Department of Mechanical and Aerospace
Engineering (DIMEAS)

Optimal Computer-aided Engineering of Propulsion and Brake Systems for Electrified and Automated Road Vehicles

A.Y. 2019/2020
XXXIII cycle

Candidate : Pier Giuseppe Anselma
Tutor : Prof. Giovanni Belingardi

Outline

- Research questions and state-of-the-art
- Objectives of the thesis
- Work overview:
  - Rapid HEV fuel economy assessment
  - Enabling battery lifetime prediction
  - Rapid powertrain sizing for OEM fleets
  - HEV design integrating on-line control
  - Optimal design of automated vehicle powertrains
  - Brake system design for electrified vehicles
- Conclusions

Research questions and state-of-the-art

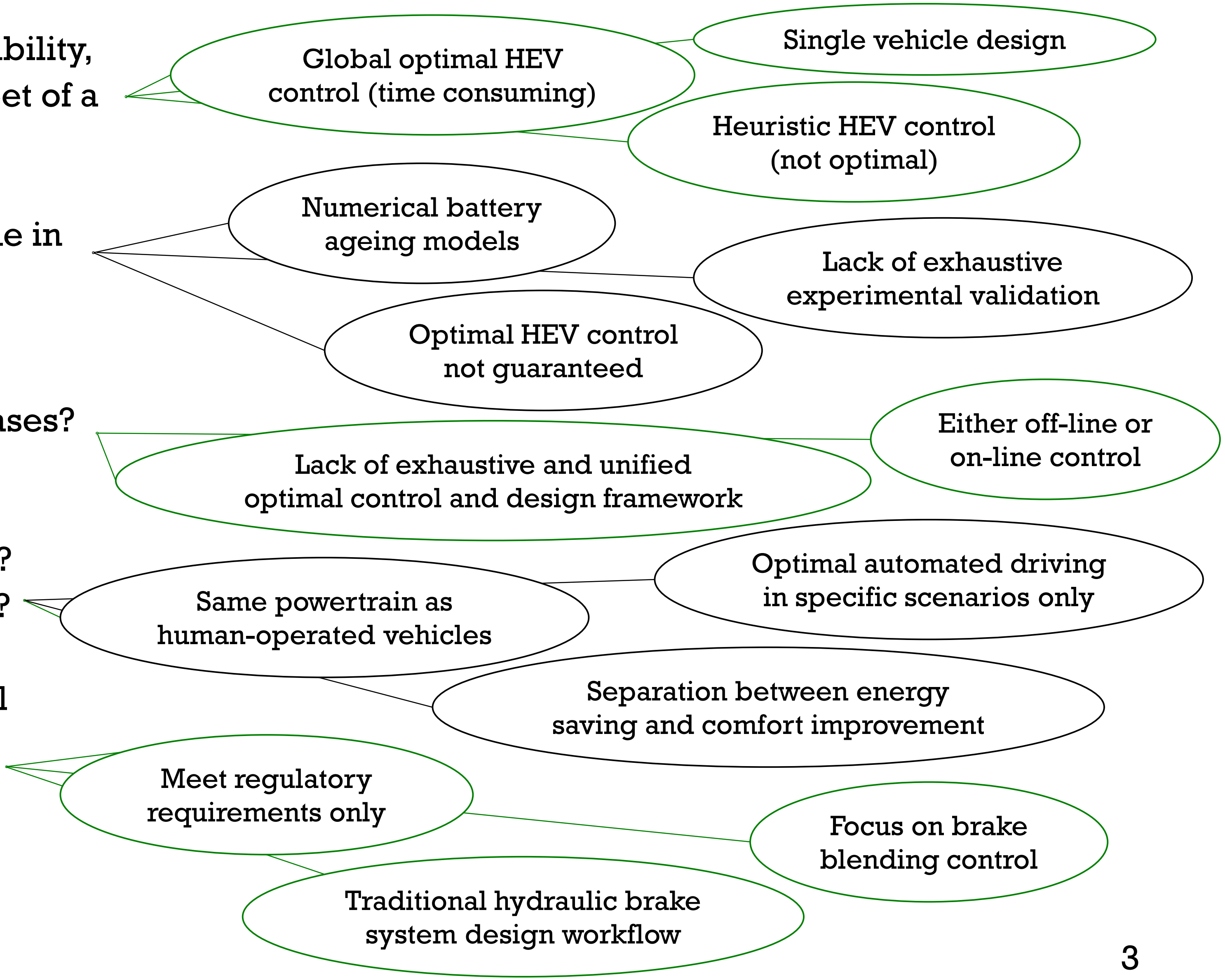
1. Best powertrain trade-off in (fuel economy, drivability, total cost of ownership…) for the overall HEV fleet of a car maker?

2. Satisfactory value of high-voltage battery lifetime in early vehicle design phases?

3. Integrate off-line and on-line optimal energy management strategies in early HEV design phases? Changes in optimal powertrain design?

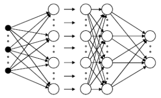
4. Optimal vehicle operation in automated driving? Does it affect optimal propulsion system design?

5. Opportunities for optimally re-design traditional hydraulic brake systems thanks to powertrain electrification?



POLITECNICO DI TORINO

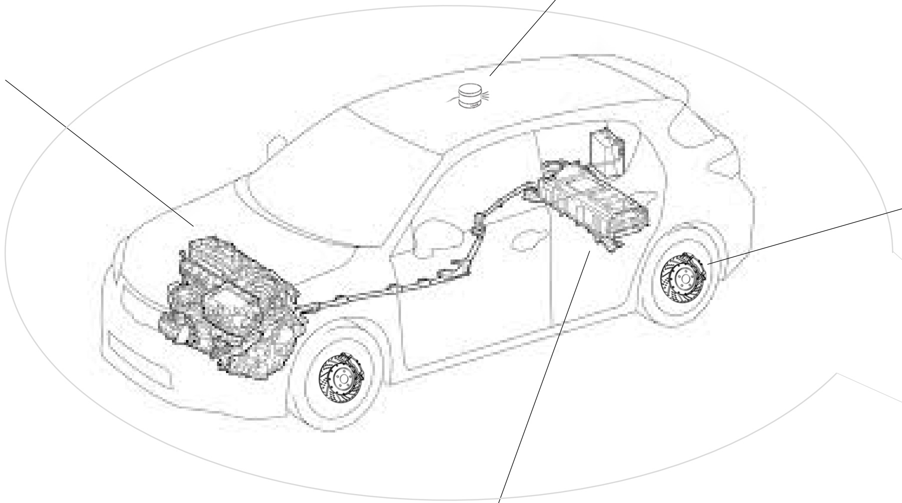
Objectives of the thesis



Chapter 5
Integrating on-line machine-learning based energy management in HEV design

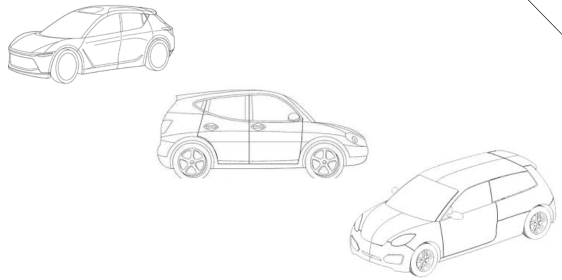
Chapter 6
Optimal design of automated vehicle powertrains

Chapter 2
Rapid assessment of the HEV fuel economy capability

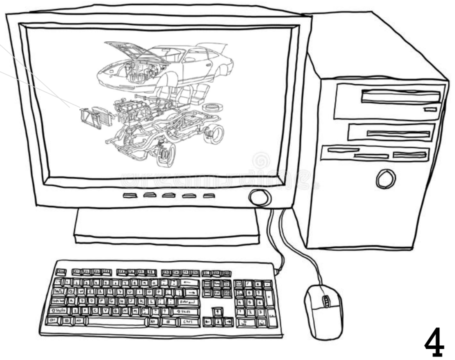


Chapter 7
Optimal design of brake systems for electrified vehicles

Chapter 4
Rapid optimal design of electrified powertrains for OEM vehicle fleets



Chapter 3
Enabling battery lifetime prediction and experimental verification



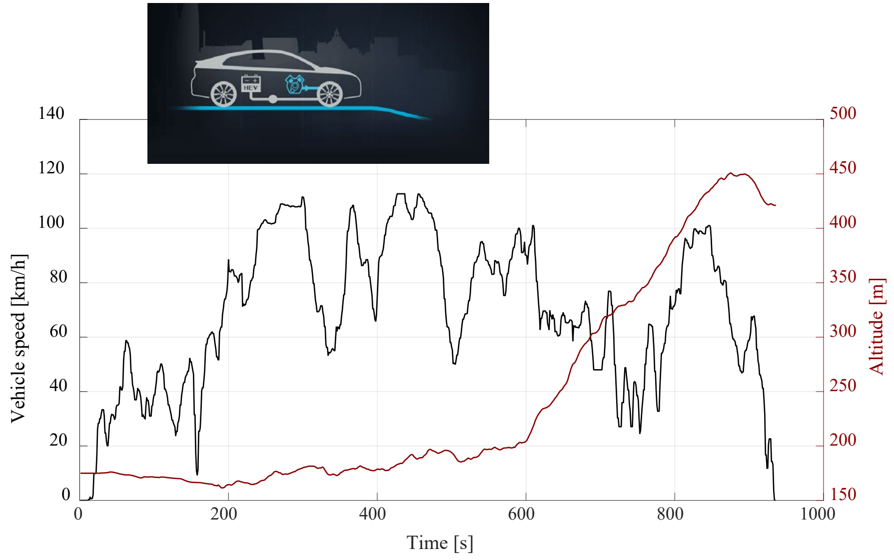
Rapid HEV fuel economy assessment

Methodology

Off-line HEV control

Objectives:

- Minimize fuel consumption
- Battery charge-sustaining operation
- Avoid frequent gear shifts
- Avoid frequent internal combustion engine (ICE) start/stop



DEVELOPMENT

Dedicated algorithm for HEV energy management strategy :
Slope-weighted energy-based rapid control analysis (SERCA)

VALIDATION

Benchmark with approaches from **literature**:

- Dynamic programming (DP)
- Pontryagin's minimum principle (PMP)
- Power-weighted Efficiency Analysis for Rapid Sizing (PEARS)

Evaluation metrics:

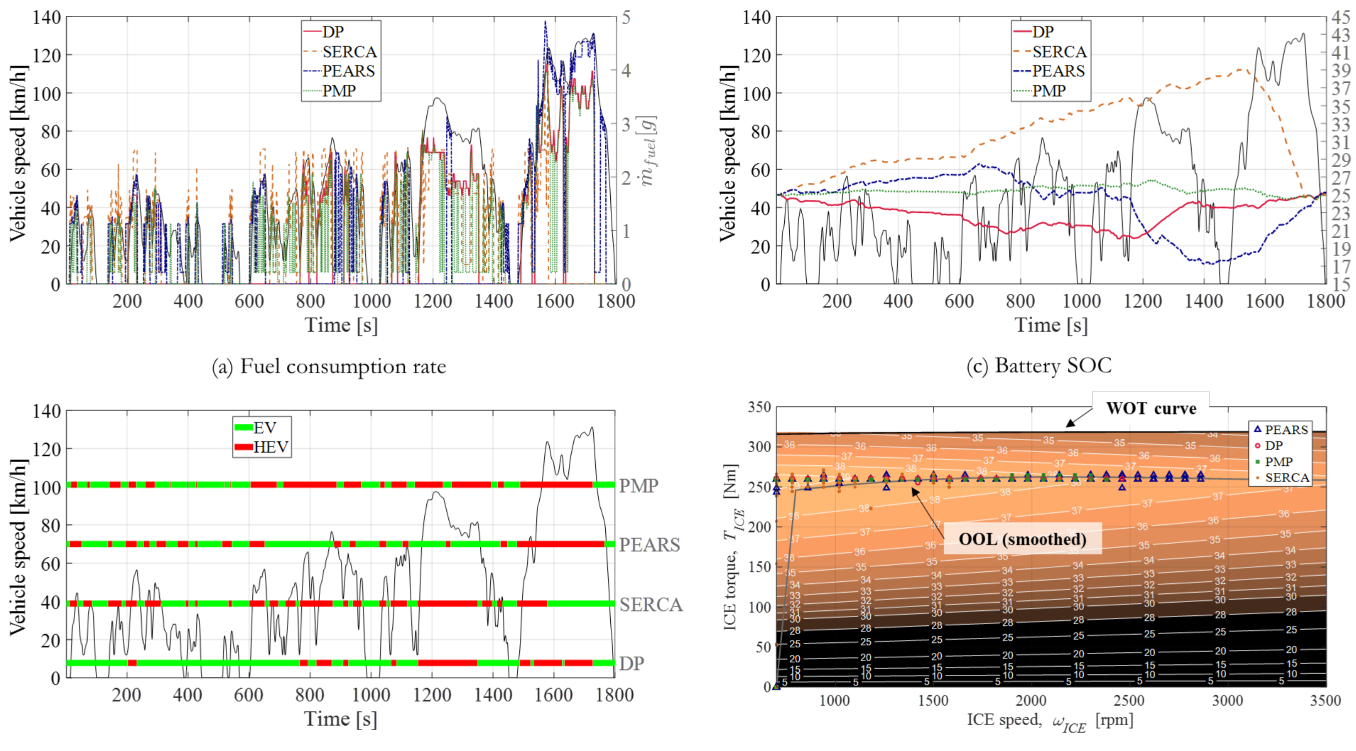
- **Fuel economy**
- **Computational cost**

APPLICATION

- Application to **rapid HEV** powertrain **sizing**
- Extension to **different** HEV **propulsion system architectures** (e.g. power-split, parallel, series-parallel)

Rapid HEV fuel economy assessment

Results



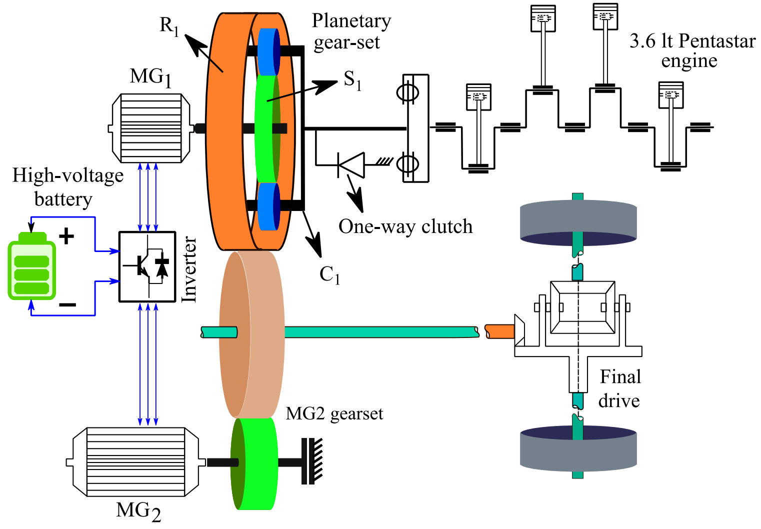
(a) Fuel consumption rate

(c) Battery SOC

(b) Mode utilization

(d) ICE operating points

WLTP	SERCA	PEARS	DP	PMP
Fuel consumption [l/100km]	8.19 (+ 0.9%)	8.19 (+ 0.9%)	8.11	8.23 (+ 1.5%)
Computational time [min]	0.7 (- 99.7%)	0.7 (- 99.7%)	265.1	0.7 (- 99.7%)



Application to rapid HEV powertrain sizing:

"Accelerated Sizing of a Power Split Electrified Powertrain", SAE Technical Paper 2020-01-0843, 2020

(selected for publication also in SAE International Journal of Advances and Current Practices in Mobility)

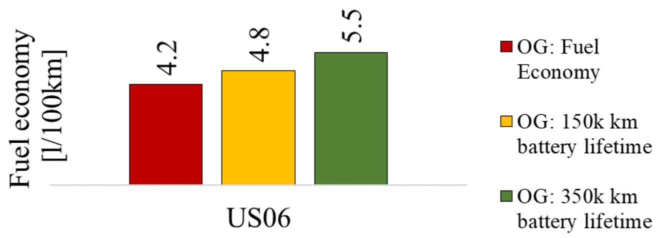
In cooperation with McMaster University (Canada) and FCA US LLC (USA)

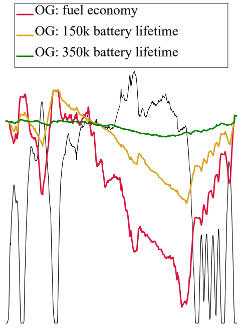
Enabling battery lifetime prediction

Methodology

DEVELOPMENT

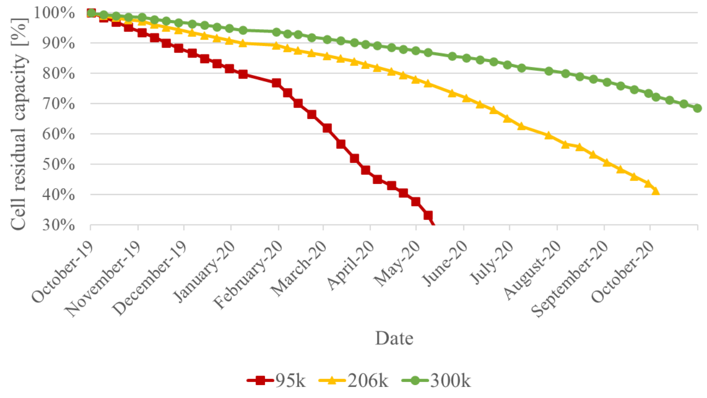
- Selection of a **numerical battery ageing model** from literature (throughput-based)
- Implementing **multi-objective** DP-based **optimal HEV energy management** based on fuel economy and **battery lifetime**





VALIDATION

- **Selection** of three **test cases** representative of ~100·10^3 km, ~200·10^3 km and ~300·10^3 km predicted battery lifetime, respectively
- **Experimental campaign** conducted at McMaster University (Canada) to **validate battery lifetime** predicted by ageing model



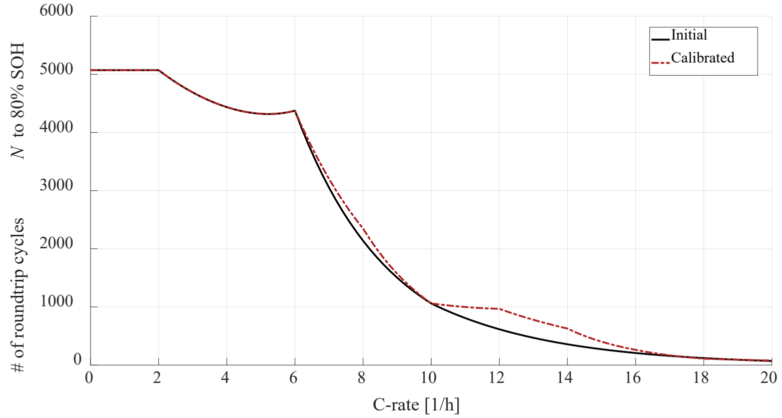
APPLICATION

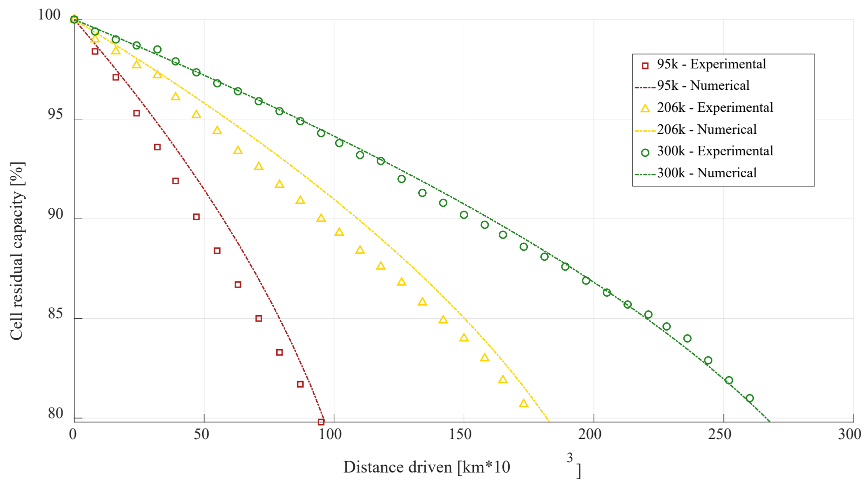
- **Calibration** of numerical battery ageing **model based** on **experimental results**
- **Sensitivity** of fuel economy and battery lifetime based on **battery pack capacity** and **control goal**

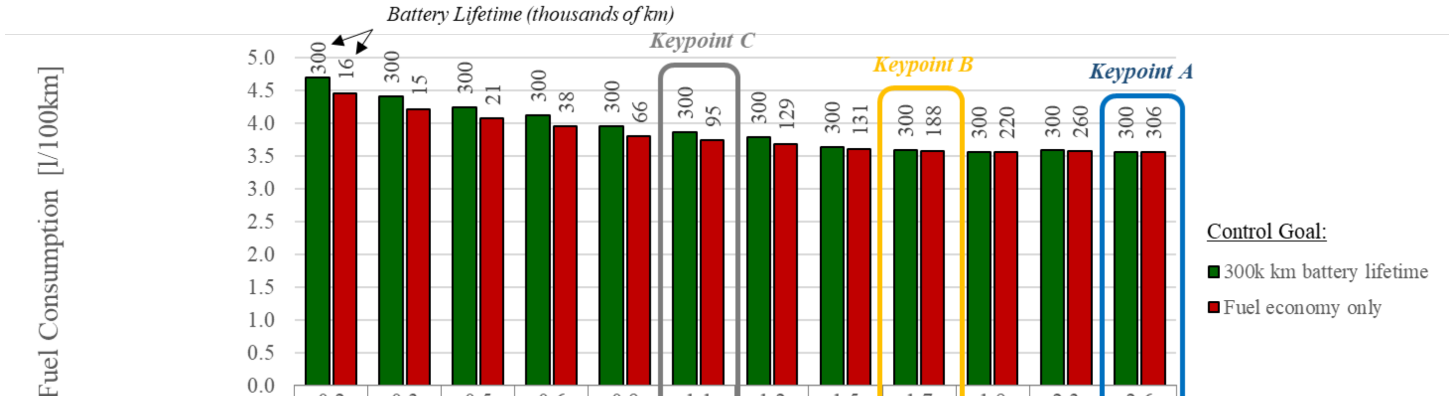
Enabling battery lifetime prediction

Results

Calibration of battery ageing model →







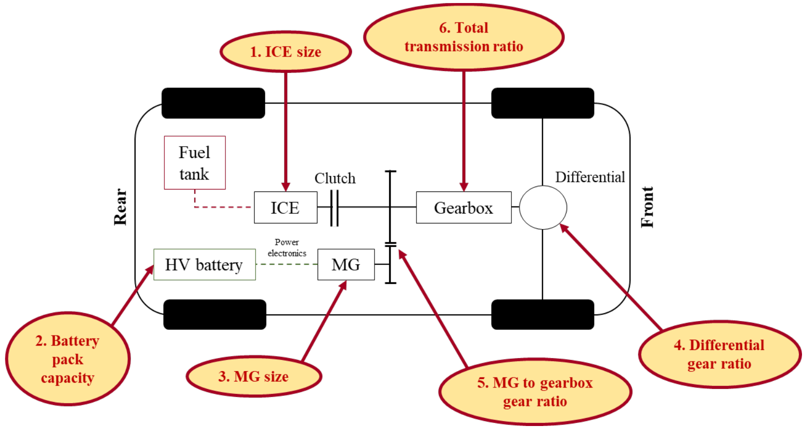
	0.2	0.3	0.5	0.6	0.9	1.1	1.2	1.5	1.7	1.9	2.3	2.6
300k km battery lifetime	4.69	4.41	4.24	4.12	3.95	3.87	3.79	3.64	3.59	3.56	3.58	3.55
Fuel economy only	4.45	4.21	4.08	3.96	3.80	3.73	3.68	3.61	3.57	3.56	3.58	3.55

Battery Pack Energy Storage [kWh]

← **Sensitivity analysis**

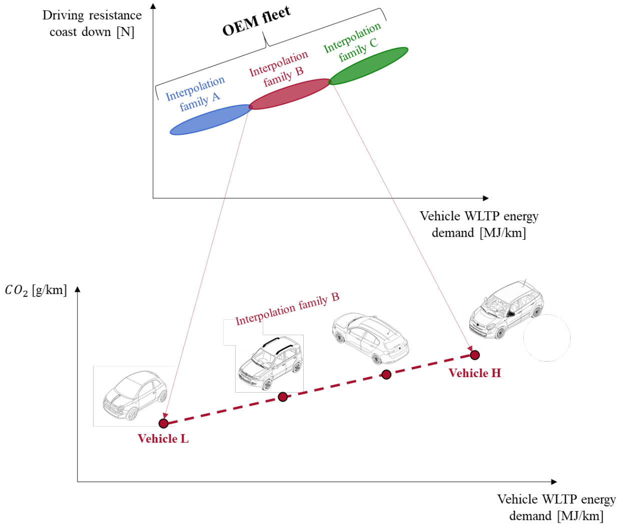
Rapid powertrain sizing for OEM fleets

Methodology



DEVELOPMENT

- HEV **retail price model** from literature
- Implementing simulation of **CO2 emission regulatory procedure**
- Consider a mix of **real-world driving missions** and operating conditions
- Rapid optimal off-line **energy management strategies** suitable for **different electrification levels** (mild HEVs, full HEVs, plug-in HEVs)

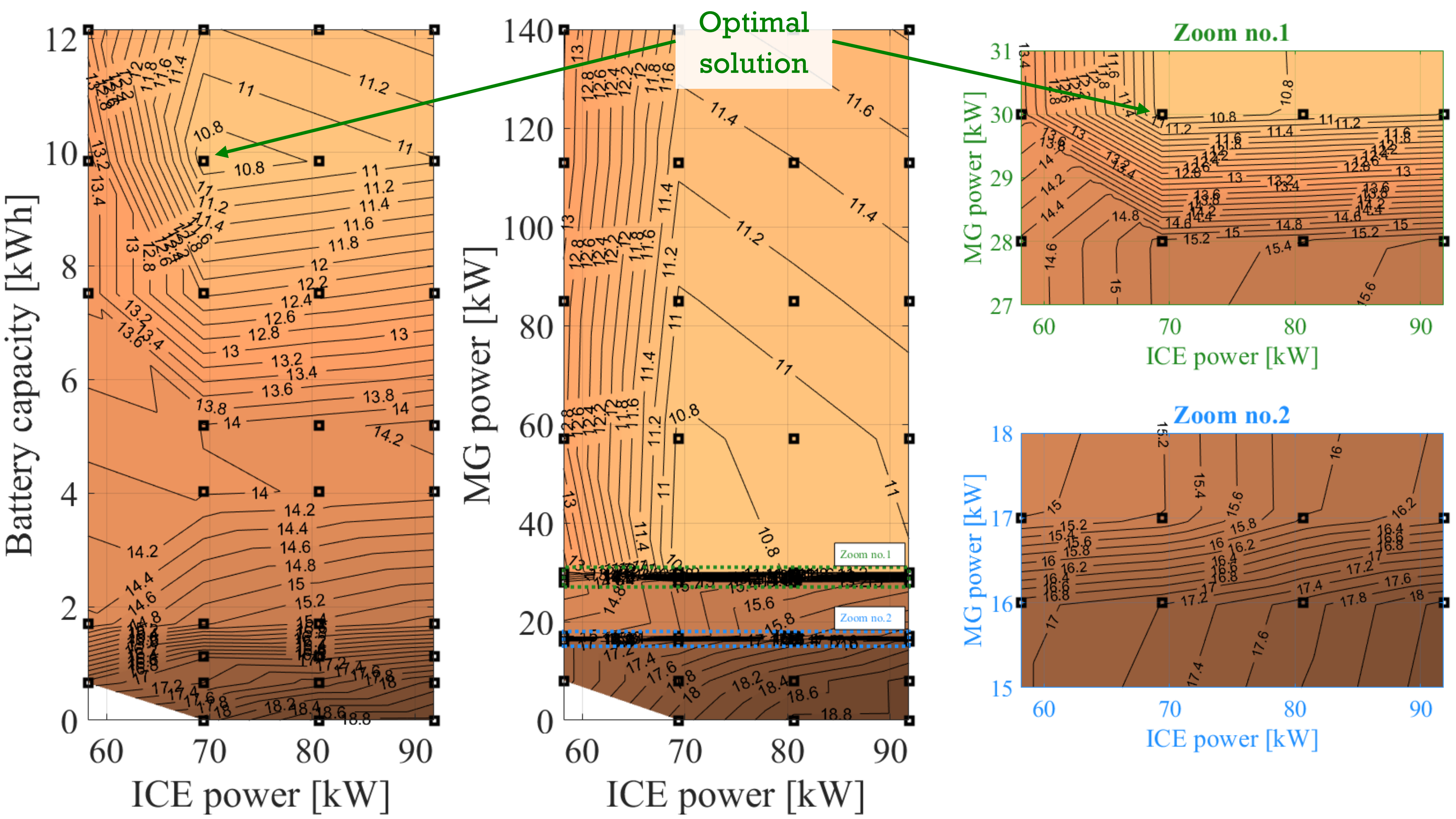


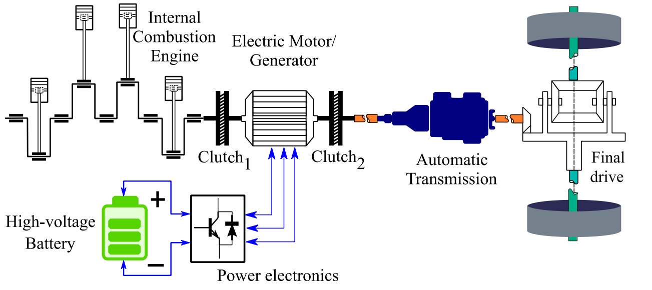
APPLICATION

- Consider a test case of **4 different vehicles** from an OEM fleet
- Parallel **P2** propulsion system architectures
- **Constraints**: battery lifetime, 0-100 km/h acceleration time, ICE activations, gear shifts
- Consider different CO2 emission regulatory scenarios (e.g. tank-to-wheel, well-to-wheel)
- **6 sizing parameters**
- **OEM minimization targets**:
  - Retail price
  - Economic sanctions for not complying with CO2 emission regulations
  - Operative costs (fuel, electricity)

Rapid powertrain sizing for OEM fleets

Results – OEM cost [billions of €]





Optimal solution:

Powertrain sizing parameters	ICE power [kW]	69
	MG power [kW]	29
	Battery capacity [kWh]	9.8
	MG to gearbox ratio	2.25
	Total transmission ratio	4
	FD ratio	3.4
Average OEM vehicle characteristics	Retail price [k€]	18.3
	CO_2 emission [g/km]	61
	Monthly fuel cost [€]	23
	Monthly electricity cost [€]	6
	Real-world fuel consumption [l/100 km]	1.5
	Real-world electricity consumption [kWh/100 km]	6.9

HEV design integrating on-line control

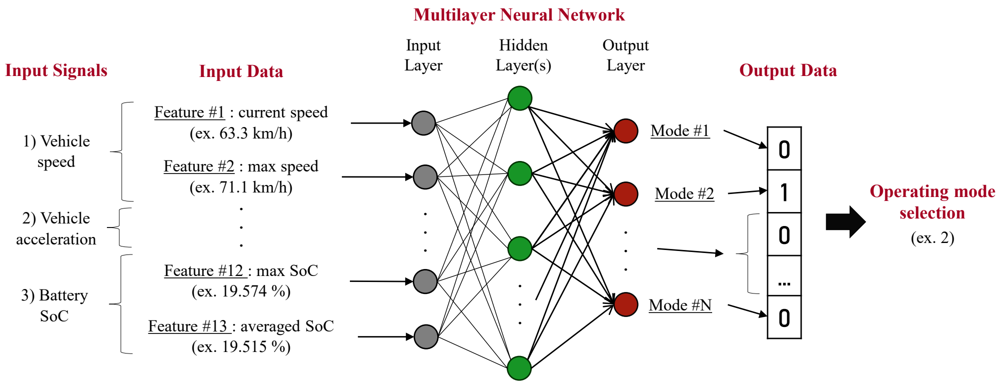
Methodology

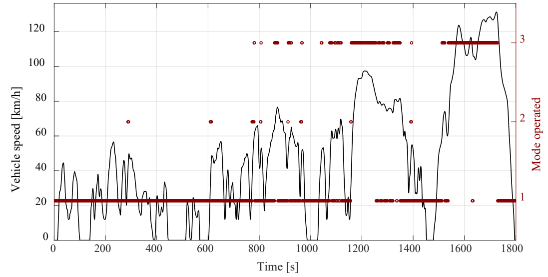
Rapidly generate **HEV control patterns** (e.g. operating mode selection, power split) **optimized off-line** for a specific propulsion system architecture

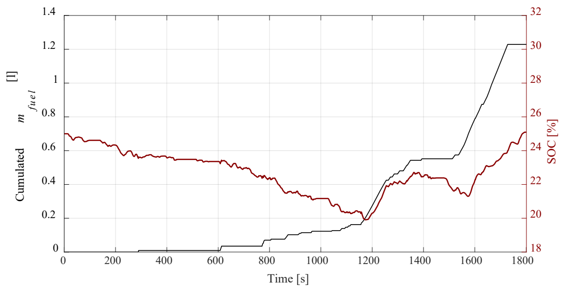
Train artificial intelligence agents (neural networks) to learn optimal HEV control behavior (supervised machine learning)

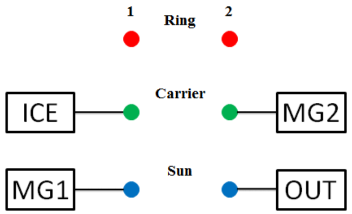
Validate fuel economy through simulations with **on-line HEV energy management** thought the trained artificial intelligence

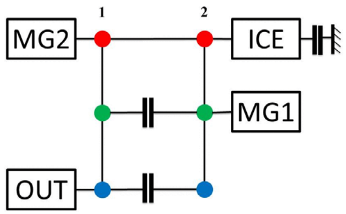
HEV design methodology including on-line control (multimode power-split HEVs)







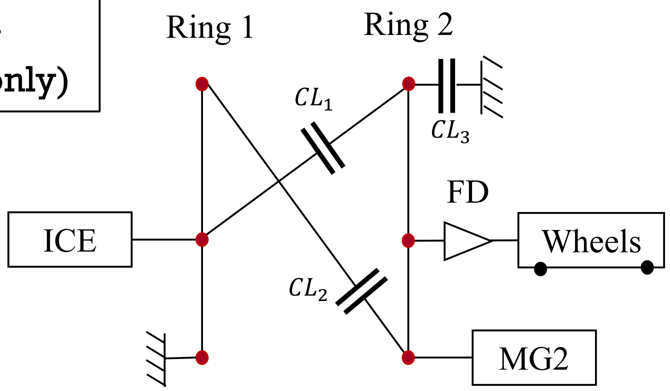




HEV design integrating on-line control

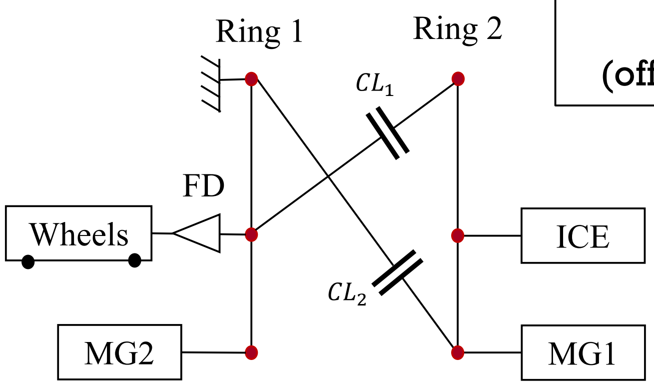
Results

Optimal solution from traditional HEV design workflow (off-line control only)



(a) "Opt_offline"

Optimal solution from developed HEV design workflow (off-line control + on-line control)



(b) "Opt_online"

	"Opt_offline"	"Opt_online"
WLTP fuel consumption Off-line (iPEARS) [l/100km]	5.27	5.38
WLTP fuel consumption On-line (Artificial Intelligence) [l/100km]	5.30	5.28
WLTP fuel consumption Off-line (DP) [l/100km]	5.21	5.25
$n_{neurons}$	20	30
n_{layers}	1	1
ΔZ [s]	8	3

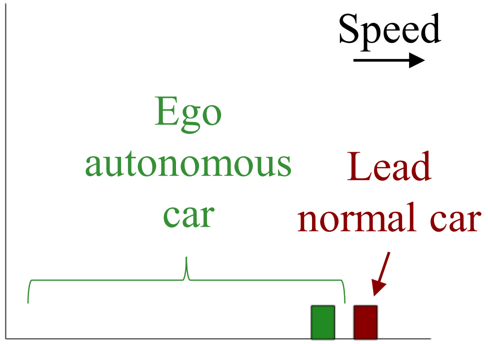
Neural network hyperparameters are optimally tuned within the design methodology

Optimal design of automated vehicle powertrains

Methodology

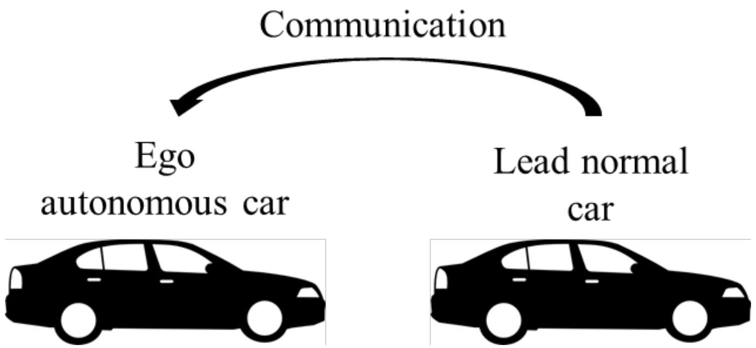
FRAMEWORK

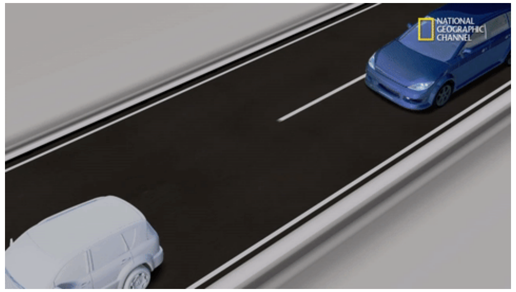
- Battery electric vehicle (**BEV**) with single-speed transmission
- Vehicle-to-vehicle (V2V) driving scenario with **off-line optimal driving management** of Ego Vehicle
- **Ideal communication** between vehicles

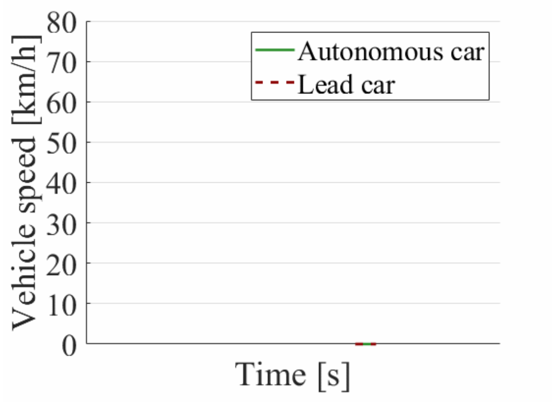


DEVELOPMENT

- Control algorithm = Dynamic Programming (**DP**)
- Control variable = **Ego Vehicle acceleration**
- Constraints :
  - Propulsion system **torque** capability
  - **Maximum** achievable inter-vehicular **distance**
  - **Minimum** safety **distance**
- Multi-objective cost function:
  - Battery **energy consumption**
  - Vehicle **jerk**







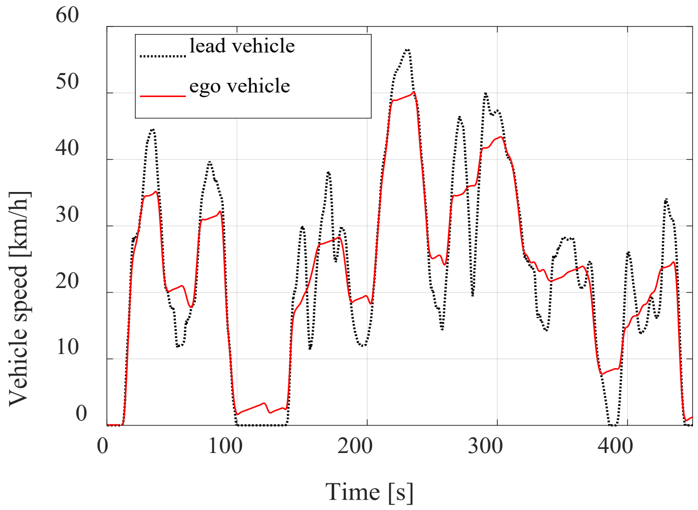
APPLICATION

- Integration in a **BEV** powertrain **design** methodology
- Design parameters : electric motor/generator (MG) and transmission ratio

Optimal design of automated vehicle powertrains

Results

Optimal powertrain-based control of automated vehicles



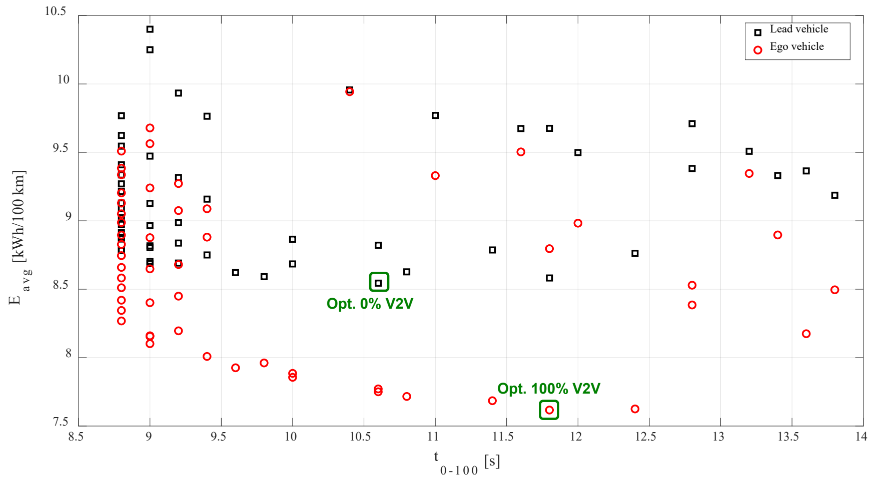
Up to ~21% battery electrical energy saving

Up to ~75% comfort improvement (acceleration root-mean-square)

Always respect safety distance

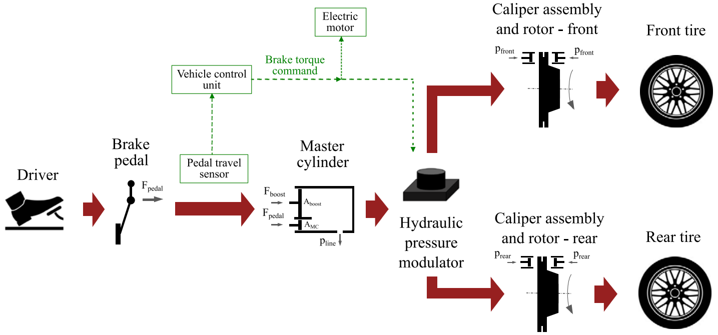
Optimal design of BEV powertrains for optimized automated V2V driving

$\%_{V2V}$	Ranking	MG size [kW]	τ	$Eavg_{mix}$ [kWh/100 km]
0%	#1	80	6.5	8.54
	#2	80	5.5	8.58
	#3	80	7.5	8.59
100%	#1	80	5.5	7.62
	#2	90	4.5	7.63
	#3	100	4.5	7.69



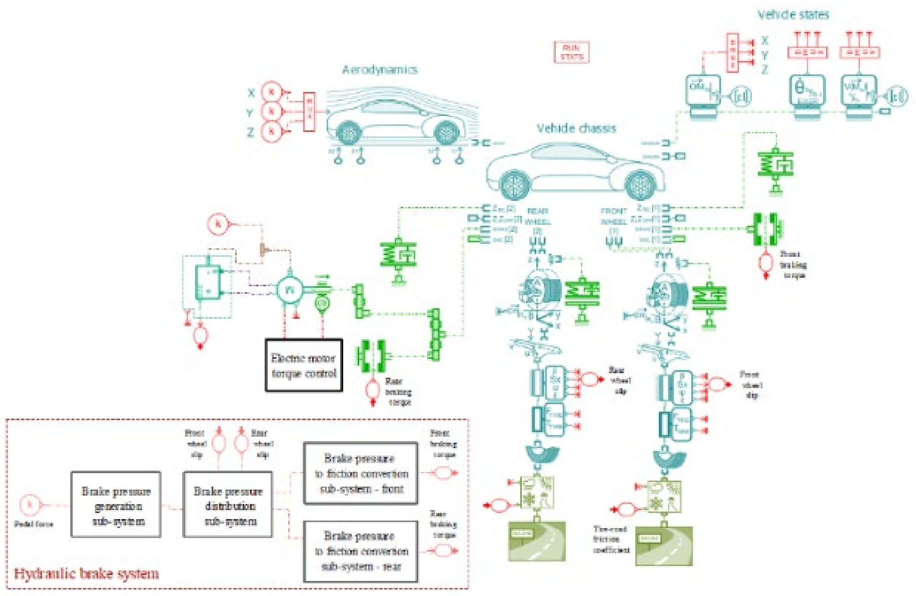
Brake system design for electrified vehicles

Methodology



FRAMEWORK

- Battery electric vehicle (**BEV**) with single-speed transmission
- **Hydraulic brake system** 1D modeling
- **7** degrees of freedom (**DOFs**) **vehicle dynamics** model
- 2 vehicle loading conditions : fully loaded and curb weight



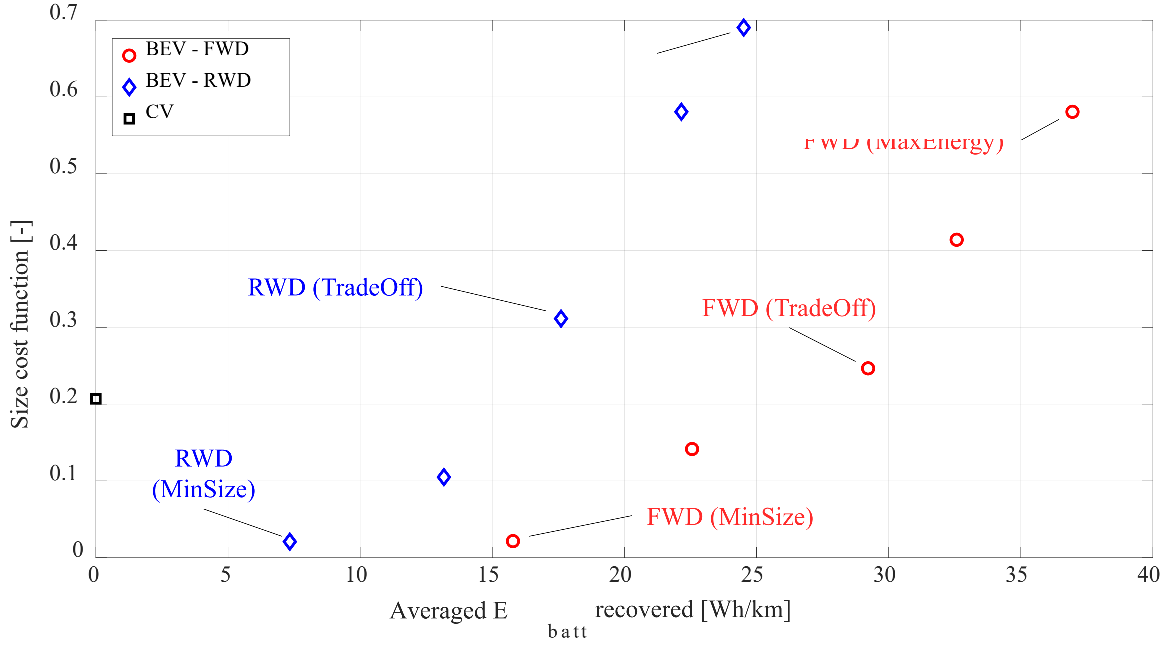
DEVELOPMENT AND APPLICATION

- **Sizing** parameters:
  - Master cylinder diameter
  - Master cylinder stroke
  - Ratio between booster assist primary piston diameter and master cylinder diameter
  - Front wheel brake piston diameter
  - Rear wheel brake piston diameter
- **Design space exploration** with particle swarm optimization (**PSO**)
  - Constraints : **ergonomics**, comply with regulatory **safety standards**
  - Multi-objective cost function: overall **system size** and **electrical energy recovery** capability in normal driving (WLTP)

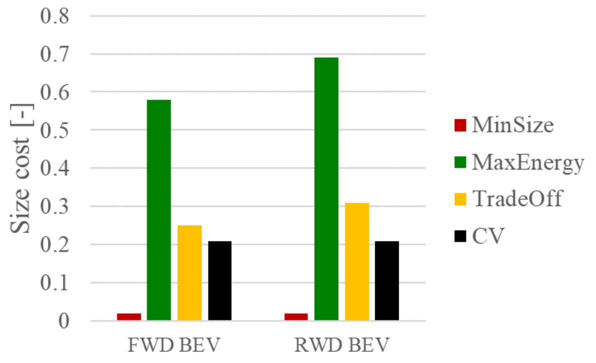
Brake system design for electrified vehicles

Results

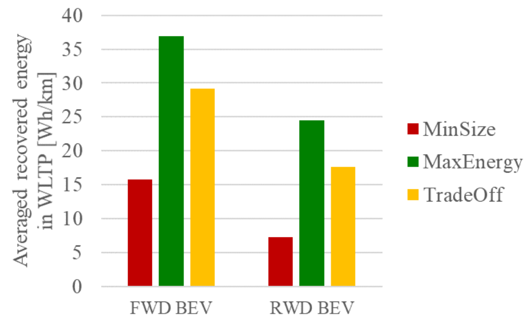
Assessing front wheel drive (FWD), rear wheel drive (RWD) and conventional ICE-powered vehicle (CV) powertrain layouts



- **Effective down-sizing** of hydraulic brake systems for an electrified road vehicle compared with conventional powertrain layout
- **FWD BEV** layout **more appealing** than **RWD BEV** from the point of view of **energy recovery** through regenerative braking
- No global optimum, rather **trade-off** is **required** between system **down-sizing** and **electrical energy recovery** enhancement



(a) Size term



(b) Energy term

Conclusions

- **Rapid near-optimal HEV control** strategy suitable for accelerating powertrain sizing methodologies and on-board supervisory control development procedures;
- Calibration through **experimental validation** of a **numerical ageing model** for predicting the high-voltage **battery lifetime** as function of its operative conditions;
- **Optimal CAE** of **electrified powertrains** for the **overall fleet** of a **car maker** while complying with various performance requirements;
- **Automated machine learning based near-optimal on-line HEV** control strategy implemented in **optimal CAE** of multimode power-split HEV powertrains;
- **Optimization framework** for controlling the operation of **automated vehicles** in **V2V** co-operative driving directly implemented in **CAE** methodologies of automated road vehicle powertrains;
- **Multi-objective CAE** of **hydraulic brake systems** for **electrified** road **vehicles** to enhance battery energy recovery capability while downsizing the overall brake system.

Thank you for your attention

Mail: pier.anselma@polito.it

Backup slides

Rapid HEV fuel economy assessment

Fuel economy benchmark

	SERCA	PEARS	DP	PMP
WLTP	8.19 (+ 0.9%)	8.19 (+ 0.9%)	8.11	8.23 (+ 1.5%)
UDDS	5.83 (+ 1.2%)	6.05 (+ 5.0%)	5.76	6.69 (+ 16.2%)
HWFET	7.42 (+ 1.5%)	7.56 (+ 3.4%)	7.31	7.71 (+ 5.5%)
NEDC	6.72 (+ 1.9%)	7.03 (+ 6.5%)	6.60	6.73 (+ 2.1%)

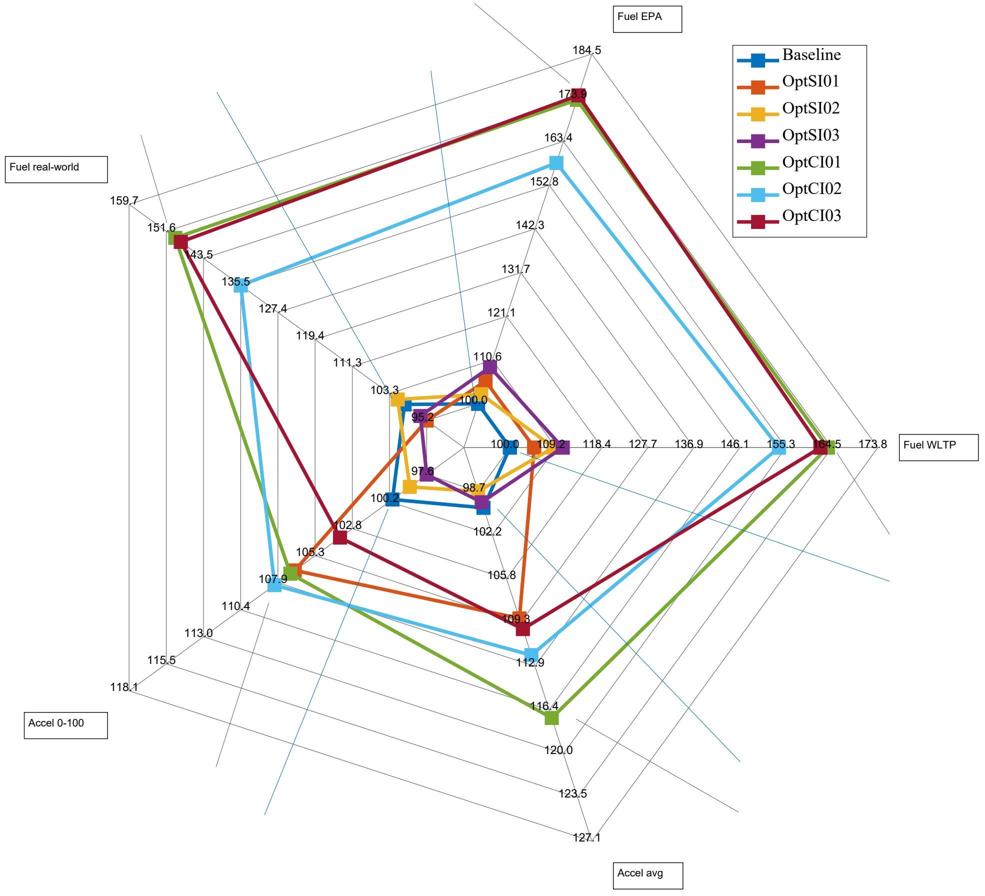
Computational time benchmark

	SERCA	PEARS	DP	PMP
WLTP	0.7 (- 99.7%)	0.7 (- 99.7%)	265.1	0.7 (- 99.7%)
UDDS	0.8 (- 99.7%)	0.5 (- 99.8%)	301.3	0.8 (- 99.7%)
HWFET	0.7 (- 99.4%)	0.4 (- 99.6%)	112.3	2.4 (- 97.9%)
NEDC	0.7 (- 99.6%)	0.5 (- 99.7%)	173.3	2.6 (- 98.5%)

POLITECNICO DI TORINO

Rapid HEV fuel economy assessment

Rapid HEV sizing

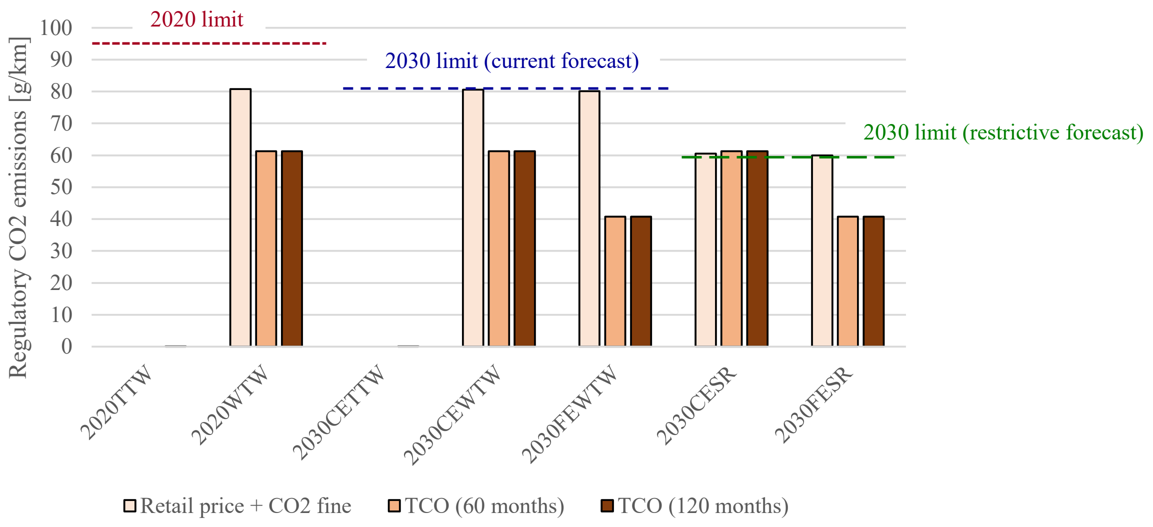


Parameter	Sizing options						
	Baseline	OptSI01	OptSI02	OptSI03	OptCI01	OptCI02	OptCI03
ICE displacement [L]	3.6	3.6	3.6	3.6	3.0	3.0	3.0
MG1 power [kW]	60	35	35	35	35	35	60
MG1 power [kW]	85	95	85	95	85	95	85
PG ratio	3.15	2.65	2.65	2.65	2.65	2.65	2.65
MG2 transfer gearset ratio	2.59	2.09	2.59	2.09	2.09	2.59	2.59
FD ratio	3.59	4.09	3.59	3.59	3.59	3.09	3.59

Rapid powertrain sizing for OEM fleets

Regulatory scenarios

	Regulatory scenario code	$\alpha_{CO2WTW\,fuel}$ $[\frac{g_{CO_2}}{g_{fuel}}]$	$\alpha_{CO2WTW\,electricity}$ $[\frac{g_{CO_2}}{kWh_{batt}}]$	Regulatory CO_2 emission limit $[\frac{g_{CO_2}}{km}]$
1	2020TTW	3.15	0	95
2	2020WTW	3.75	508	95
3	2030CETTW	3.15	0	81
4	2030CEWTW	3.75	508	81
5	2030FEWTW	3.75	238	81
6	2030CESR	3.75	508	59
7	2030FESR	3.75	238	59



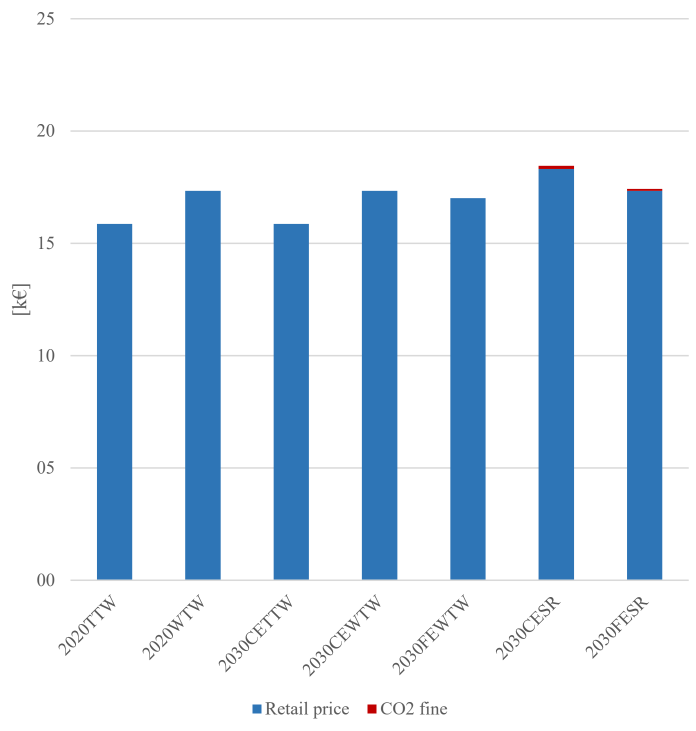
Rapid powertrain sizing for OEM fleets

Results

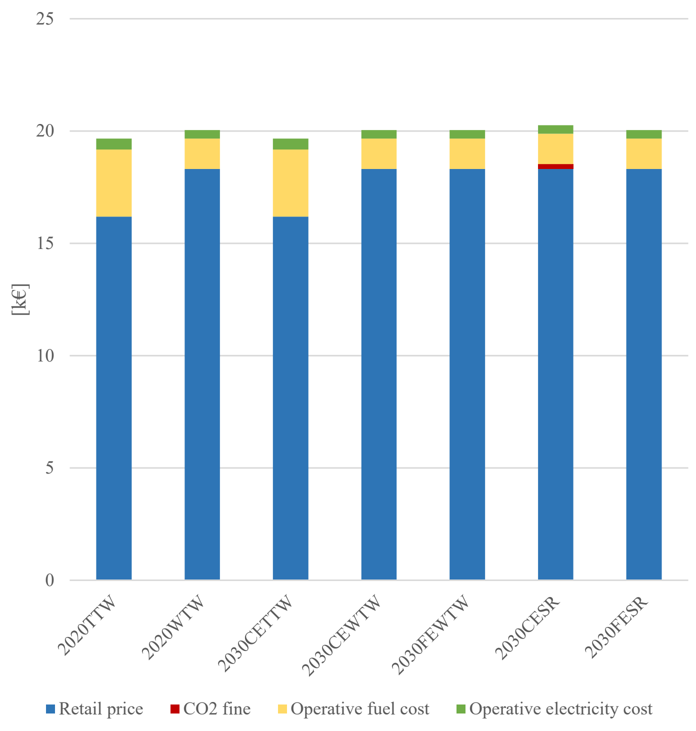
Regulatory scenario code	Optimization target	$P_{ICE_{MAX}}$ [kW]	$P_{MG_{MAX}}$ [kW]	Battery capacity [kWh]	MG to gearbox ratio	$\tau_{G,tot}$	FD ratio	RP [k€]	CO_2 fine [€]	Monthly fuel cost [€]	Monthly electricity cost [€]	EFC_{WLTP} [l/ 100km]	EE_{WLYP} [kWh/ 100km]	EFC_{RW} [l/ 100km]	EE_{RW} [kWh/ 100km]	J_{OEM} [billions of €]
2020TTW	Retail price + CO_2 fine	69	29	4.0	2.25	4.00	3.40	15.9	0	57	11	0.0	10.6	3.7	12.4	7.7
	TCO (60 months)	81	29	4.0	2.25	4.00	2.60	16.2	0	50	8	0.0	9.8	3.2	8.8	9.5
	TCO (120 months)	81	29	9.8	2.25	4.00	2.60	18.6	0	22	6	0.0	7.4	1.4	6.8	10.7
2020WTW	Retail price + CO_2 fine	69	29	7.5	2.25	4.67	3.40	17.3	0	44	11	1.5	7.6	2.8	12.1	8.4
	TCO (60 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	9.7
	TCO (120 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	10.5
2030CETTW	Retail price + CO_2 fine	69	29	4.0	2.25	4.00	3.40	15.9	0	57	11	0.0	10.6	3.7	12.4	7.7
	TCO (60 months)	81	29	4.0	2.25	4.00	2.60	16.2	0	50	8	0.0	9.8	3.2	8.8	9.5
	TCO (120 months)	81	29	9.8	2.25	4.00	2.60	18.6	0	22	6	0.0	7.4	1.4	6.8	10.7
2030CEWTW	Retail price + CO_2 fine	69	29	7.5	2.25	4.00	3.40	17.3	0	42	11	1.5	7.6	2.7	11.4	8.4
	TCO (60 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	9.7
	TCO (120 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	10.5
2030FEWTW	Retail price + CO_2 fine	58	29	7.5	2.25	4.67	4.20	17.0	0	43	11	1.9	11.2	2.8	11.9	8.2
	TCO (60 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	9.7
	TCO (120 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	10.5
2030CESR	Retail price + CO_2 fine	69	29	9.8	4.00	4.67	3.40	18.3	143	30	6	1.0	6.5	2.0	6.5	8.9
	TCO (60 months)	69	29	9.8	2.25	4.00	3.40	18.3	218	23	6	0.8	7.6	1.5	6.9	9.8
	TCO (120 months)	69	29	9.8	2.25	4.00	3.40	18.3	218	23	6	0.8	7.6	1.5	6.9	10.7
2030FESR	Retail price + CO_2 fine	69	29	7.5	2.25	4.00	3.40	17.3	89	42	11	1.5	7.6	2.7	11.4	8.4
	TCO (60 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	9.7
	TCO (120 months)	69	29	9.8	2.25	4.00	3.40	18.3	0	23	6	0.8	7.6	1.5	6.9	10.5

Rapid powertrain sizing for OEM fleets

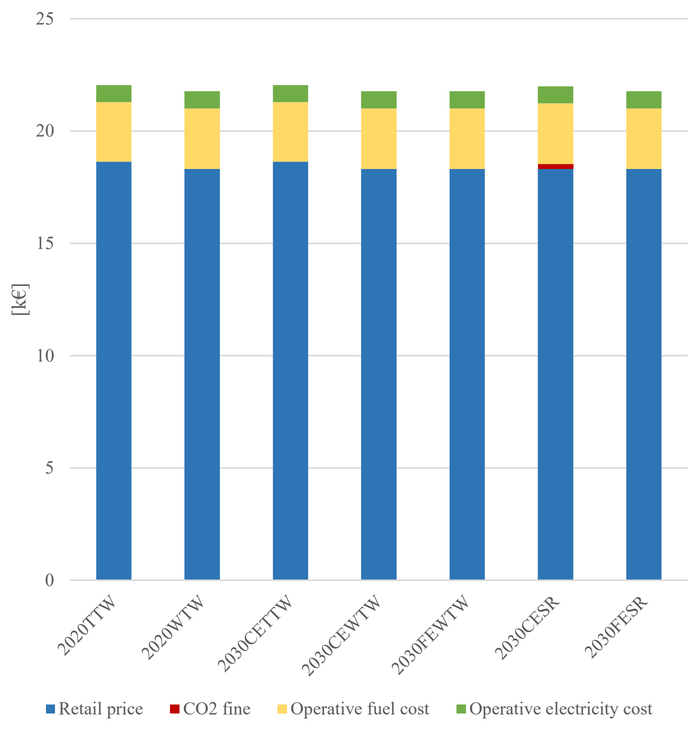
Results



(a) Retail price + CO2 fine



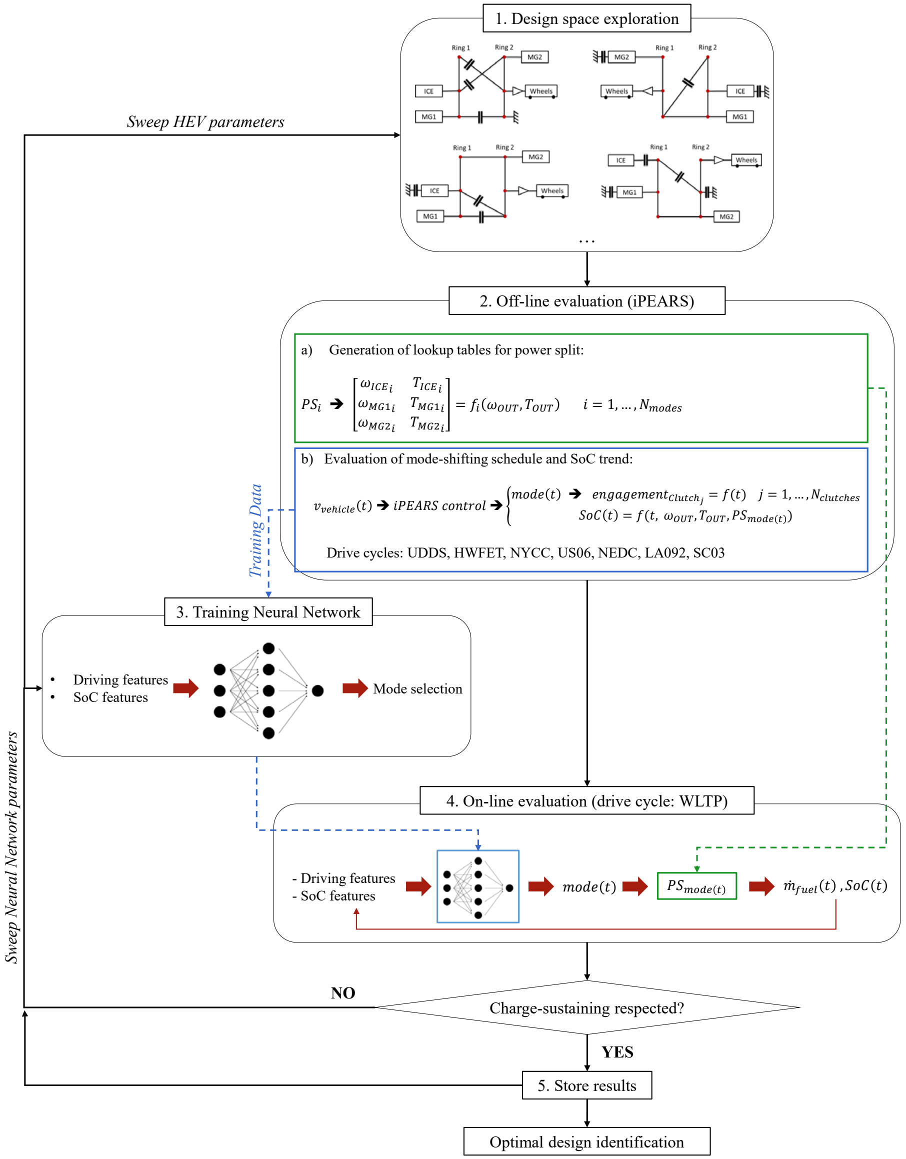
(b) TCO (60 months)



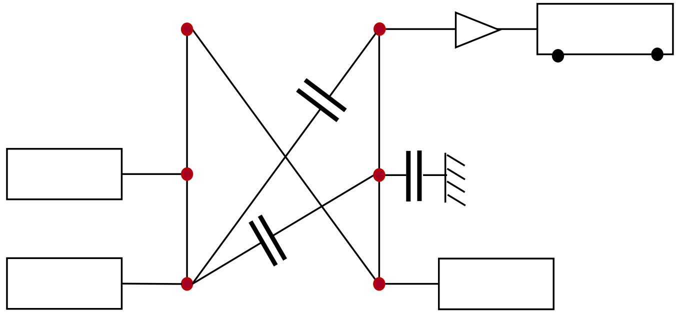
(c) TCO (120 months)

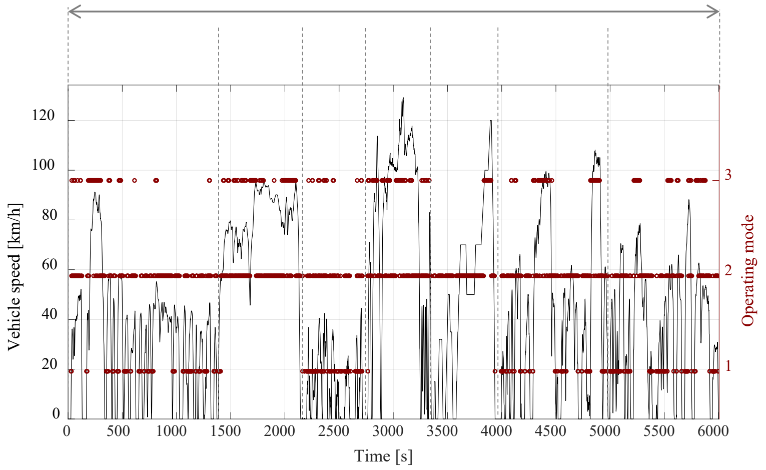
POLITECNICO DI TORINO

HEV design integrating on-line control

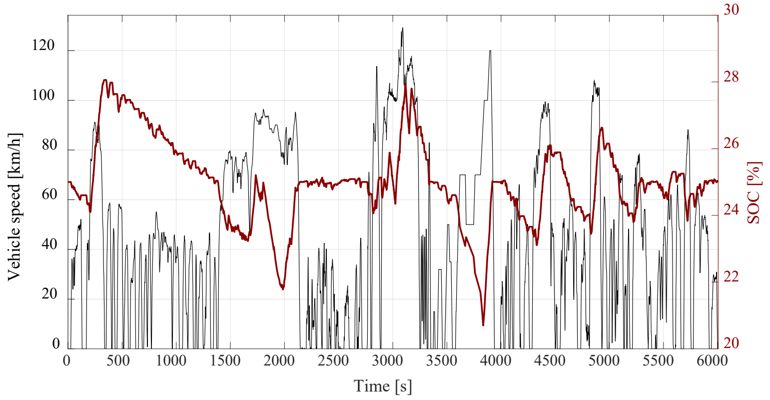


HEV design integrating on-line control





(c) NN training data – operating modes

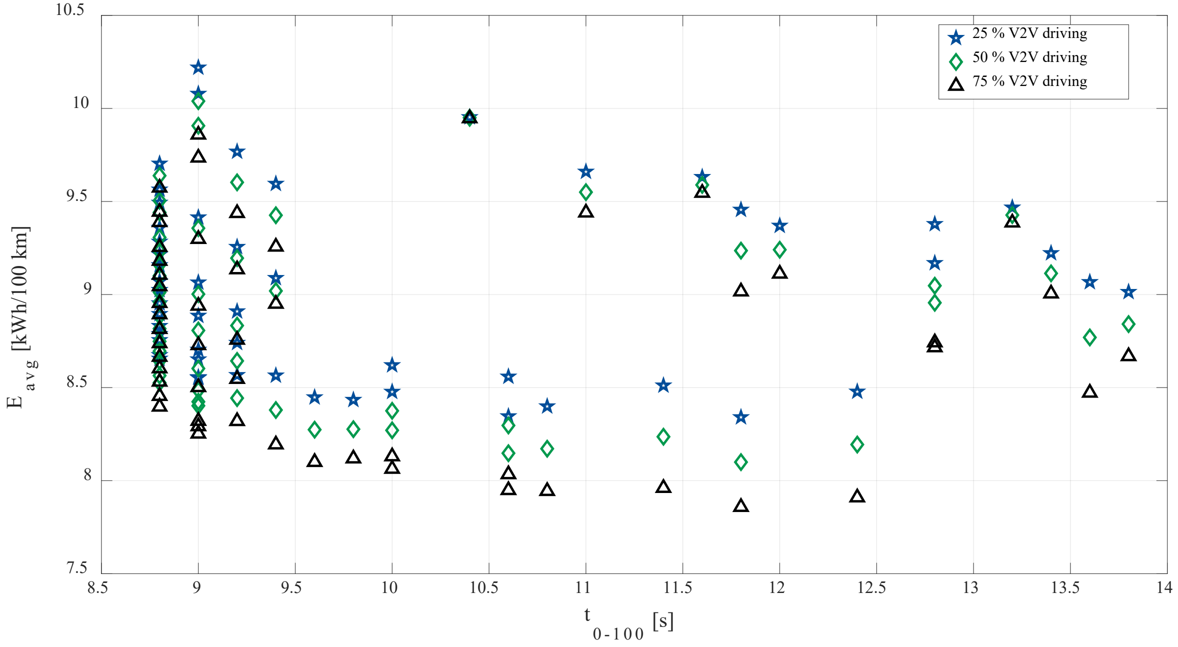


(d) NN training data – SOC

Optimal design of automated vehicle powertrains

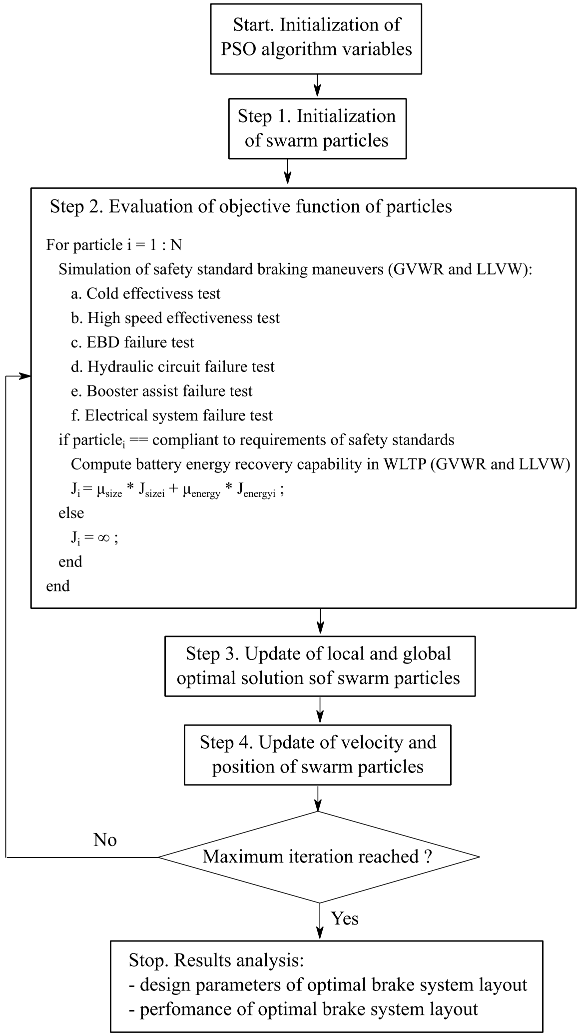
Drive cycle	Parameter	Design#1 (MG size = 80 kW ; τ = 6.5)	Design #2 (MG size = 90 kW ; τ = 4.5)	Design #3 (MG size = 100 kW ; τ = 4.5)
UDDS	Wh_{batt} (Lead vehicle) [kWh/100km]	8.95	9.51	9.50
	Wh_{batt} (Ego vehicle) [kWh/100km]	8.29 (-7.9%)	8.26 (-15.1%)	8.32 (-14.2%)
	Rms $\ddot{x}$ (Lead vehicle) [m/s^2]	0.62	0.62	0.62
	Rms $\ddot{x}$ (Ego vehicle) [m/s^2]	0.15 (-76.1%)	0.15 (-75.9%)	0.15 (-75.9%)
HWFET	Wh_{batt} (Lead vehicle) [kWh/100km]	6.84	6.70	6.75
	Wh_{batt} (Ego vehicle) [kWh/100km]	6.64 (-3.0%)	6.42 (-4.3%)	6.47 (-4.1%)
	Rms $\ddot{x}$ (Lead vehicle) [m/s^2]	0.30	0.30	0.30
	Rms $\ddot{x}$ (Ego vehicle) [m/s^2]	0.09 (-70.2%)	0.09 (-71.3%)	0.09 (-70.8%)
NEDC	Wh_{batt} (Lead vehicle) [kWh/100km]	8.93	9.09	9.14
	Wh_{batt} (Ego vehicle) [kWh/100km]	8.31 (-7.4%)	8.19 (-11.1%)	8.25 (-10.8%)
	Rms $\ddot{x}$ (Lead vehicle) [m/s^2]	0.42	0.42	0.42
	Rms $\ddot{x}$ (Ego vehicle) [m/s^2]	0.13 (-69.1%)	0.13 (-68.9%)	0.13 (-68.9%)
WLTP	Wh_{batt} (Lead vehicle) [kWh/100km]	8.69	8.94	8.95
	Wh_{batt} (Ego vehicle) [kWh/100km]	7.50 (-15.8%)	7.37 (-21.3%)	7.43 (-20.5%)
	Rms $\ddot{x}$ (Lead vehicle) [m/s^2]	0.52	0.52	0.52
	Rms $\ddot{x}$ (Ego vehicle) [m/s^2]	0.13 (-74.5%)	0.13 (-74.4%)	0.13 (-74.5%)

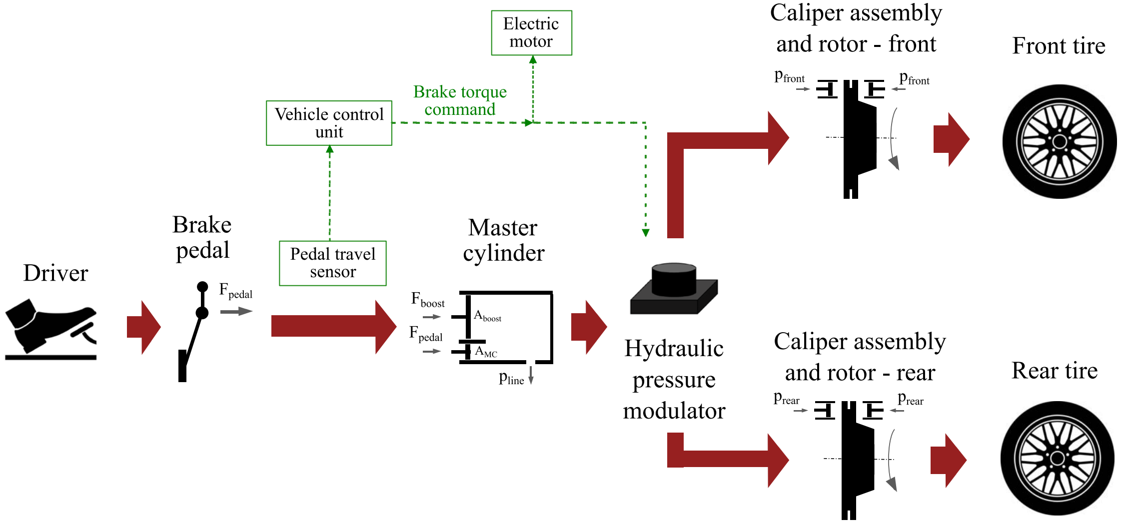
Optimal design of automated vehicle powertrains

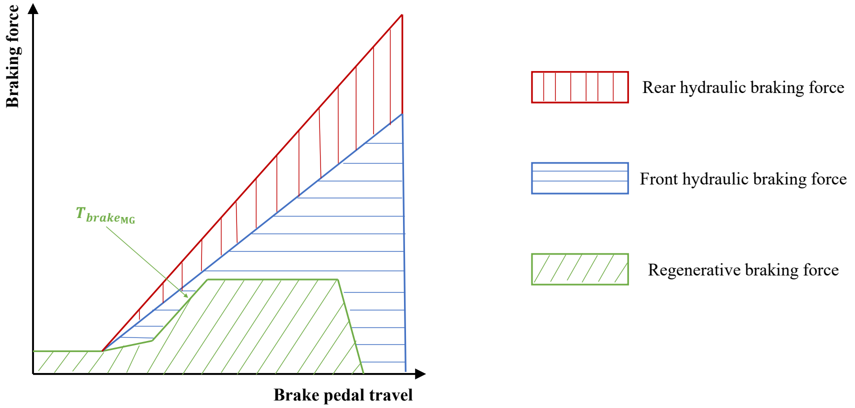


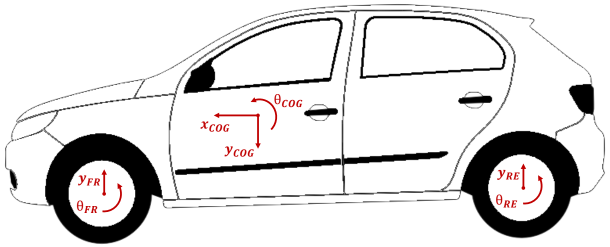
$\%_{V2V}$	Ranking	MG size [kW]	τ	$Eavg_{mix}$ [kWh/100 km]
0%	#1	80	6.5	8.54
	#2	80	5.5	8.58
	#3	80	7.5	8.59
25%	#1	80	5.5	8.34
	#2	80	6.5	8.35
	#3	90	5.5	8.40
50%	#1	80	5.5	8.10
	#2	80	6.5	8.15
	#3	90	5.5	8.17
75%	#1	80	5.5	7.86
	#2	90	4.5	7.91
	#3	90	5.5	7.94
100%	#1	80	5.5	7.62
	#2	90	4.5	7.63
	#3	100	4.5	7.69

Brake system design for electrified vehicles

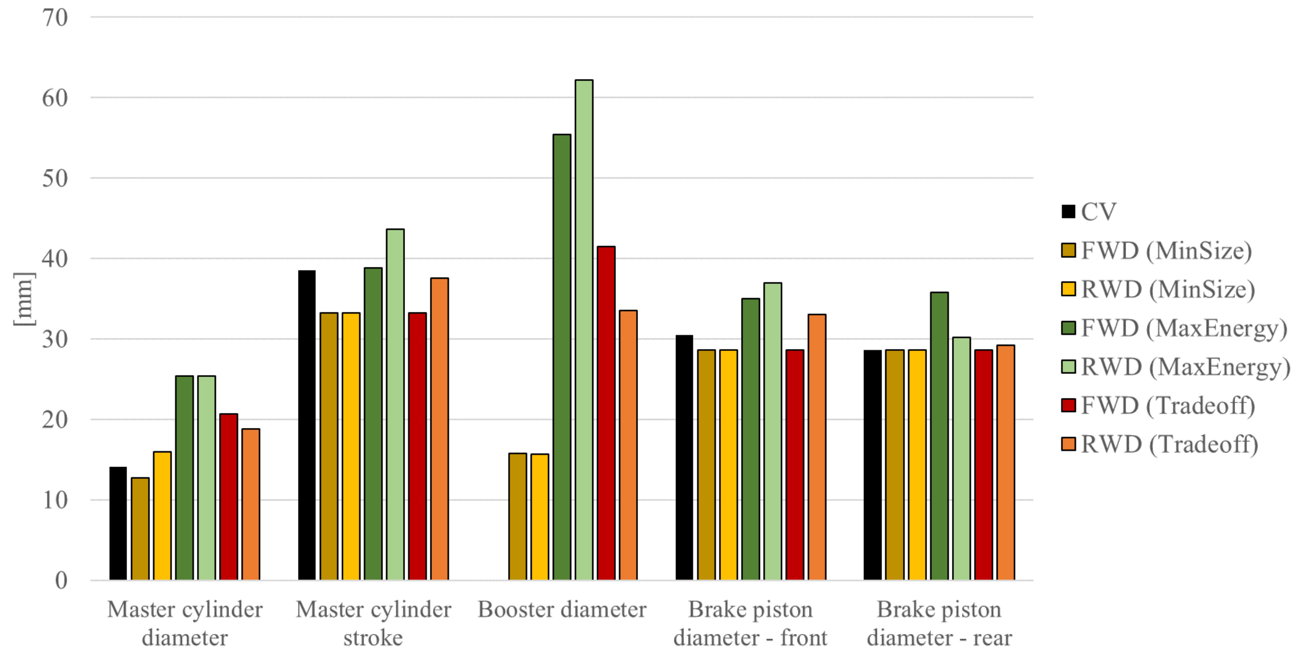


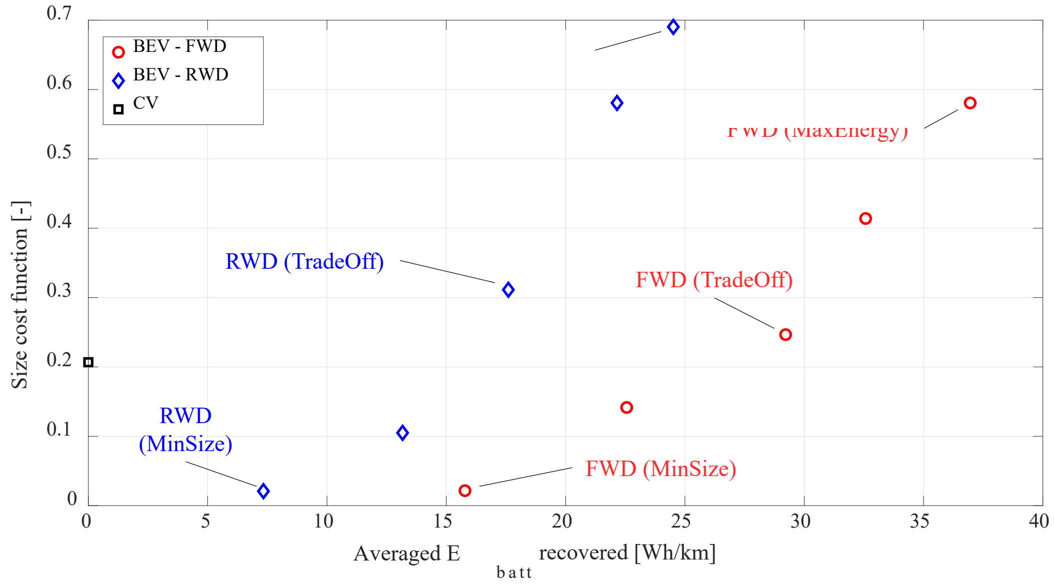






Brake system design for electrified vehicles





POLITECNICO DI TORINO