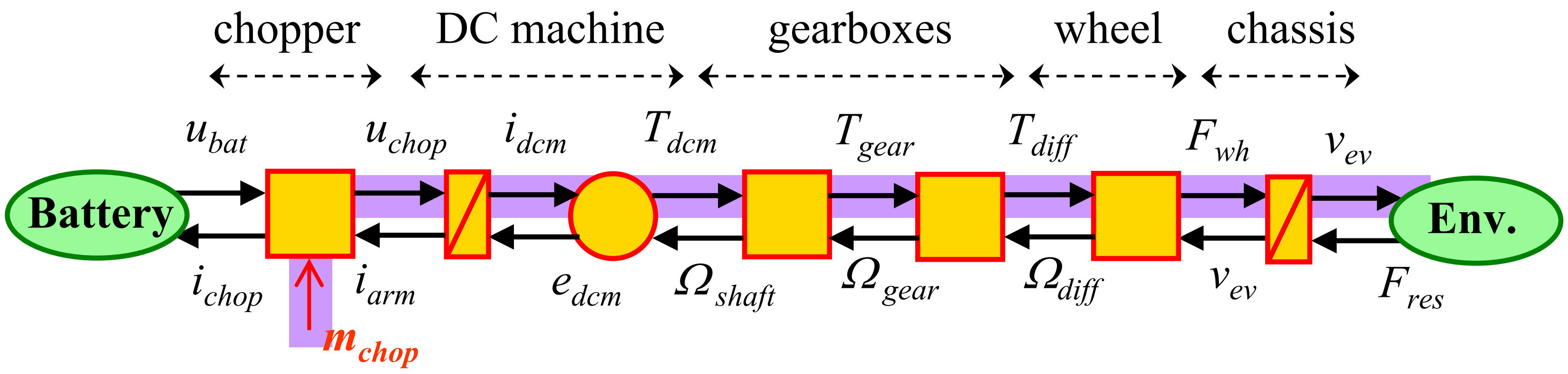
$$M_{eq} = M + \frac{J_{shaft}}{\left(k_{gear}^2 k_{diff}^2 R_{wh}^2\right)}$$





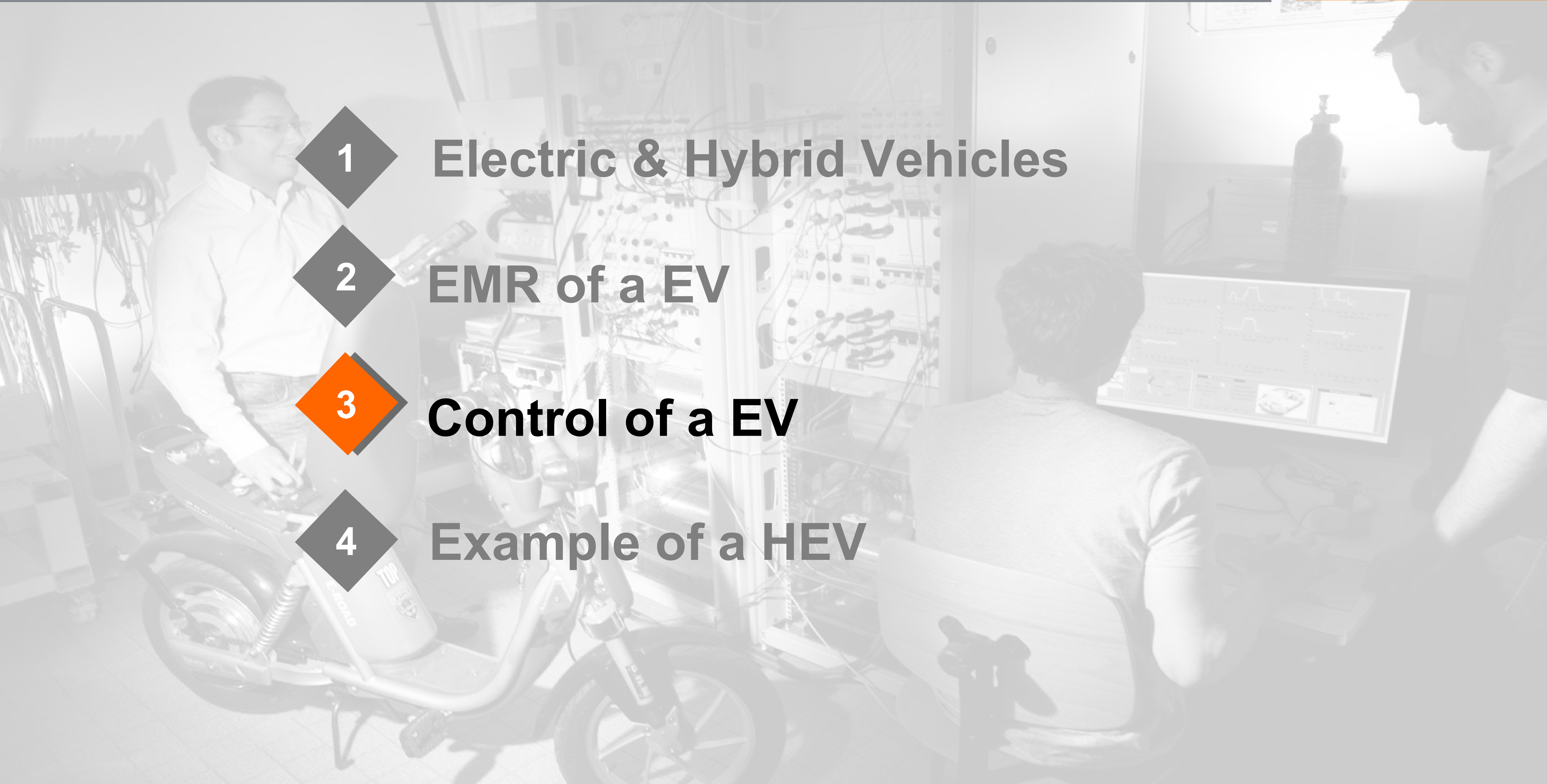
$$F_{res} = k_{roll} Mg \cos\alpha + \frac{1}{2}\rho_{air} A C_x v_{ev}^2 + Mg \sin\alpha$$

Tuning path

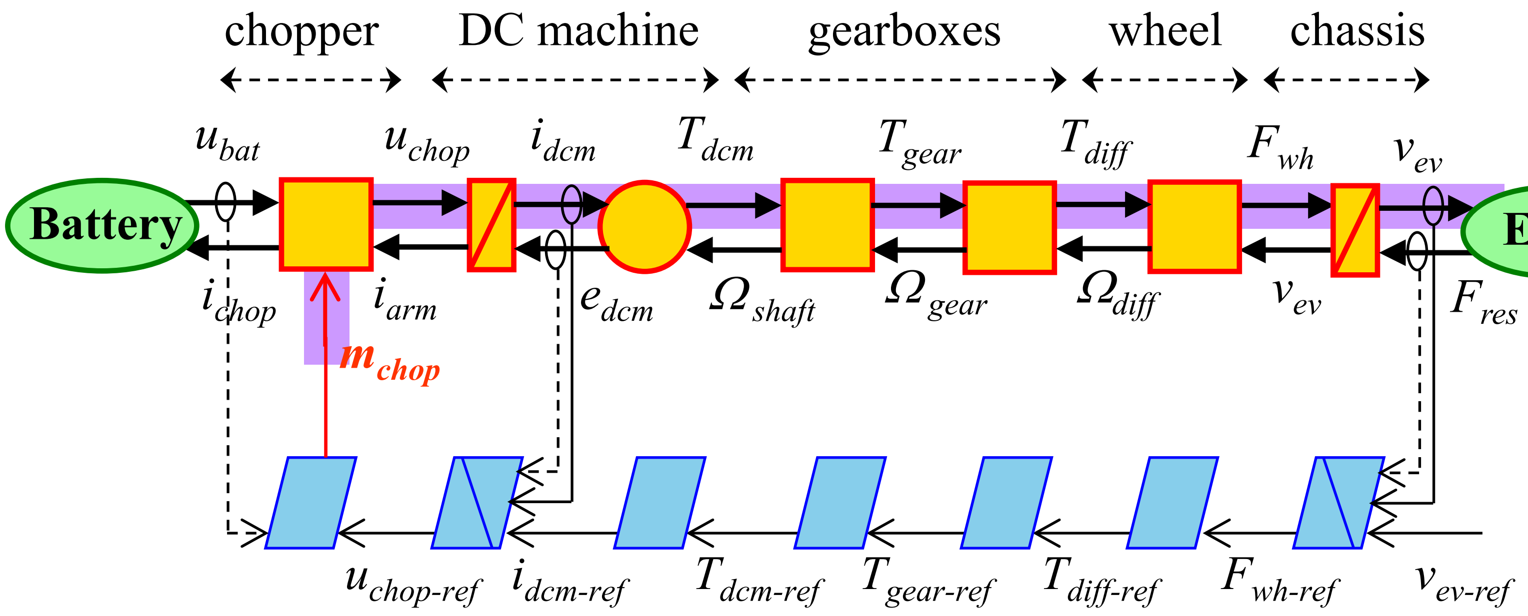


Objective: control the EV velocity

Tuning variable: modulation ratio of the DC-DC converter

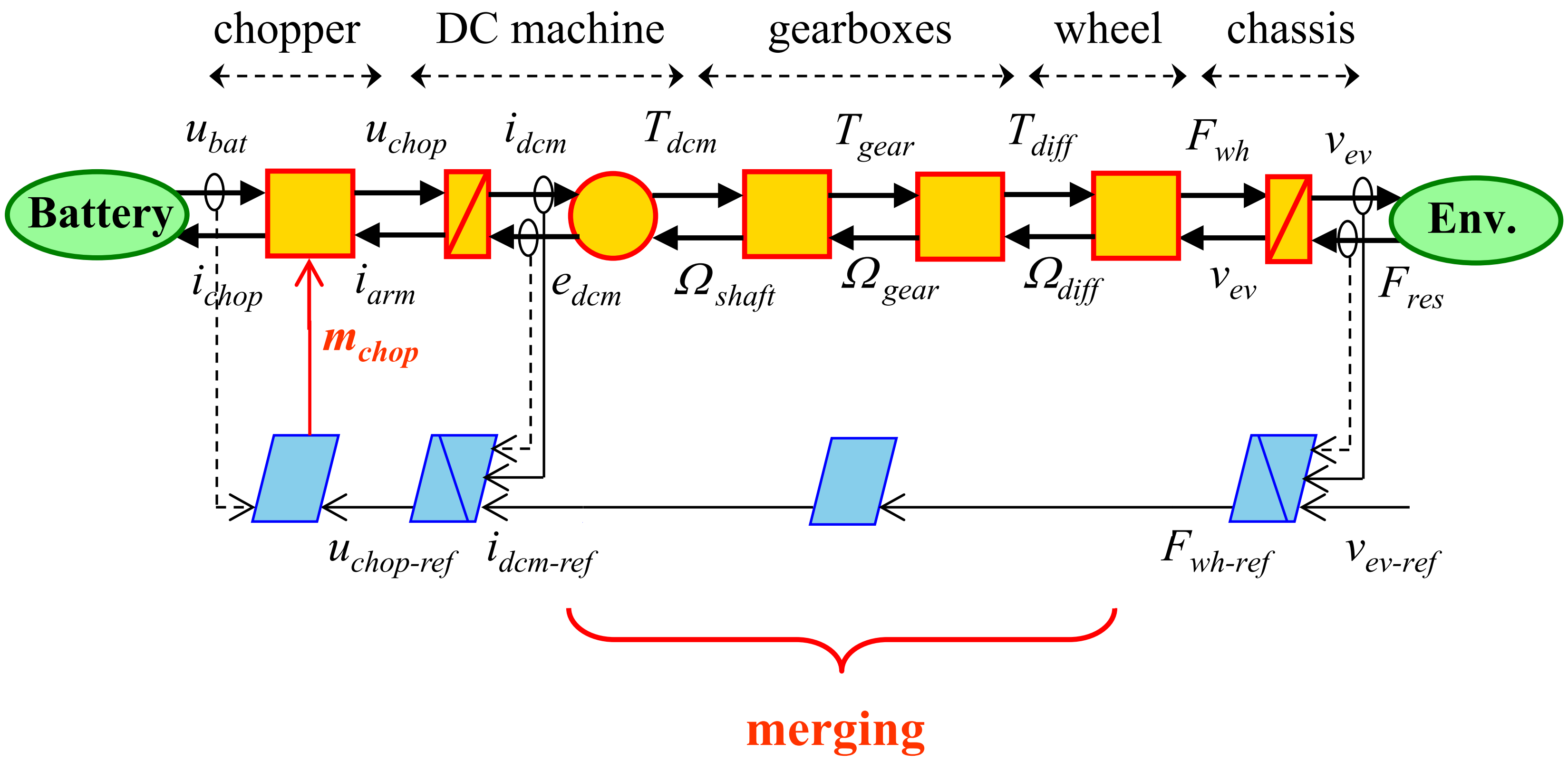


1. Electric & Hybrid Vehicles
2. EMR of a EV
3. **Control of a EV**
4. Example of a HEV



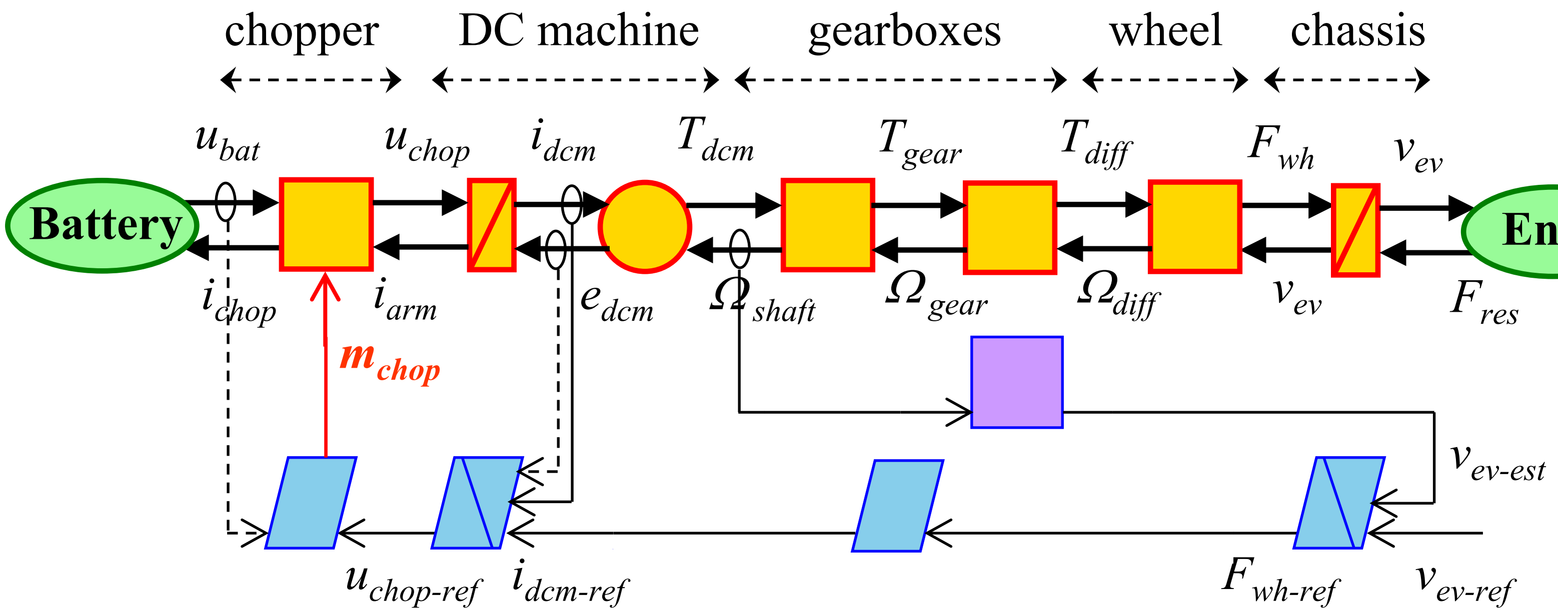
Maximum Control Structure:

- inversion of each element step-by-step
- all variables are assume measurable



Example of simplification:

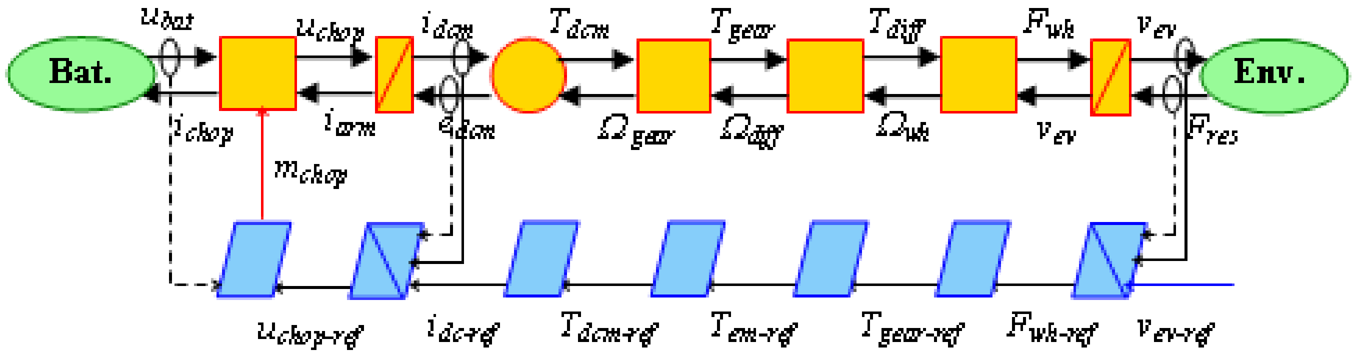
- merging of gains $k_{tot}=k_1k_2k_3k_4$

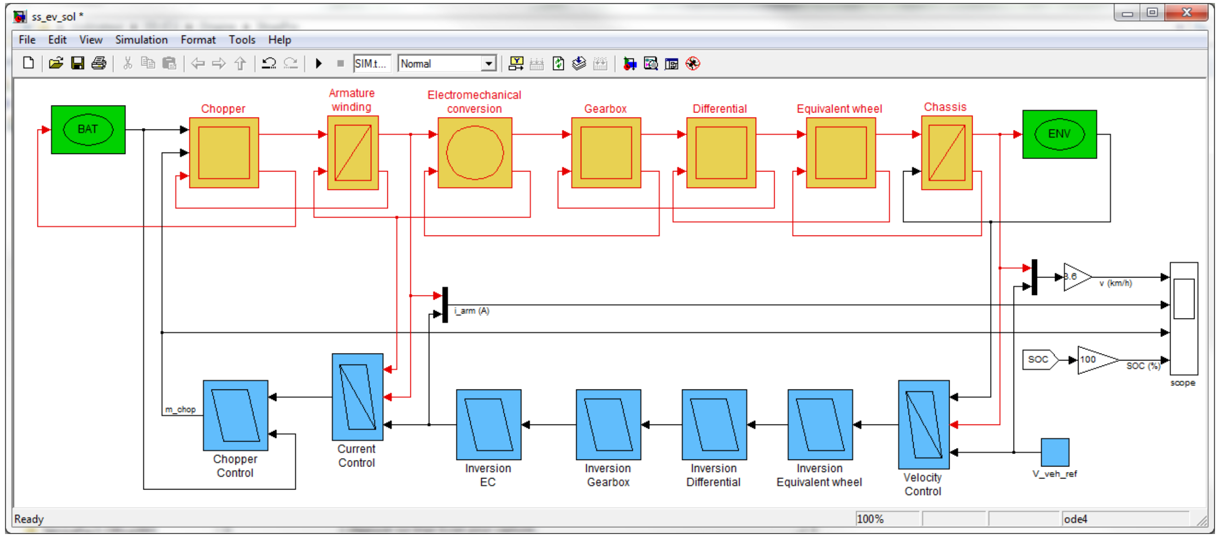


Example of estimation:

- estimation of velocity

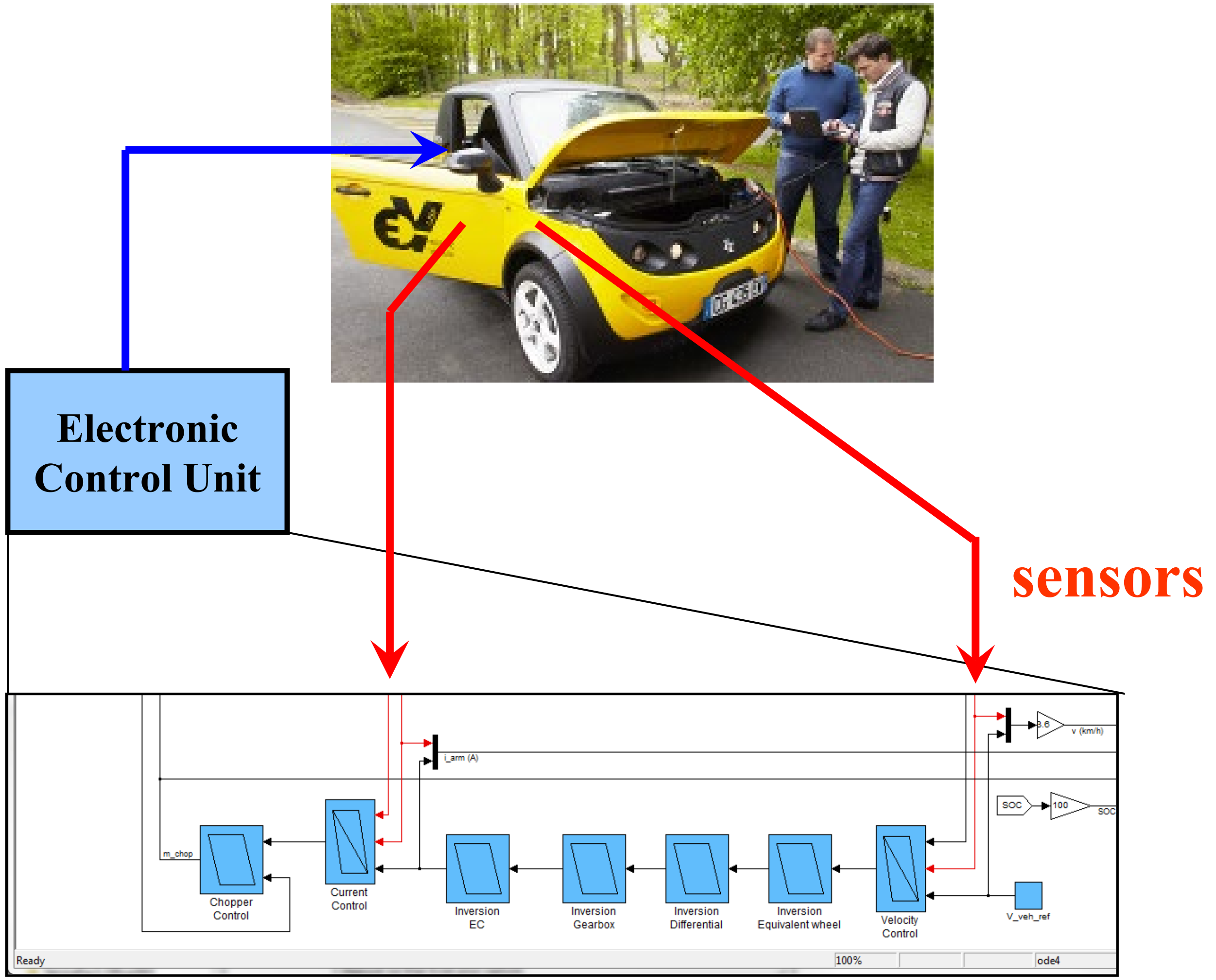
Simulation using a functional software

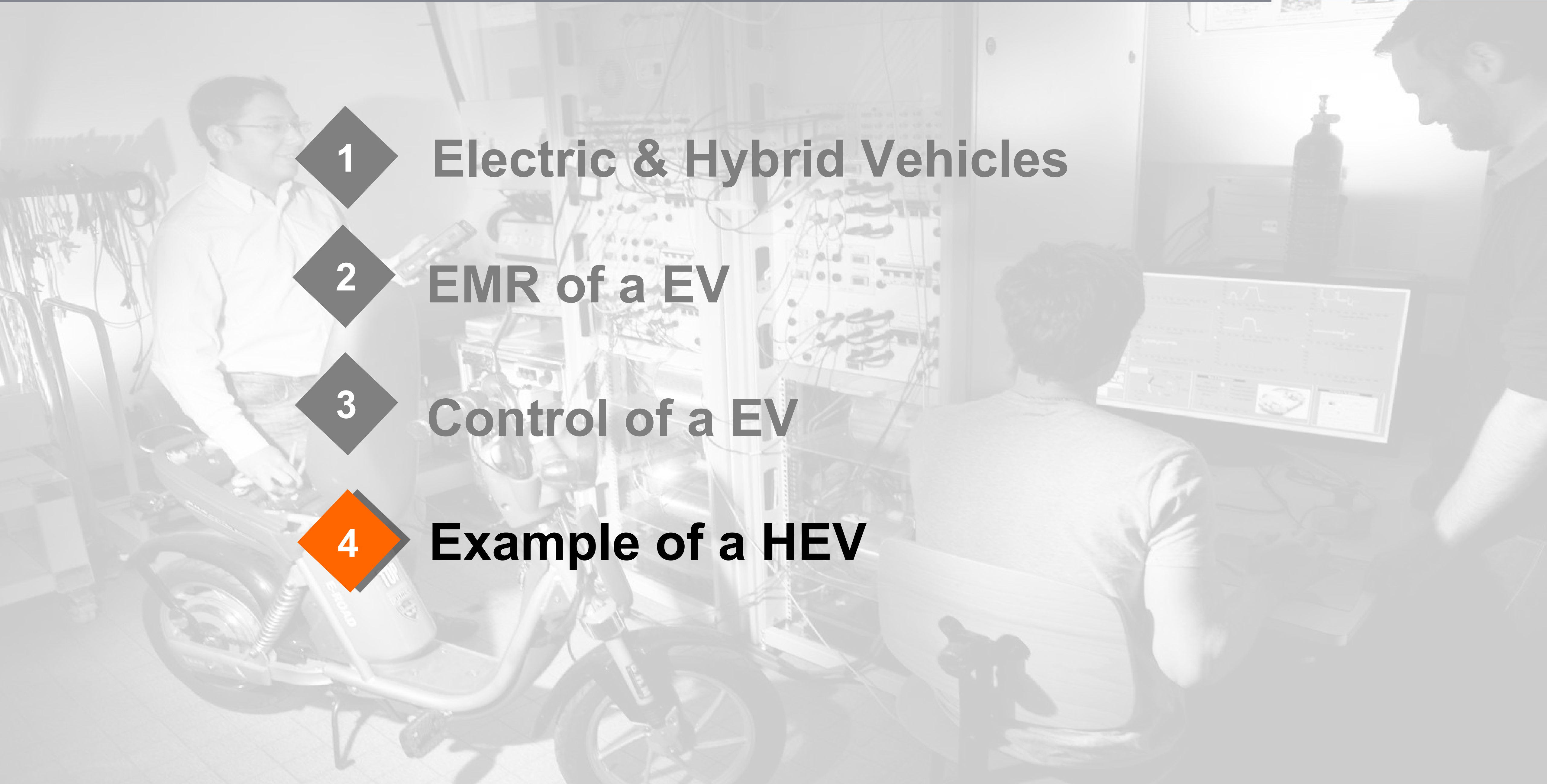




Matlab-Simulink ©, using the EMR library

Implmentation on the real vehicle





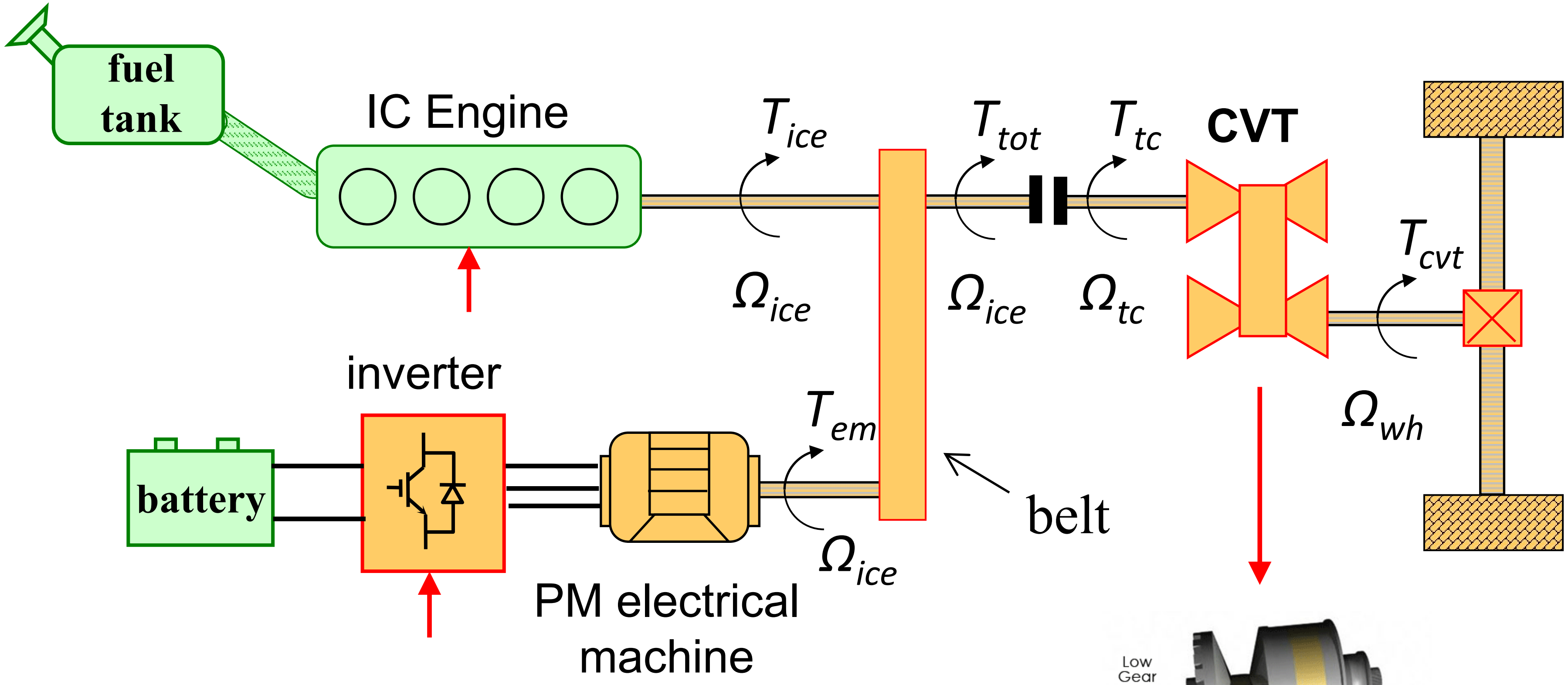
1 Electric & Hybrid Vehicles

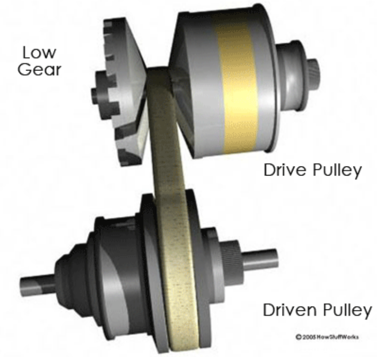
2 EMR of a EV

3 Control of a EV

4 Example of a HEV

Parallel HEV using a Continuous Variable Transmission (CVT)

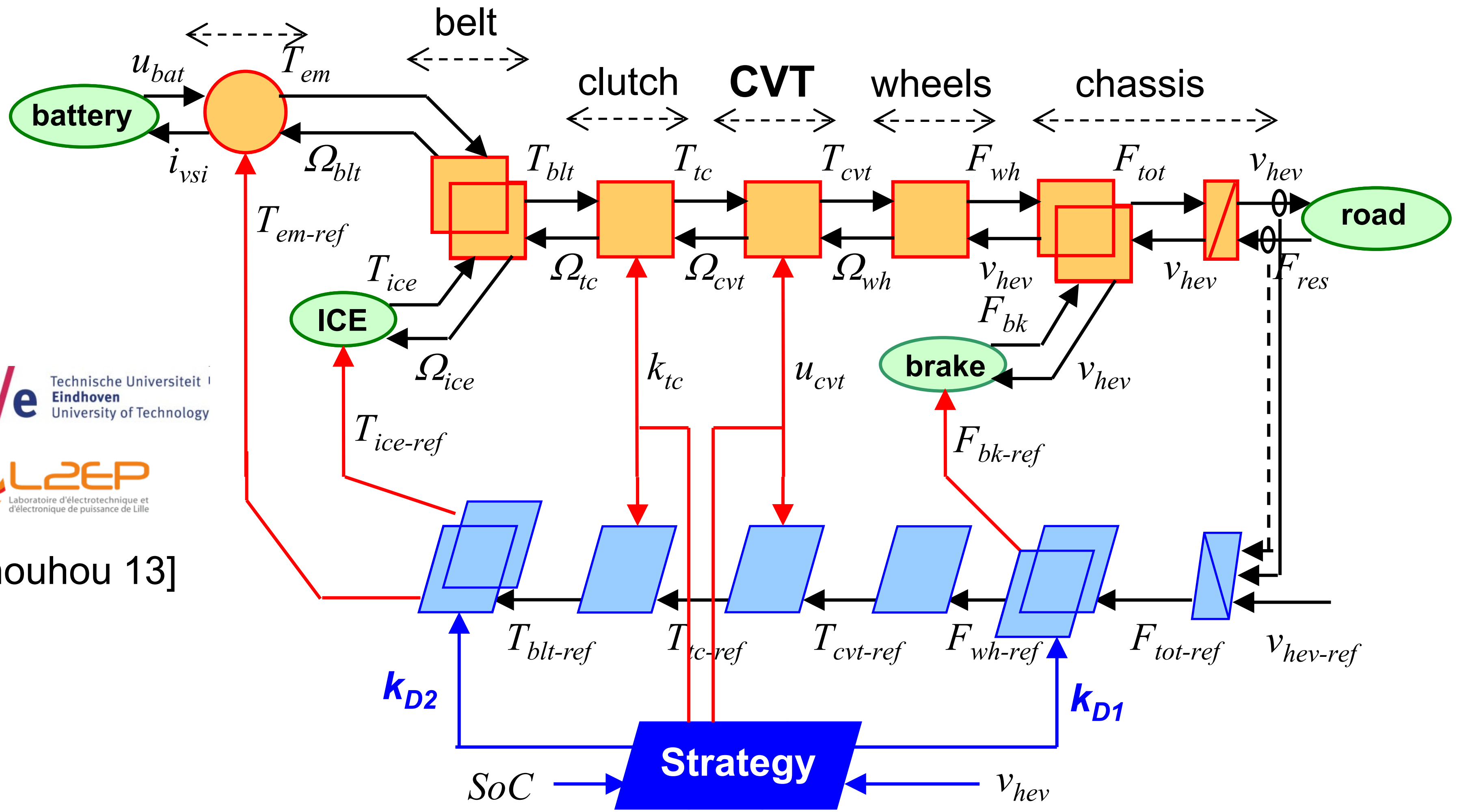




CVT: gearbox with a continuous ratio

Interest: accurate adaptation of the ICE speed

Drawback: efficiency max of 85%



Technische Universiteit Eindhoven University of Technology

L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

[Chouhou 13]

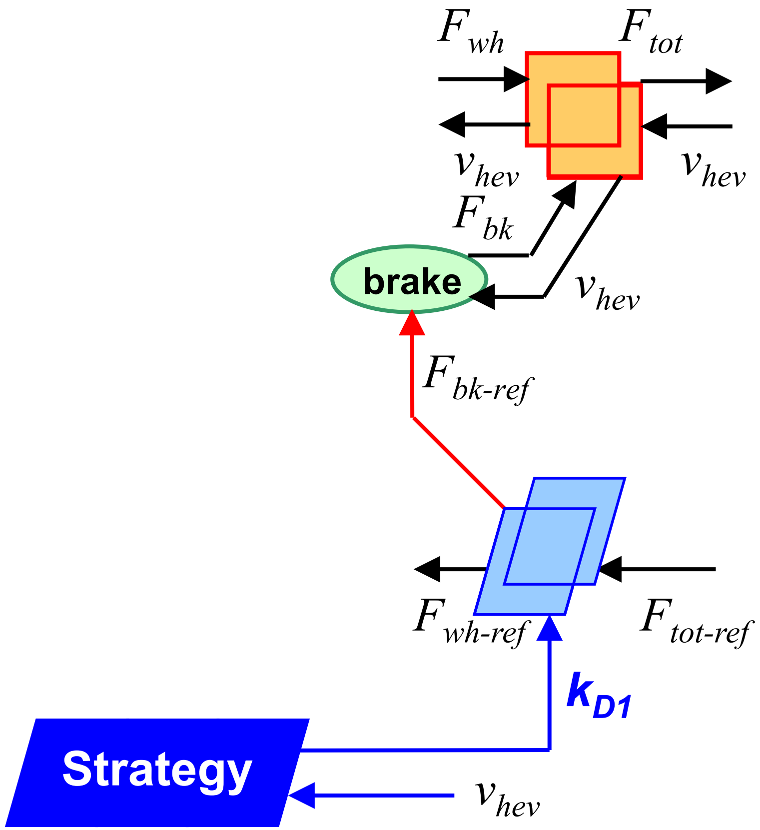
EMS for fuel reduction:
- choice of the CVT ratio (u_{cvt})
- energy distribution between e-drive and ICE (k_{D2})
- brake distribution between e-brake and m-brake (k_{D1})

Example of a part of the strategy: braking management

modelling $F_{tot}=F_{wh}+F_{bk}$

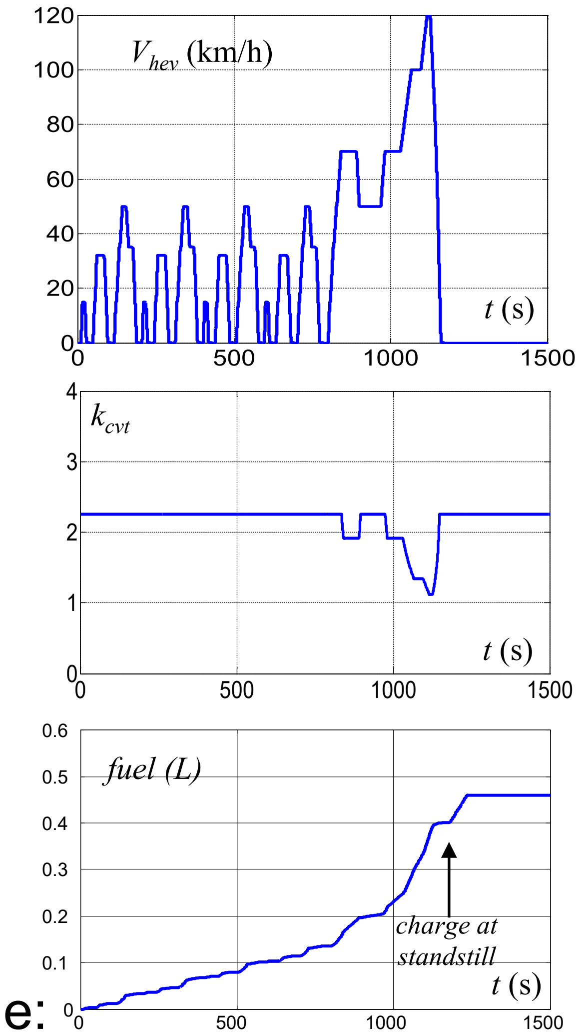
control $F_{wh-ref}=k_{D1}F_{tot-ref}$
$F_{bk-ref}=(1-k_{D1})F_{tot-ref}$

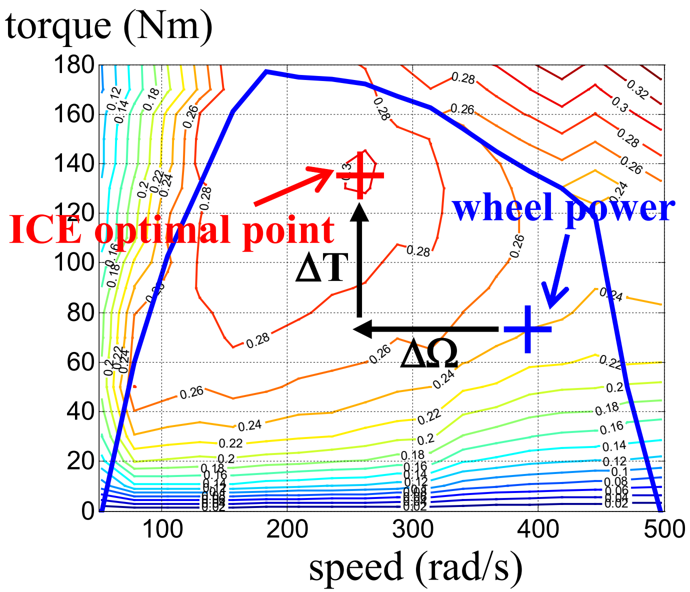
Strategy
$k_{D1f}=1$ *traction*
$k_{D1f}=0.5$ *50% e-braking (front wheels)*
50% mech-braking (rear wheels)
$k_{D1f}=0$ *100% mech-braking when SoC is 100%*



Performances of the CVT-based HEV

[Mayet 16]





ruled-based EMS:

- □ imposed by the CVT
- ΔT imposed by the e-drive

4-gear Thermal Vehicle:
5.04 L/100 km
CVT-based HEV:
4.02 L/100 km

1 Research @ L2EP

2 Control team

3 eV activities

4 Examples

electricity
& Vehicles

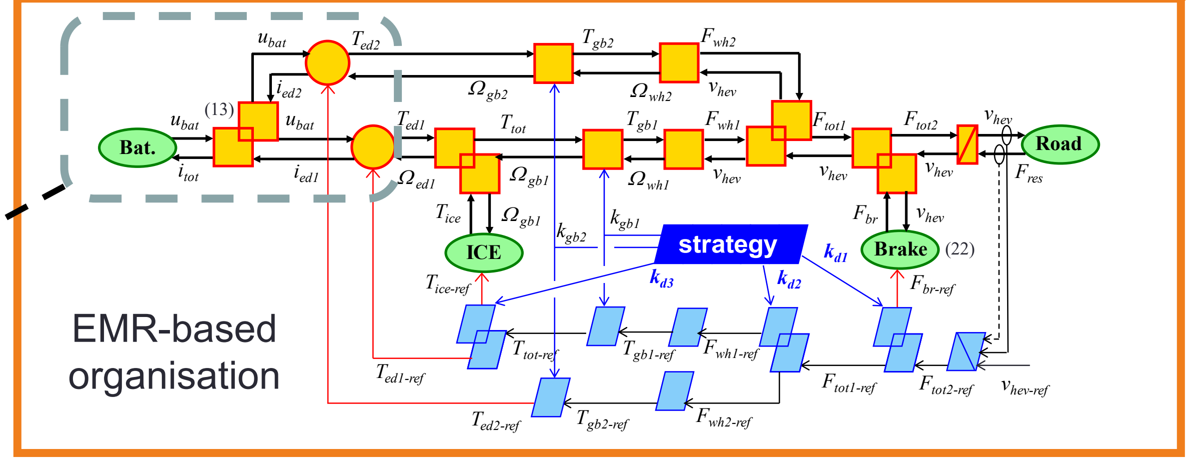
Objective of the eV group

Validation of new concepts of electrified vehicles for more sustainable transport

Originalities:

- from real components to **real vehicles**
- **graphical formalism (EMR)** for model and control organisation
- **Hardware-In-the-Loop testing** (coupling hardware & software)

Off-line simulation (vehicle model)



Hardware to be tested

Software

Example from H2020 PANDA

Plug-in Hybrid demo car

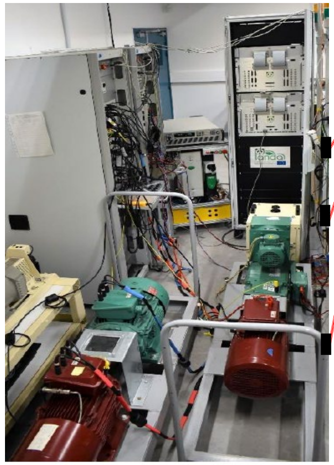
Objective of the “eV” group

Validation of new concepts of electrified vehicles for more sustainable transport

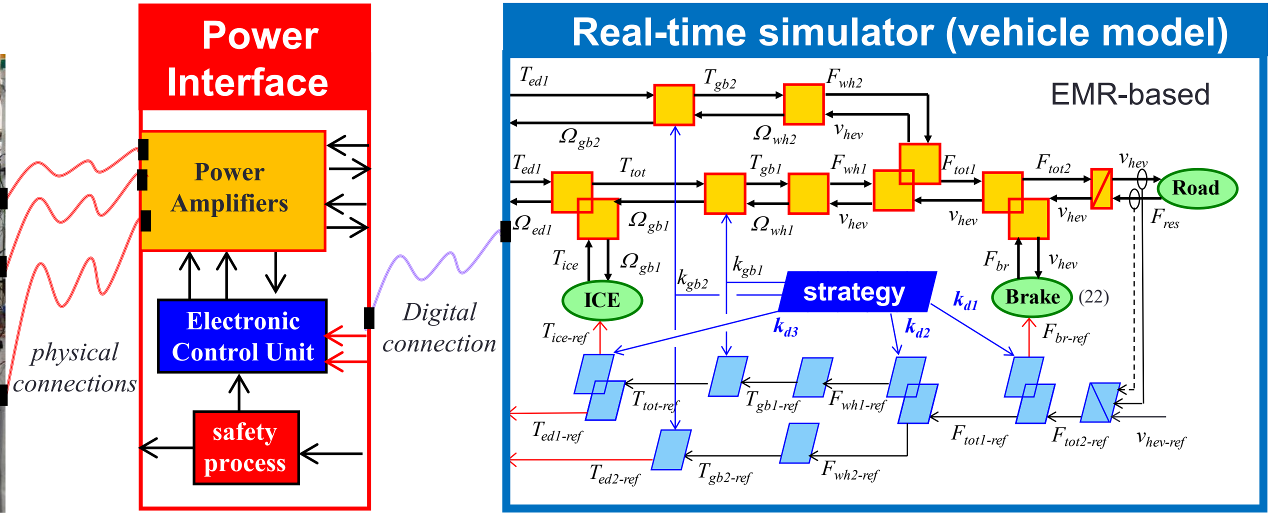
Originalities:

- from real components to **real vehicles**
- **graphical formalism (EMR)** for model and control organisation
- **Hardware-In-the-Loop testing** (coupling hardware & software)

real e-motors under test



Hardware



Software

Example from H2020 PANDA

Plug-in Hybrid demo car

- e-storage workplace (R. German)
- e-charging workspace (P. Delarue)
- e-drive workspace (N. K. Nguyen)
- e-transmission workspace (W. Lhomme)
- e-vehicle workspace (A. Bouscayrol)

Virtual visit @
https://lt360.site/ce2i/l2ep/ev-ulille.php

Industry

National Labs

MEGEVH
French network on HEV's

Education

Master ULille / A&M ParisTech, etc.

International summer schools:
EMR
ACES
HIL

Demo & driving

International Labs

eCAMPUS
International Lab
(France / Canada)

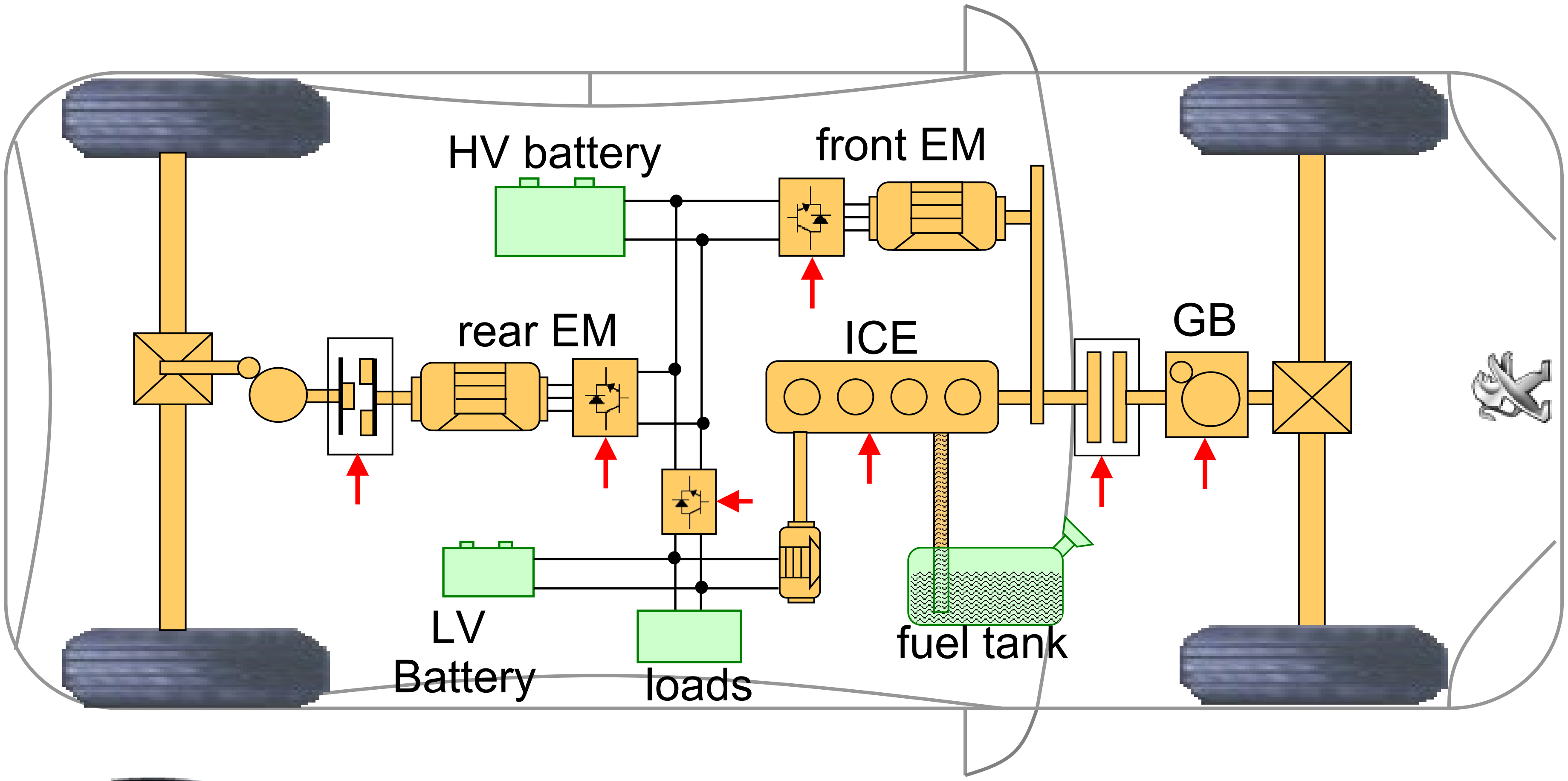
1 Research @ L2EP

2 Control team

3 eV activities

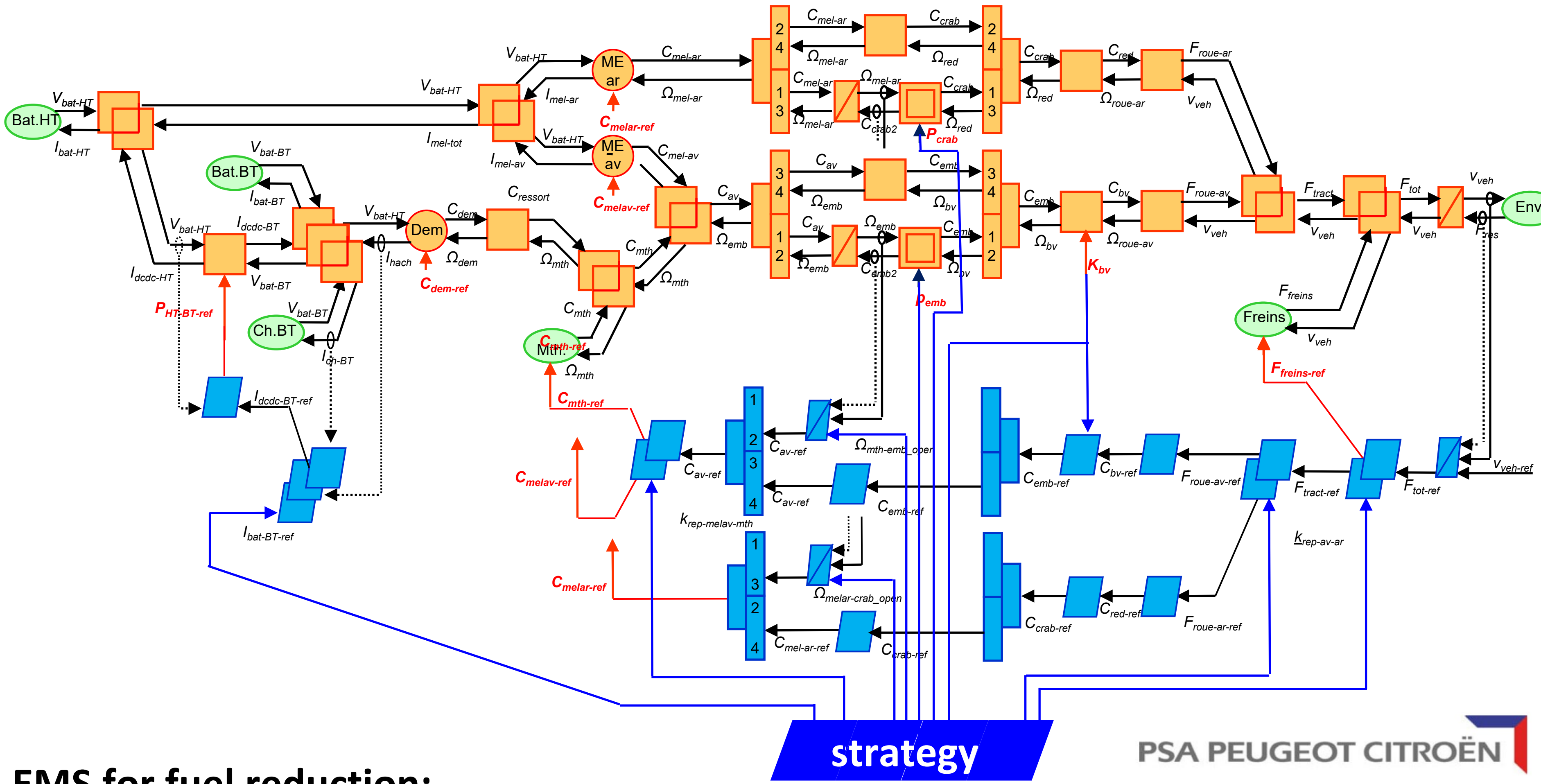
4 **Examples**

Double-parallel diesel HEV 3008 HY4



PSA PEUGEOT CITROËN

Diesel HEV: increase of the ICE efficiency
Double parallel: increase the energy recovery



EMS for fuel reduction:

- energy distribution between EM1, EM2 and ICE
- brake distribution between e-brake and m-brake
- management of the balance of batteries
- management clutches and gear ratio

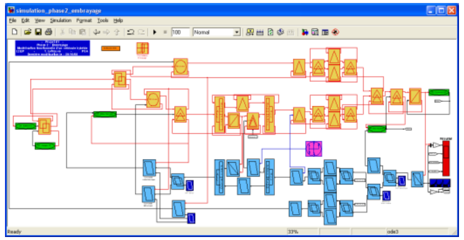
PSA PEUGEOT CITROËN

MEGEVH French network on HEV's

L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

[Letrouvé 13]

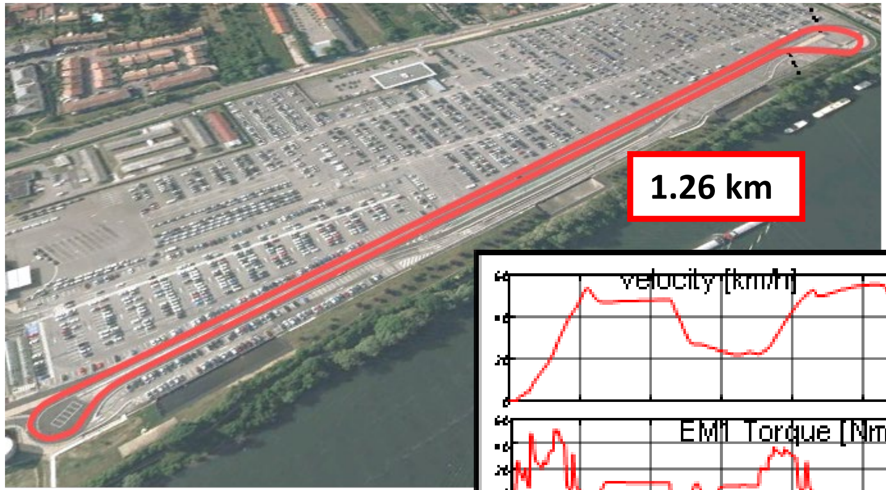
Validation of the Double-parallel HEV control



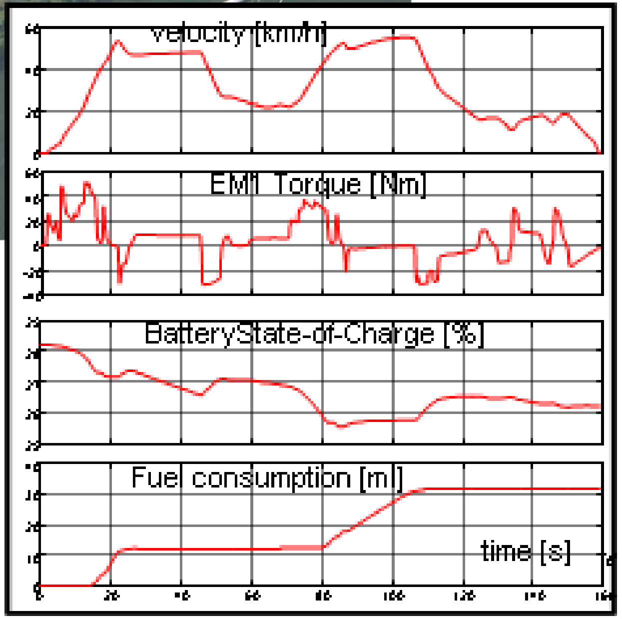
Simulation on Matlab-Simulink©

Test on « HIL » plate-form

Validation on prototype



Test driving cycle at PSA Poissy



Ruled-based EMS

PSA PEUGEOT CITROËN

MEGEVH
French network on HEV's

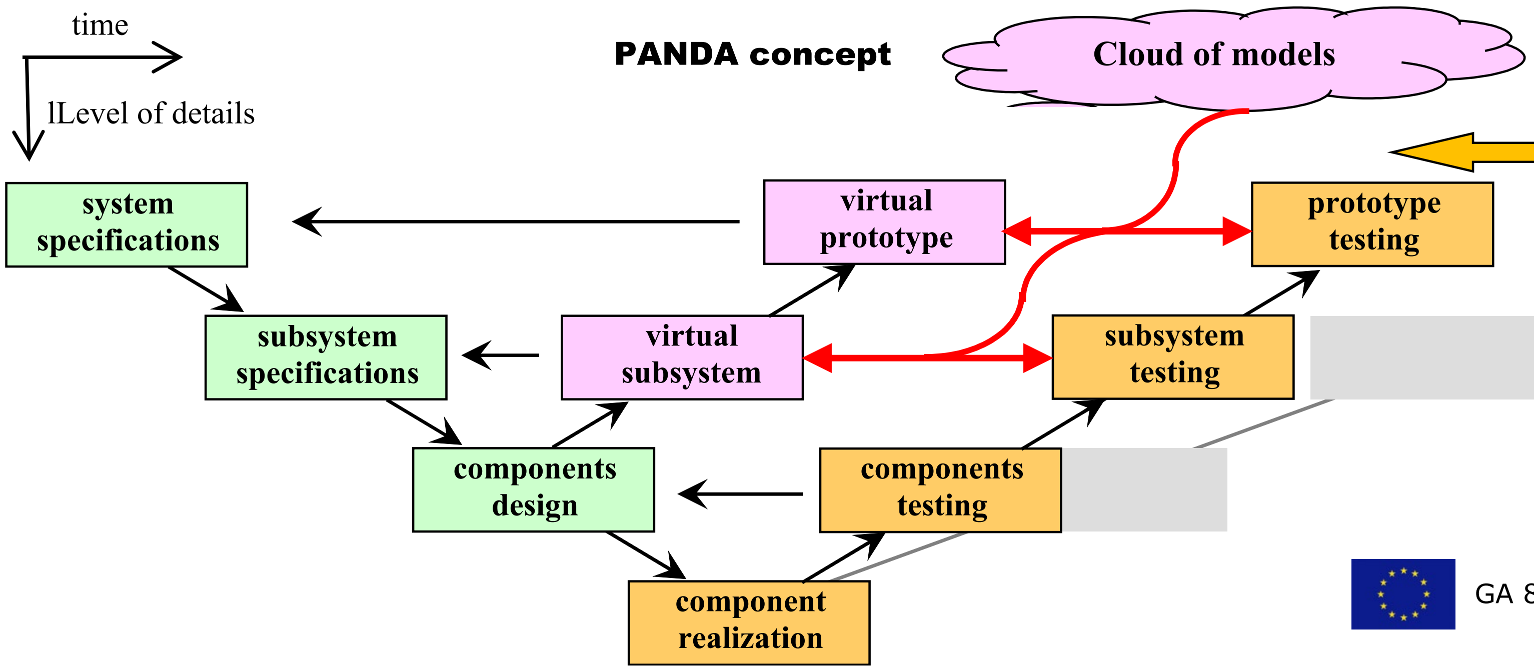
L2EP
Laboratoire d'électrotechnique et d'électronique de puissance de Lille

[Letrouvé 13]

Coordination RIA H2020

Powerful Advanced N-level Digital Architecture for models of EVs and components

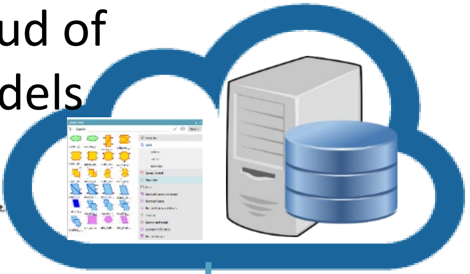
Grant Agreement 824256 - 3,5 M € - 3 years – 11 partners – 6 countries

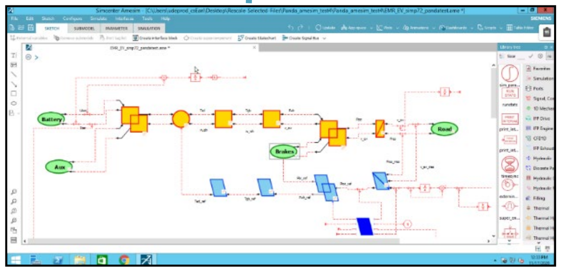


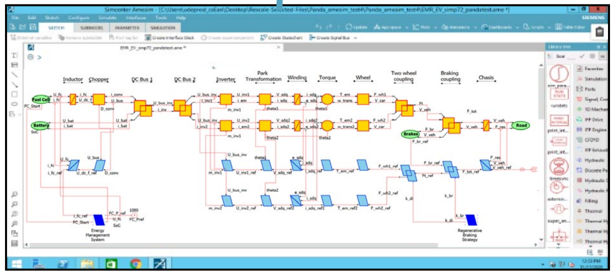
GA 824256

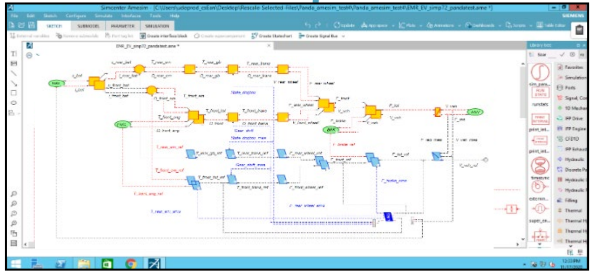
Unified model organization of electrified vehicles and their components
For virtual and real testing (EMR at the core of the project)

Cloud of models







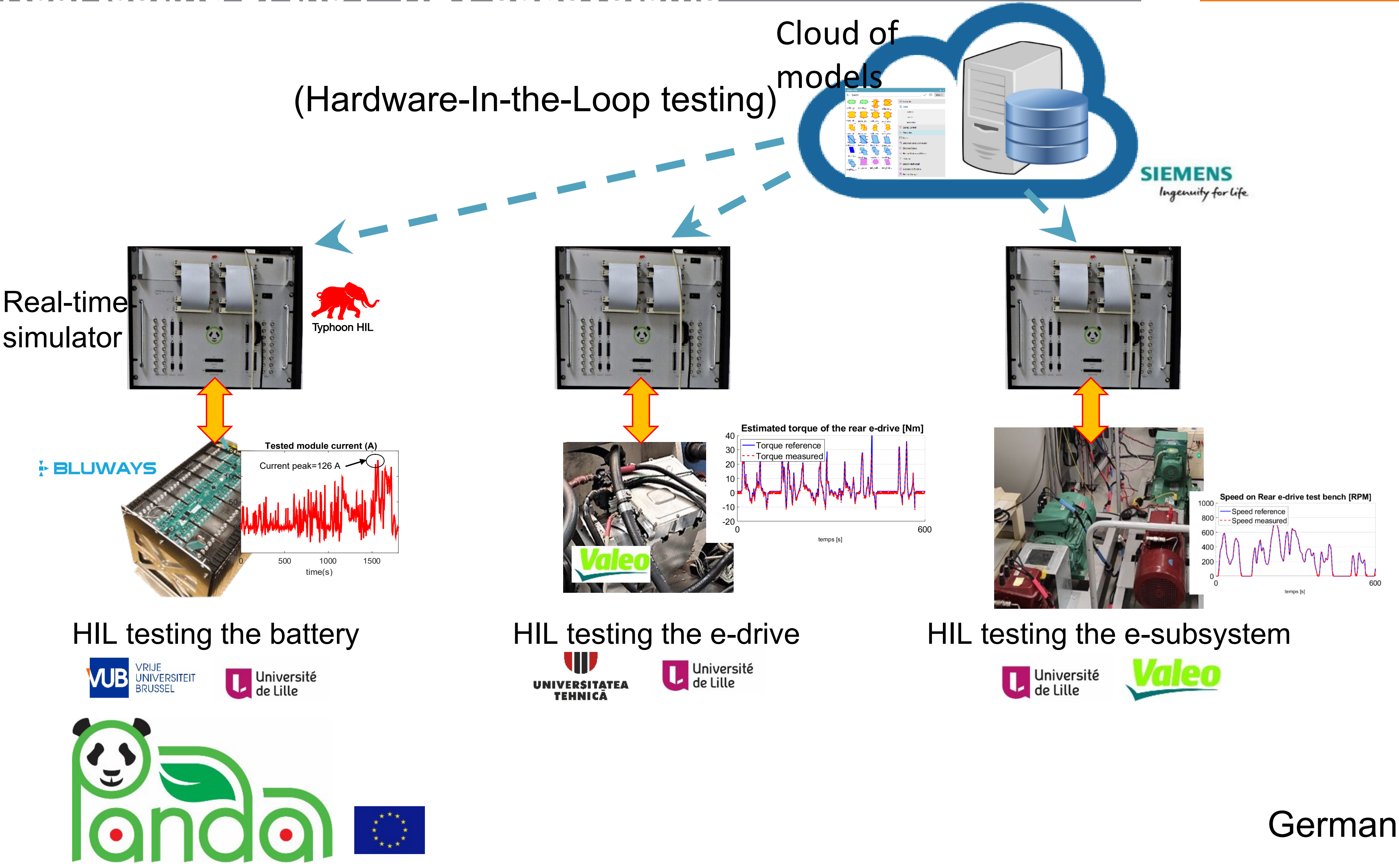


BEV (Renault Zoe)
Accuracy 97%

FCV (Mobipost)
Accuracy 95%

P-HEV (Valeo Demo Car)
Accuracy
97%

Real testing of the P-HEV subsystems

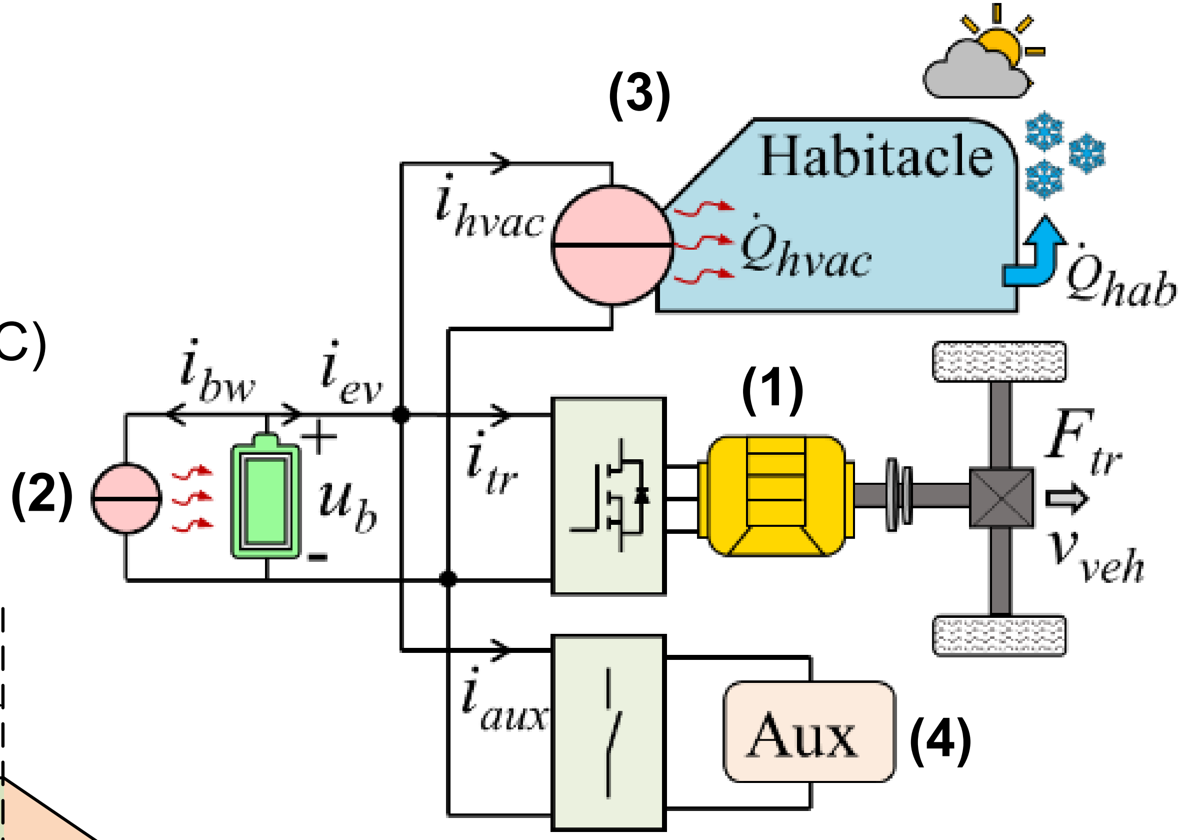


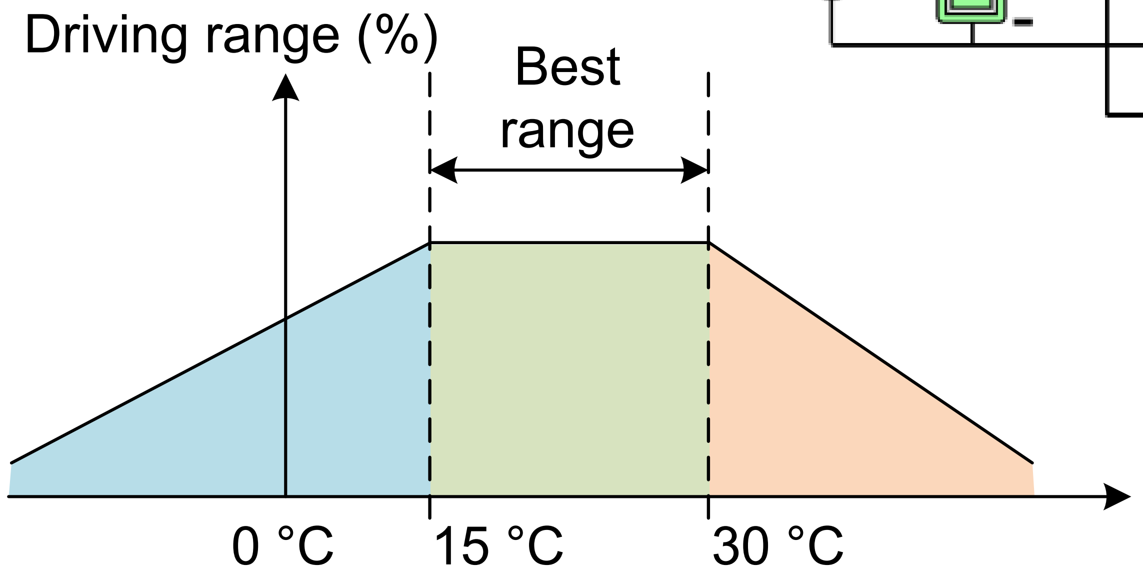
German 24]

EV consumption & Climatic condition

Main subsystems of an EV

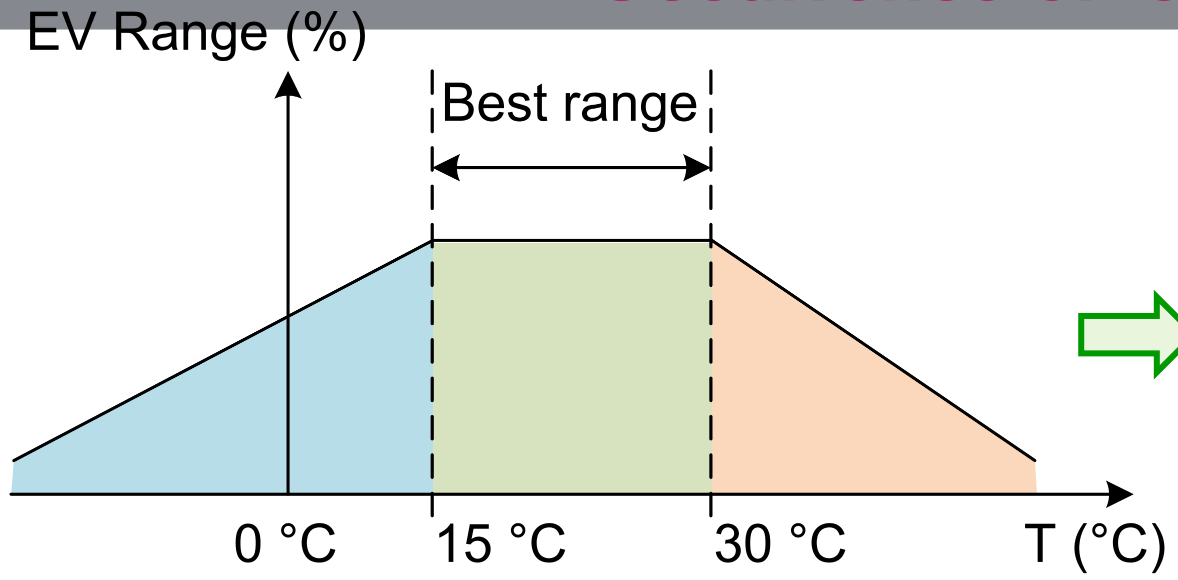
1. Electric powertrain
2. Energy storage
3. Comfort subsystem (HVAC)
4. auxiliaries





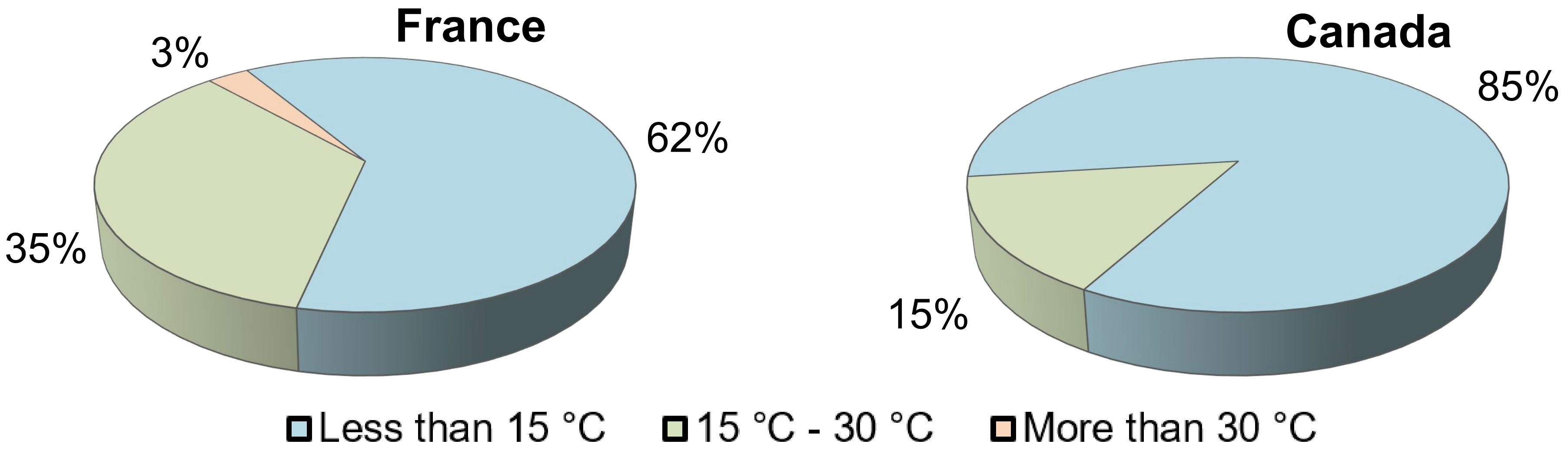
[Mansour 18]

Occurrence of low temperature

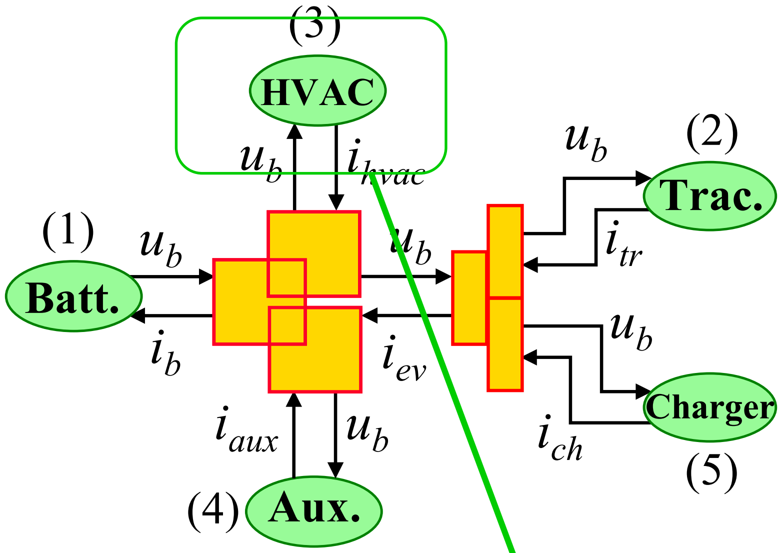


Ambient temperature must be considered

[Allen 14]
[Mansour 18]

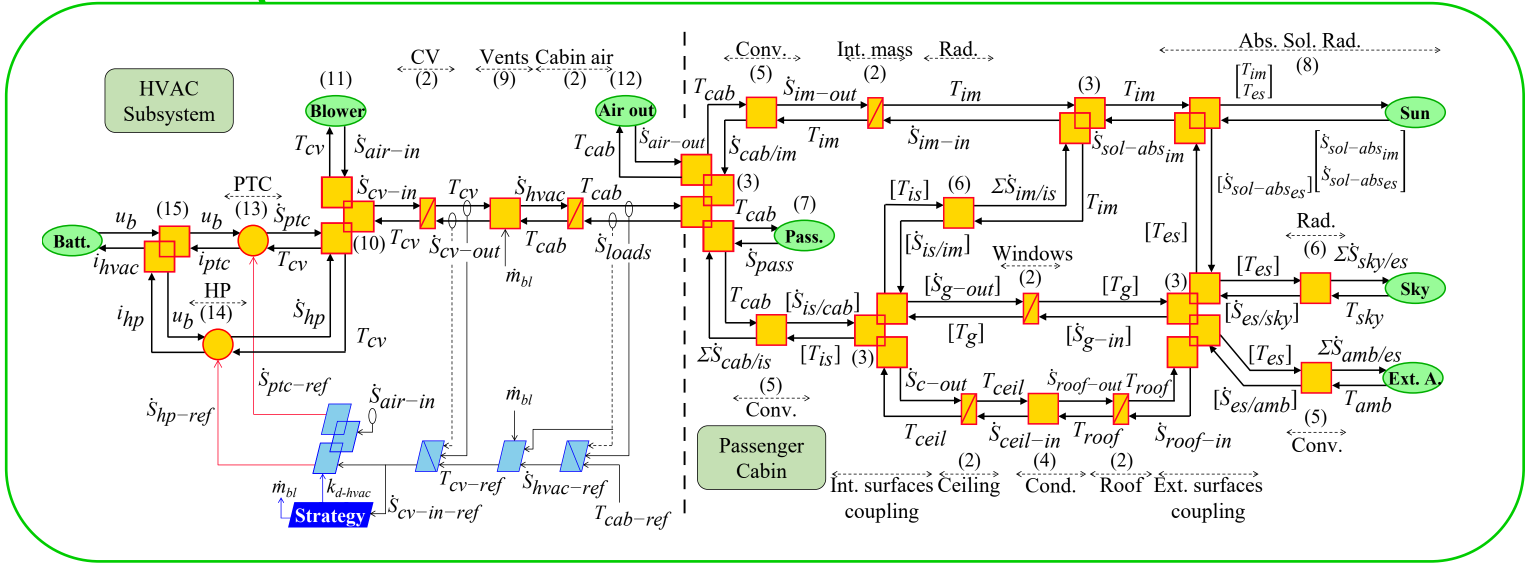


Flexible simulation model



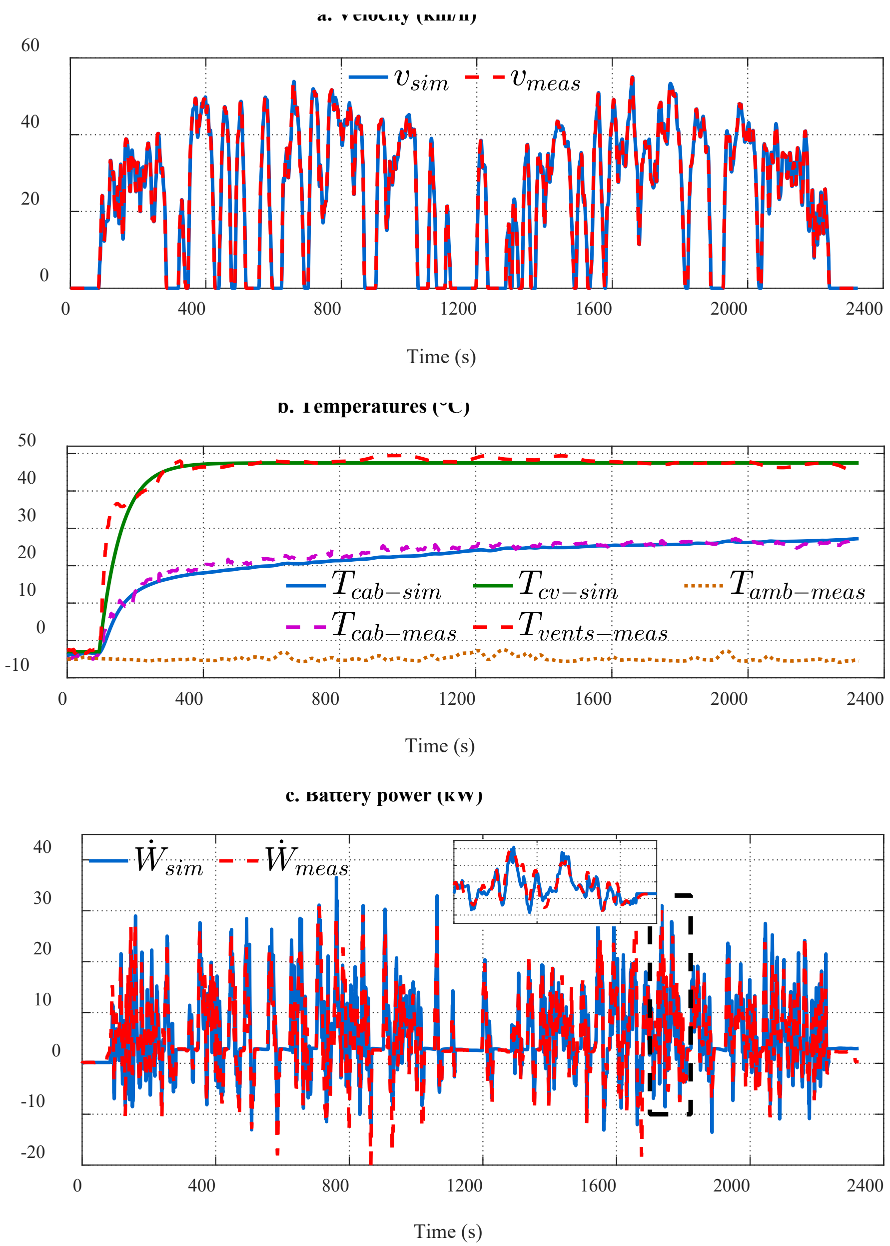
EMR (Energetic Macroscopic Representation) formalism to interconnect multi-physical models of different subsystems

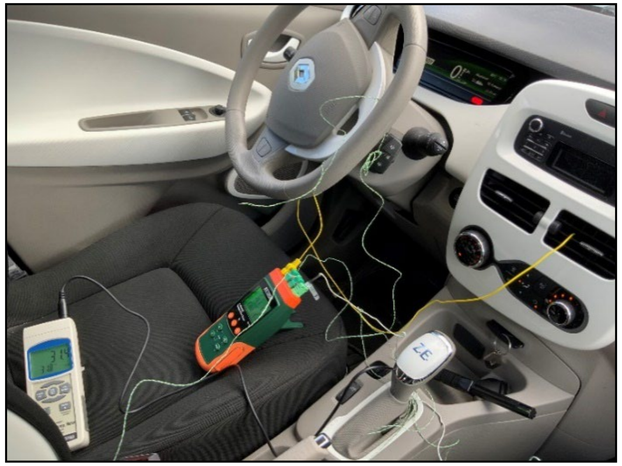
Management of the complexity while ensuring high flexibility



[Ramsey 2022]

Simulation validation

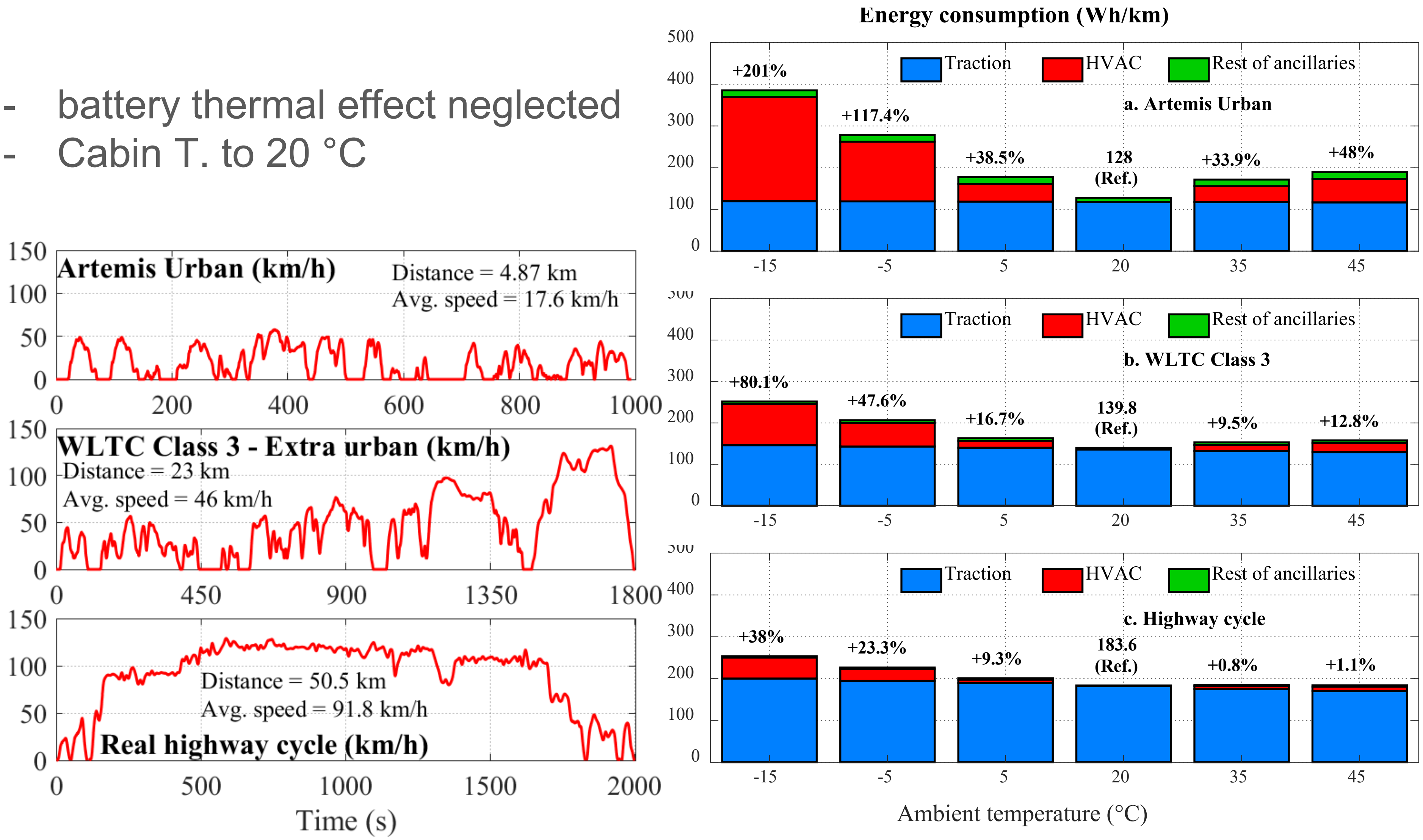




Error on the energy consumption = 2.8%

consumption vs. climate & driving cycle

- battery thermal effect neglected
- Cabin T. to 20 °C



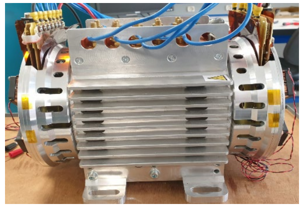
[Ramsey 2022]

New topology for a e-bus?

ALTAS interurban mini bus
(5800kg / 20 seats / e-drive 160 kW /
Li-Ion NMC Bat. 115 kWh)

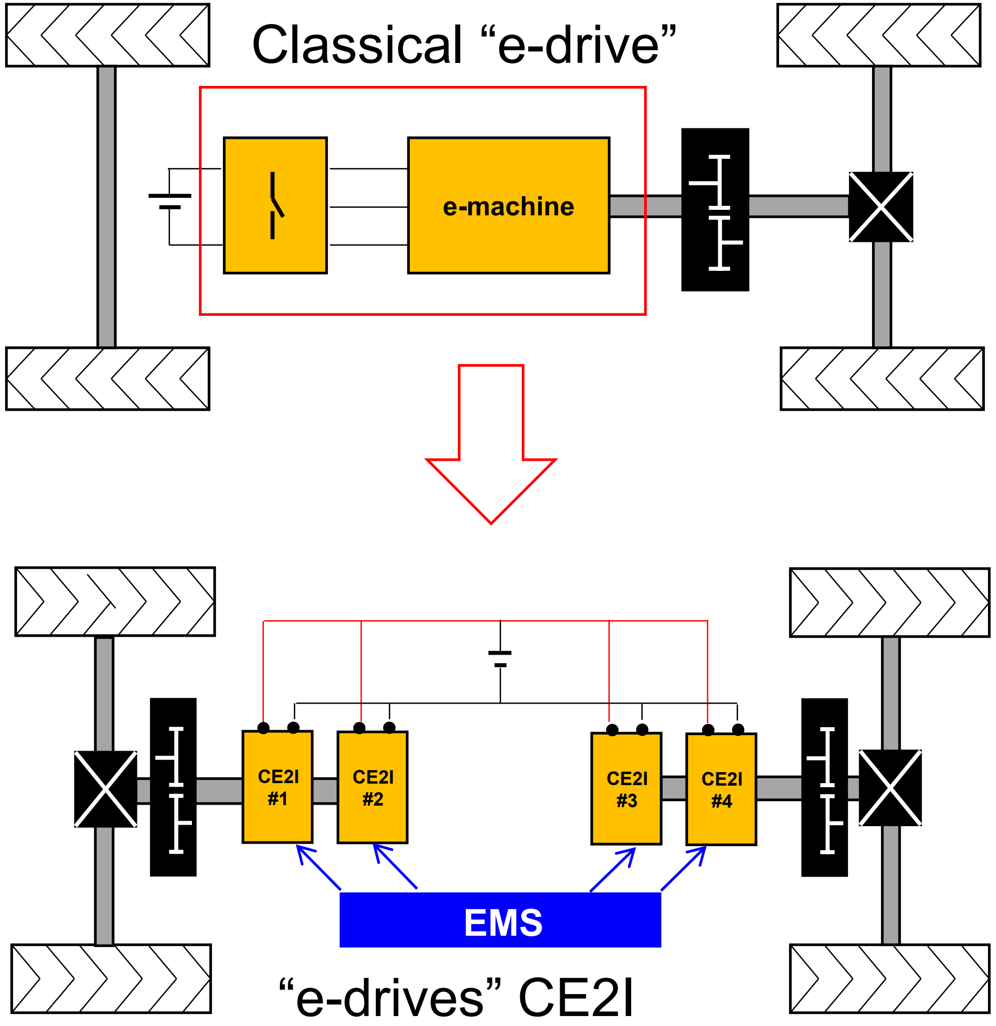
https://www.atlasautobus.com

CE2I e-drive (40 kW):
(Integration of 5-phase machine
+ GAN converter)



New e-bus topology:
- 2 in the front axle
- 2 in the rear axle
- specific energy management

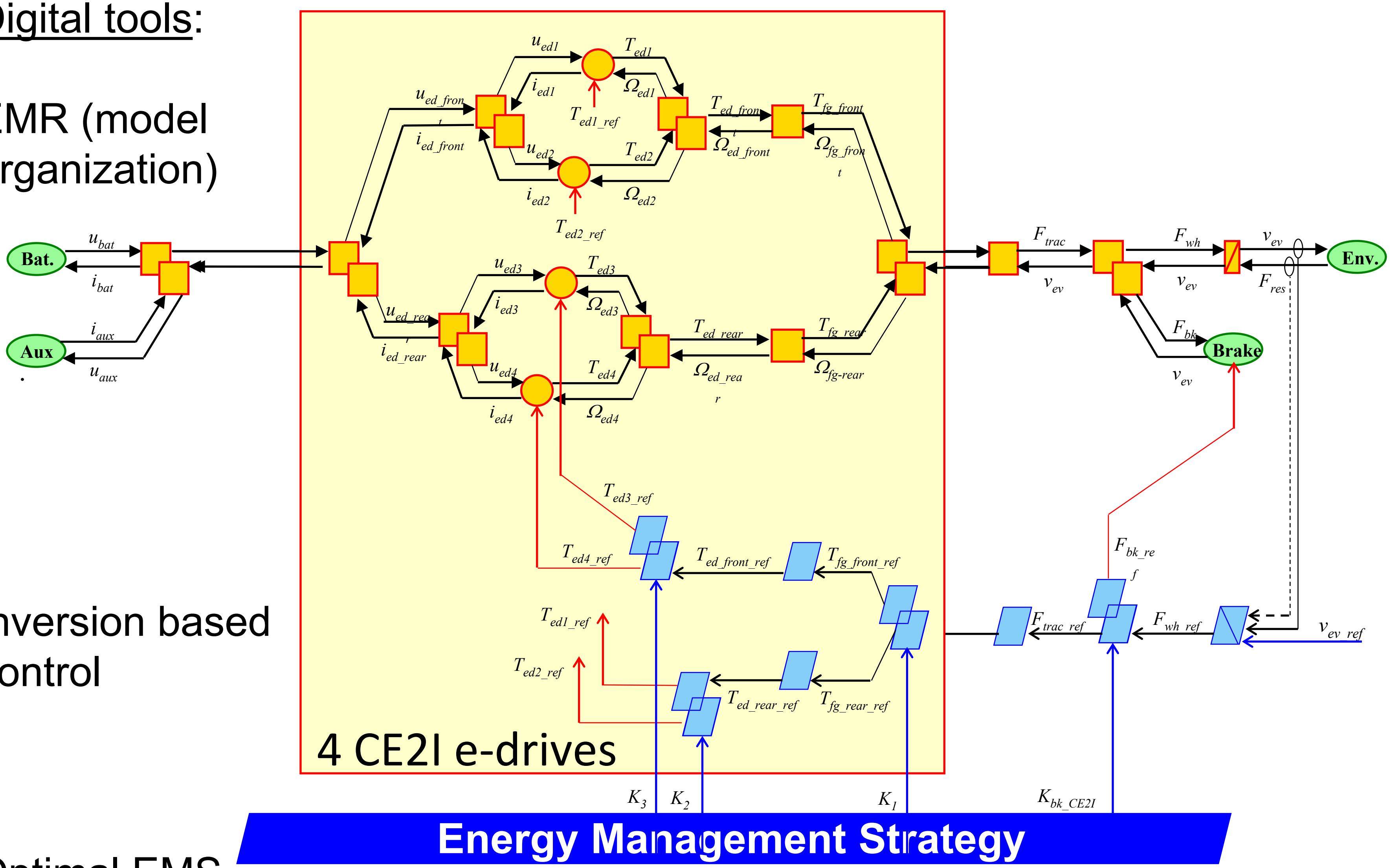
Which benefit?



Simulation of the different e-buses

<u>Digital tools</u>:

EMR (model organization)

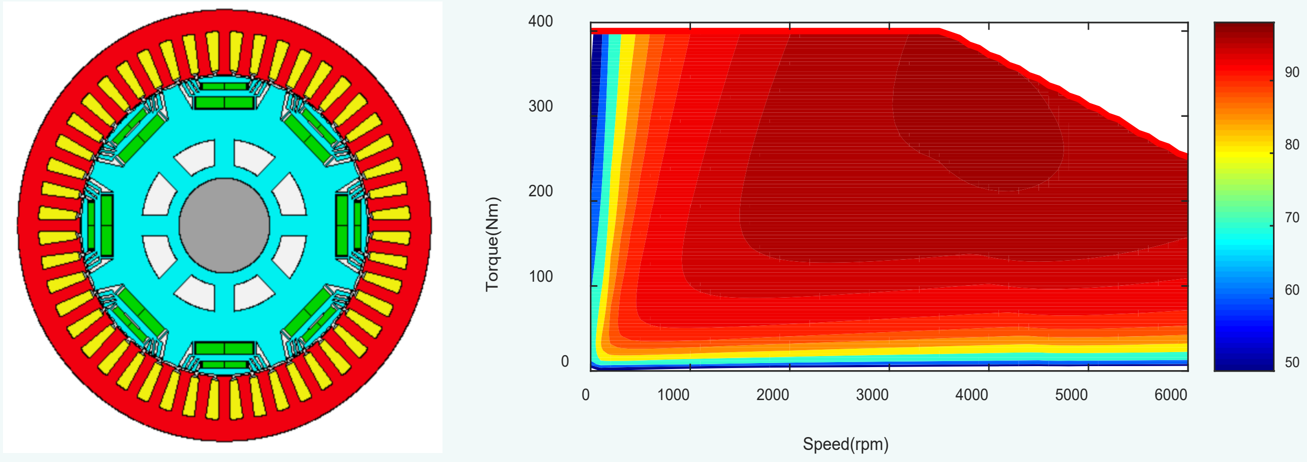


Inversion based control

Optimal EMS (Dynamic Programming)

e-drive static models

Classical electrical machine



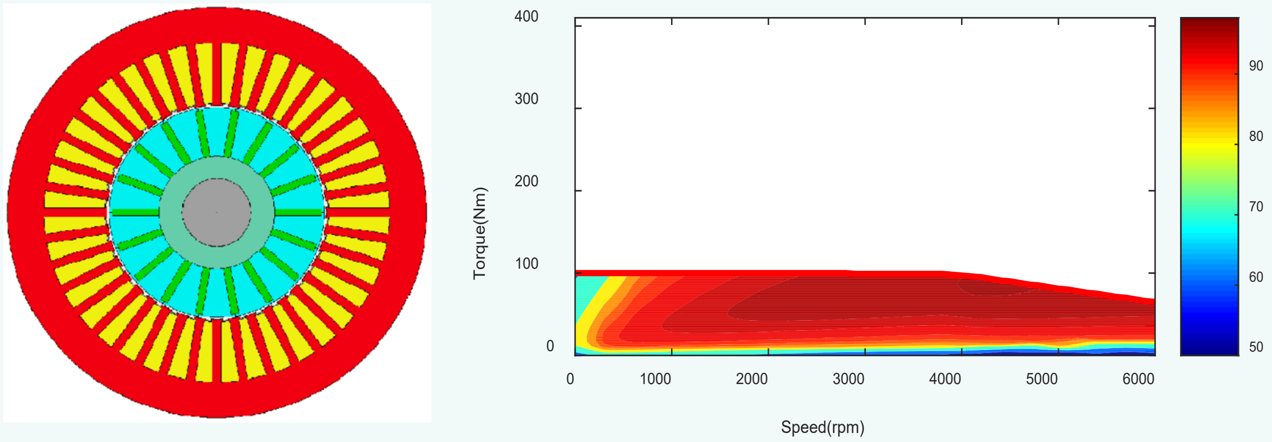
From MotorCAD

3-phase MSAP

160 kW

400 Nm max

CE2I electrical machine



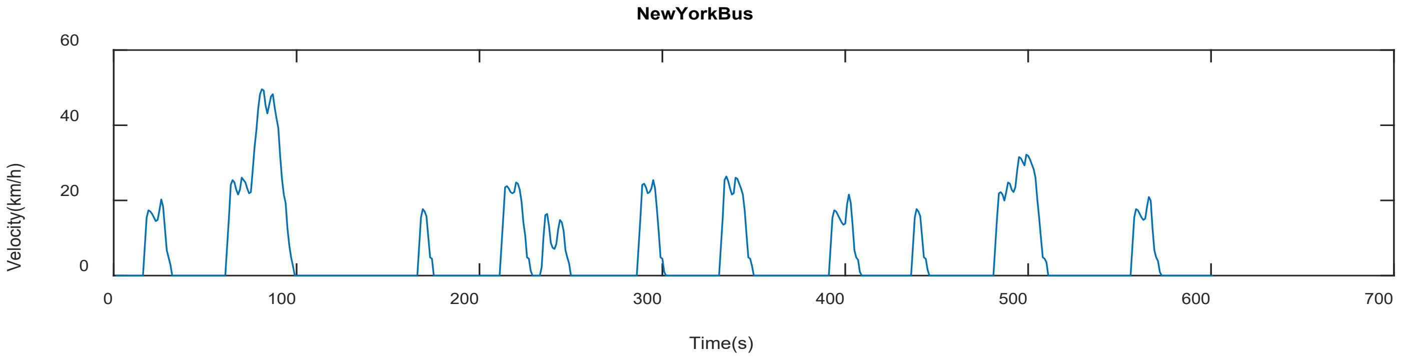
From CE2I program

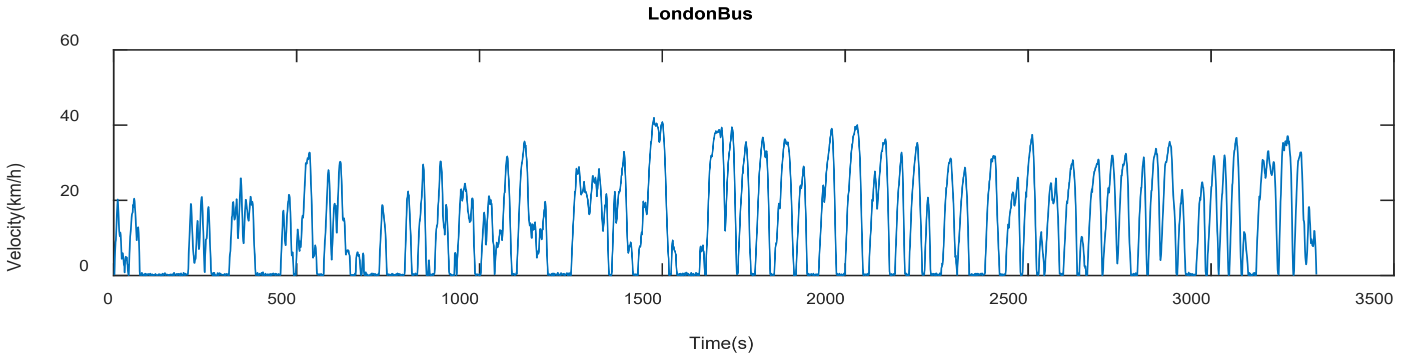
10-phase MSAP

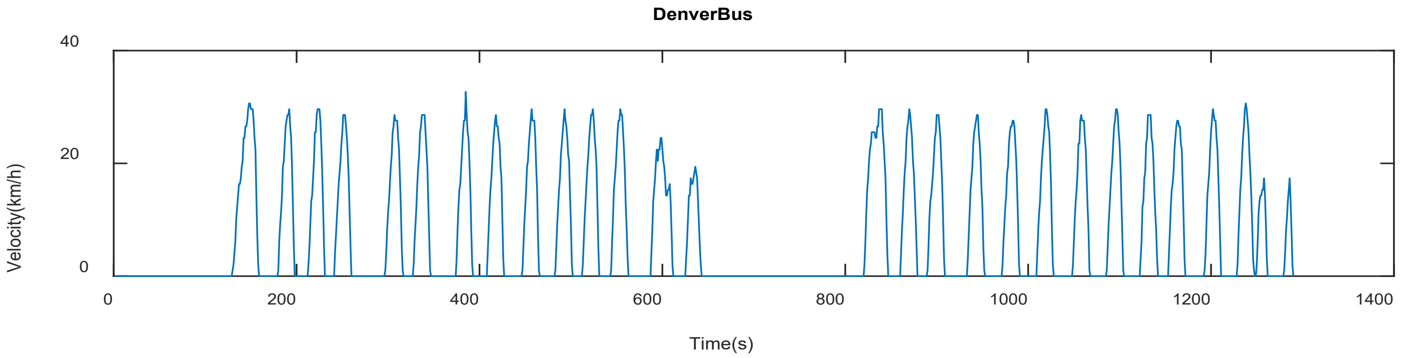
40 kW

100 Nm max

Driving cycles for test







From ADVISOR2022 database

Simulation results

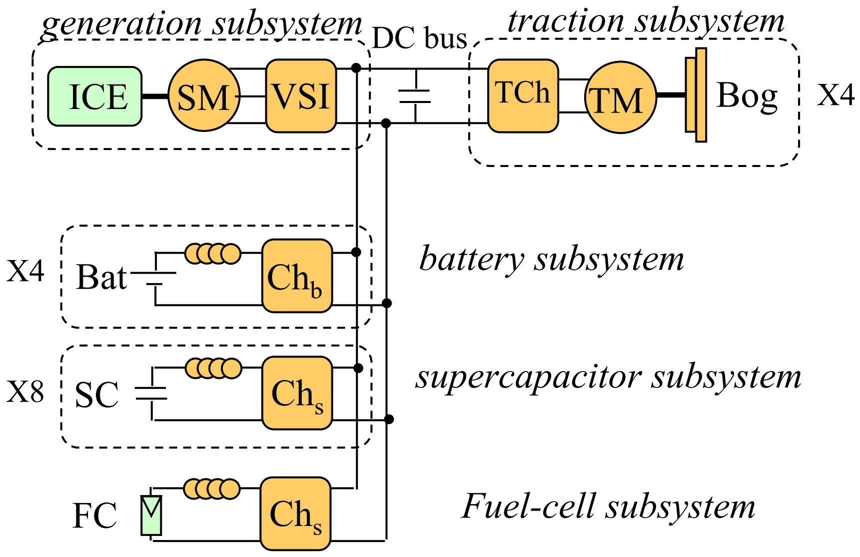
- Braking strategy : 60% à l'avant et 40% à l'arrière (stabilité)

	Consumption (kWh/100km)		
Driving cycles	**New York**	**London**	**Denver**
Classical e-drive	77.0	43.8	66.1
4 CE2I e-drive	58.4	32.0	48.3
Energy savings	**25.2 %**	**26.9 %**	**27.0 %**

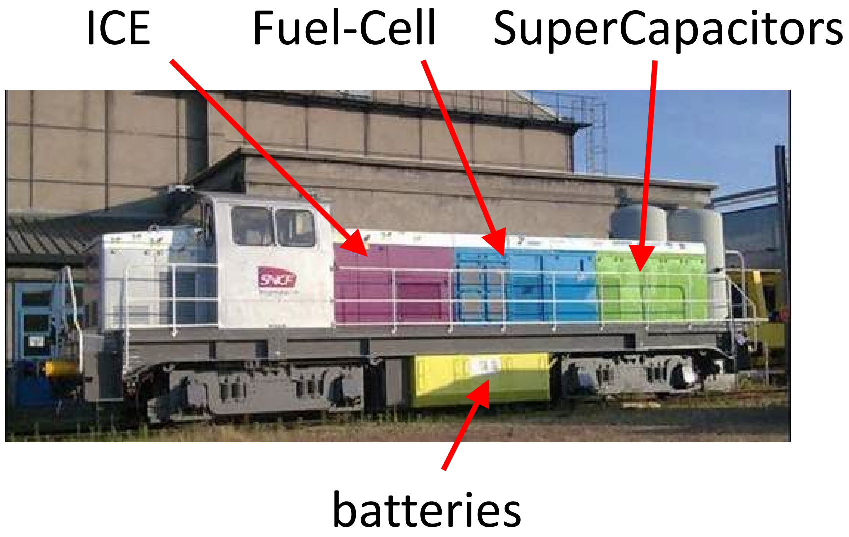
Energy savings despites 30 kg surplus:

1) Braking energy recovery
2) Energy distribution (4 e-drive)
3) Better efficiency

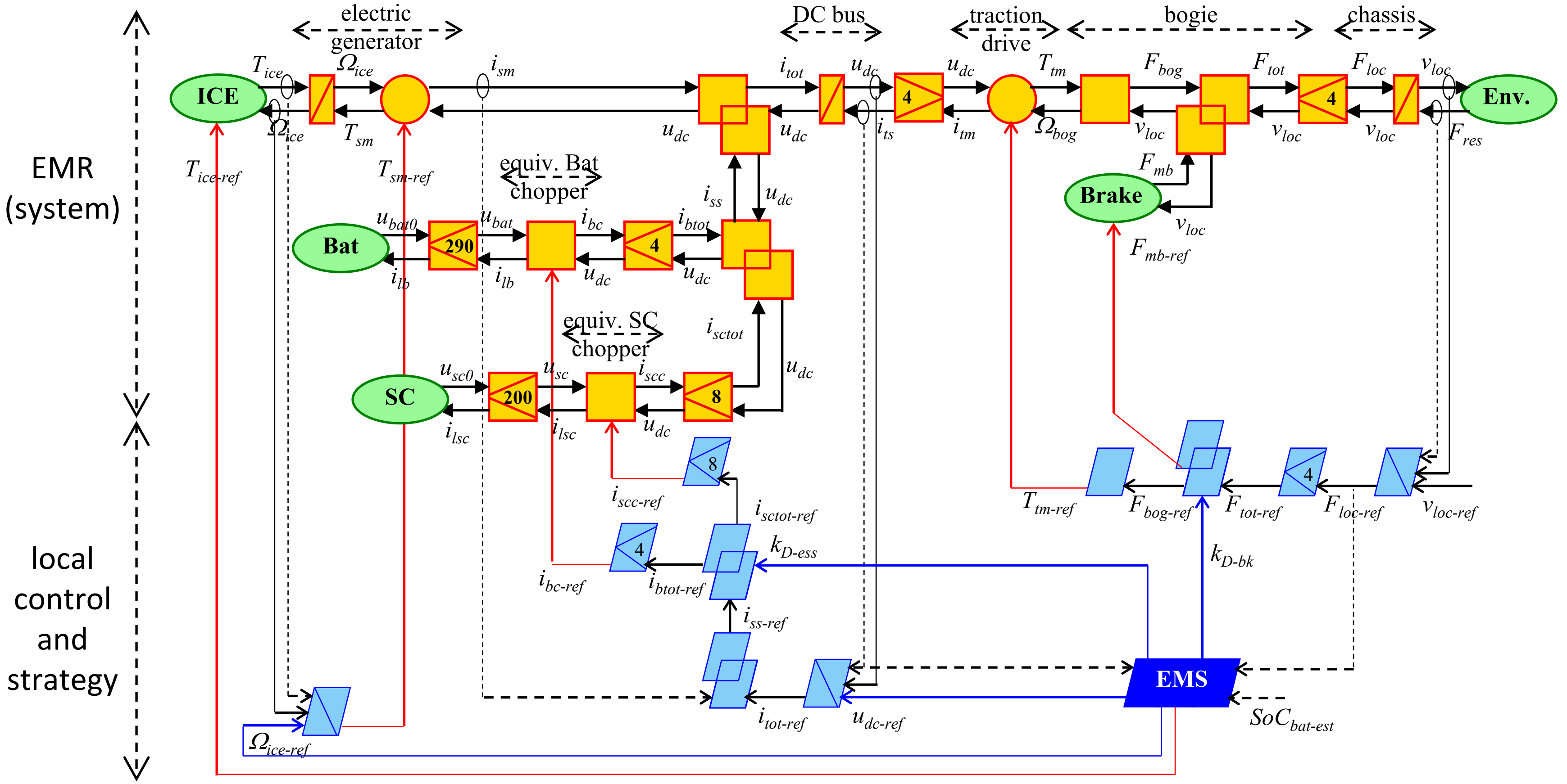
[Li 25]



Experimental demonstrator PLATHEE:
(BB 63 000 diesel electric locomotive)
- diesel engine (215 kW)
- batteries NiCd (194 kWh)
- supercapacitors (7 kWh)
- fuel-cell system



Interest of Hybrid locomotive:
(switching and shunting and locomotives)
- reduction of fuel consumption
- reduction of emission in railway stations
- reduction of noise in railway stations

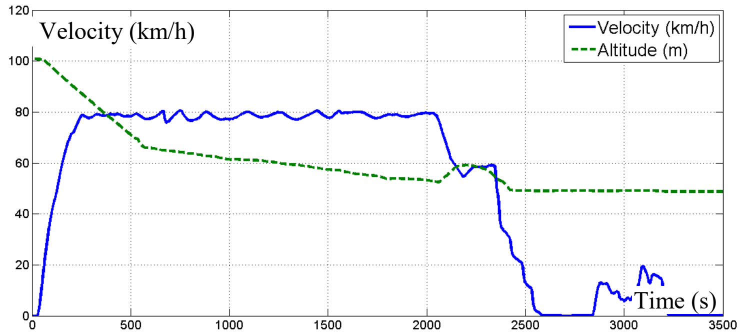


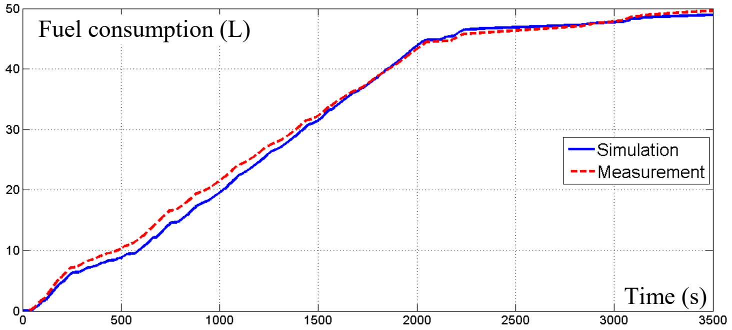
EMS for fuel reduction:

- energy distribution between Bat, SCap, FC, ICE
- braking management
- DC bus regulation

[Mayet 12]

SNCF
L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille
MEGEVH French network on HEV's

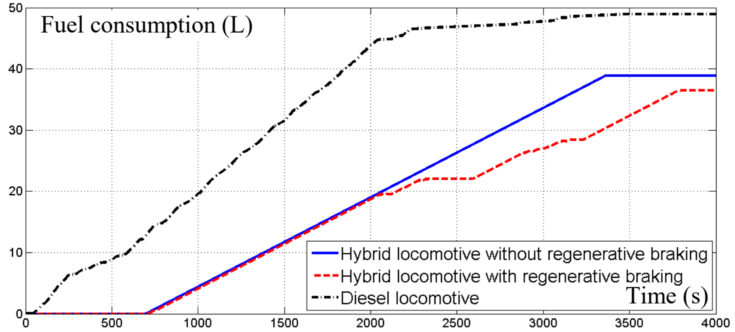




Experimental validation

229 t (locomotive + 3 wagons)
50 km (inter-city track)
ICE + Bat + SC

model accuracy 95%



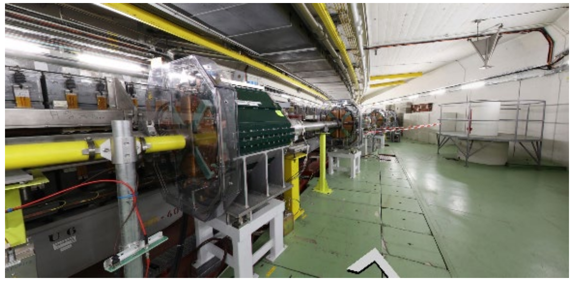
Hybrid with filtering EMS (rule-based)

Locomotives	Fuel consumption	Comparison
Diesel (reference)	48.95 L	100 %
Hybrid without regenerative braking	38.88 L	79.43 %
Hybrid with regenerative braking	36.42 L	74.36 %

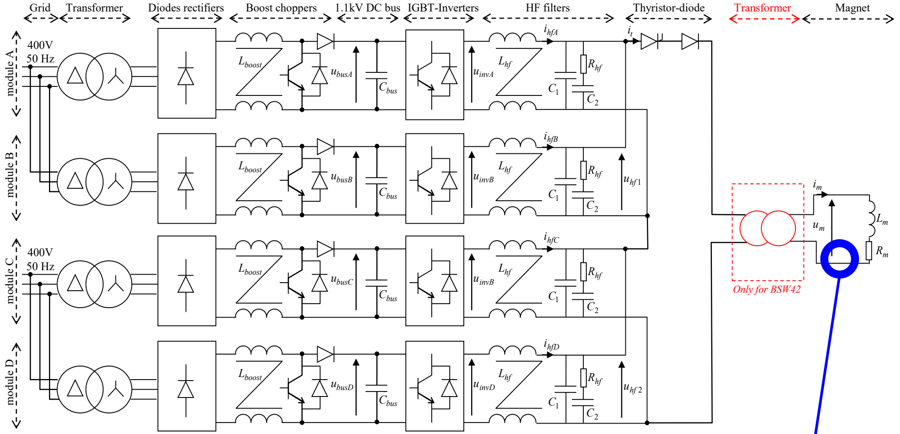
SNCF L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille MEGEVH French network on HEV's

[Mayet 12]

PS beam injection

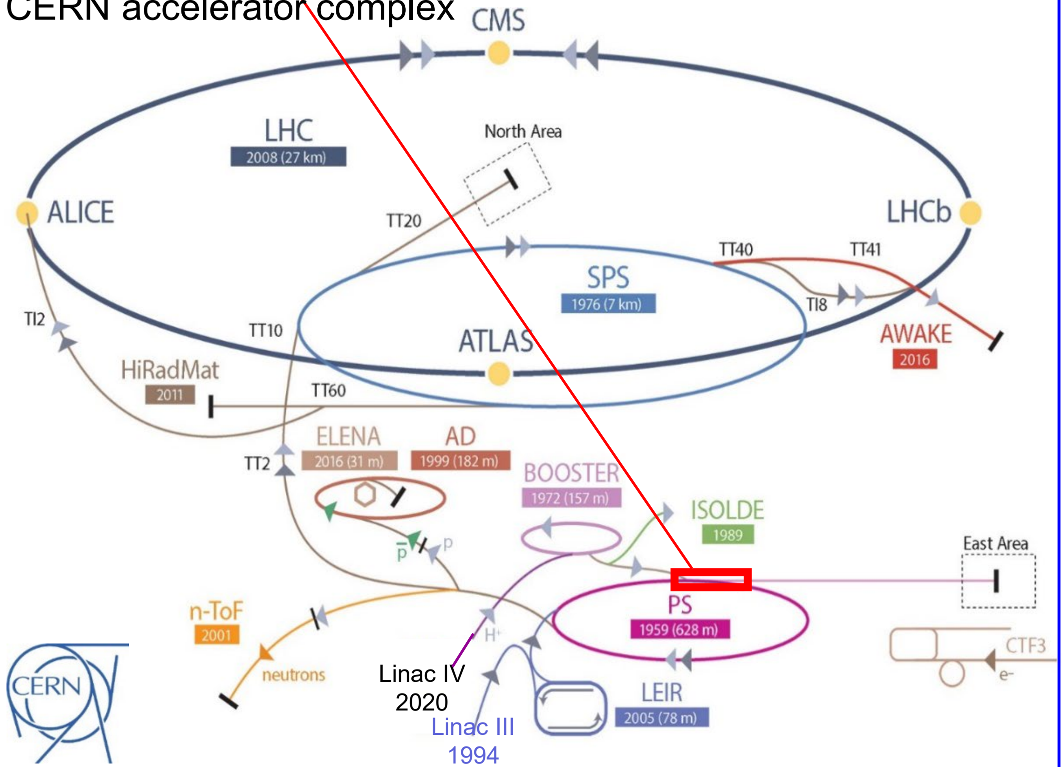


supply system for each bumper: SIRIUS FP2P2S power converter



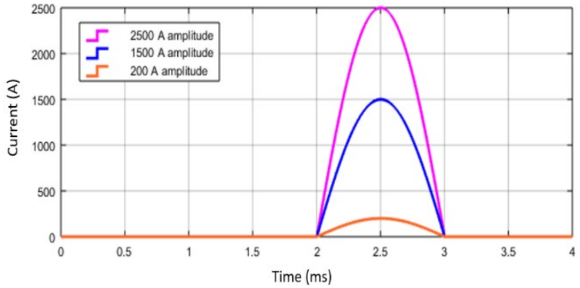
4 classical magnets + 1 with pulsed transformer

CERN accelerator complex



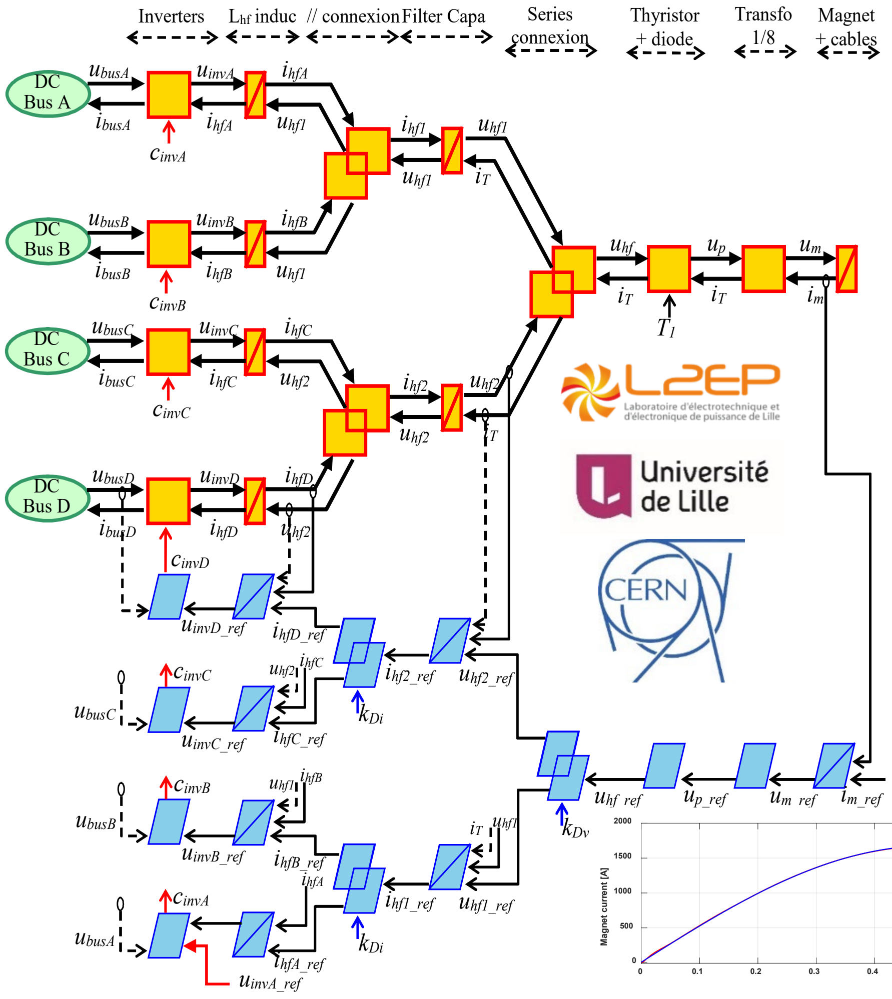
Bumper magnets control requirements

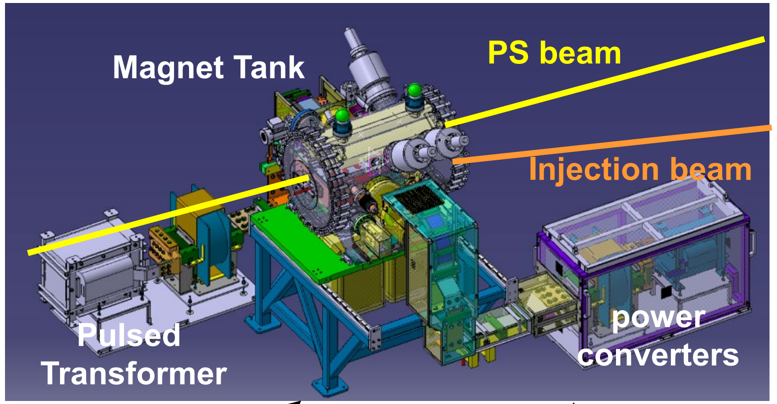
- complex supply system
- ½ sine wave up to 2.5 kA (classical) and 20 kA with transformer
- 1ms period
- repetition every 1.2s 24h/24h
- instantaneous error < +/- 3 A



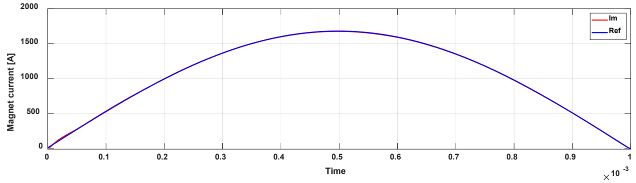
High current / High dynamics
Ultra-high accuracy

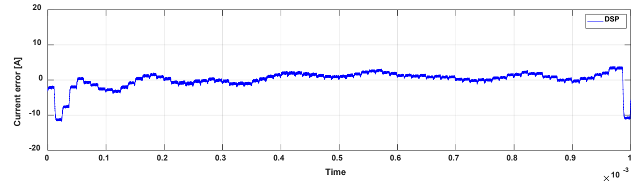
Control derived from EMR formalism of L2EP Univ. Lille

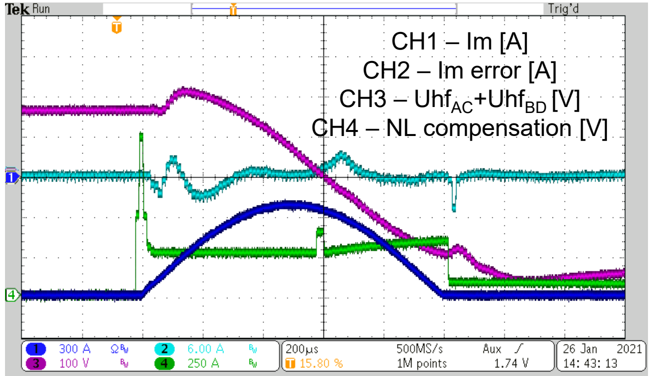




Experimental results







Power converters in operation since March 2021

Conclusion

EV and P-HEV are key vehicles

for reduction of the GHG of transport

HEV is complex to control

EMR methodology is useful in that aim

Extensions to other vehicles

trucks, subways, trains, ships, airplanes…

eV platform of L2EP of Univ. Lille

Nissan Leaf of CUMIN Univ.Lille

[Chan 10] C. C. Chan, A. Bouscayrol, K. Chen, “Electric, Hybrid and Fuel Cell Vehicles: Architectures and Modeling", IEEE trans. on Vehicular Technology, vol. 59, no. 2, February 2010, pp. 589-598 (L2EP Lille and Honk-Kong Univ.).

[German 24] R. German, T. Kalogianis, A. Bouscayrol, J. He, F. Tournez, M. Berecibar, C. Husar, M. Ciocan, S. Costa, A. Genic, B. Lemaire-Semail, "A flexible cloud-based HIL testing of batteries for various electrified vehicles," IEEE Transactions on Vehicular Technology, vol. 73, no. 4, pp. 4610-4620, April 2024, doi: 10.1109/TVT.2023.3337655

[Li 25] K. Li, W. Lhomme, A. Bouscayrol, B. Lemaire-Semail, K. Stockman, C. Brocart,"Energy savings of a four-drive electric bus with two cascaded smart integrated drives on each axle," IEEE Transactions on Transportation Electrification, vol. 11, no. 1, pp. 4145-4156, February 2025.

[Mayet 12] C. Mayet, P. Delarue, A. Bouscayrol, E. Chatot, J.N. Verhille, “Electrokinematical simulation for flexible energetic studies of railway systems", IEEE transactions on Industrial Electronics, Vol. 65, no. 4, April 2018, pp. 3592-3600 Print ISSN: 0278-0046, Online ISSN: 1557-9948, DOI: 10.1109/TIE.2017.2750632

[Ramsey 22] D. Ramsey, A. Bouscayrol, L. Boulon, “Flexible Simulation of an Electric Vehicle to Estimate the Impact of Thermal Comfort on the Energy Consumption", IEEE transactions on Transportation Electrification, Vol. 8, no.2, pp. 2288-2298, June 2022, Print ISSN: 2332-7782, Online ISSN: 2332-7782, DOI: 10.1109/TTE.2022.3144526

Thanks for your attention!

……………..

L2EP
Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Université de Lille | Arts et Métiers Sciences et Technologies | centralelille | JUNIA Grande école d'ingénieurs