

The PHEV Control Benchmark

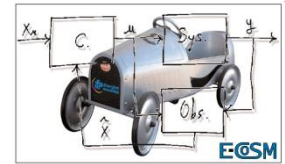
Team: LiU

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Linköping University

Benchmark spirit



- Objective: design a supervisory controller (energy management) for the GM Voltec plug-in HEV (Chevrolet Volt) to
 - minimize fuel and energy consumption on 2 test cycles
 - and meet some performance criteria

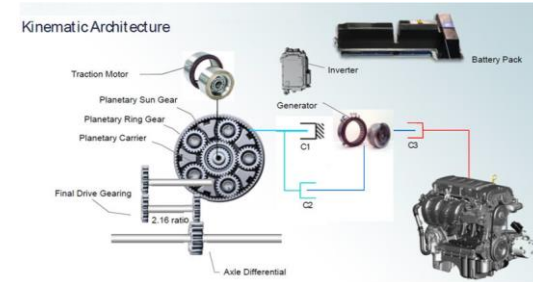
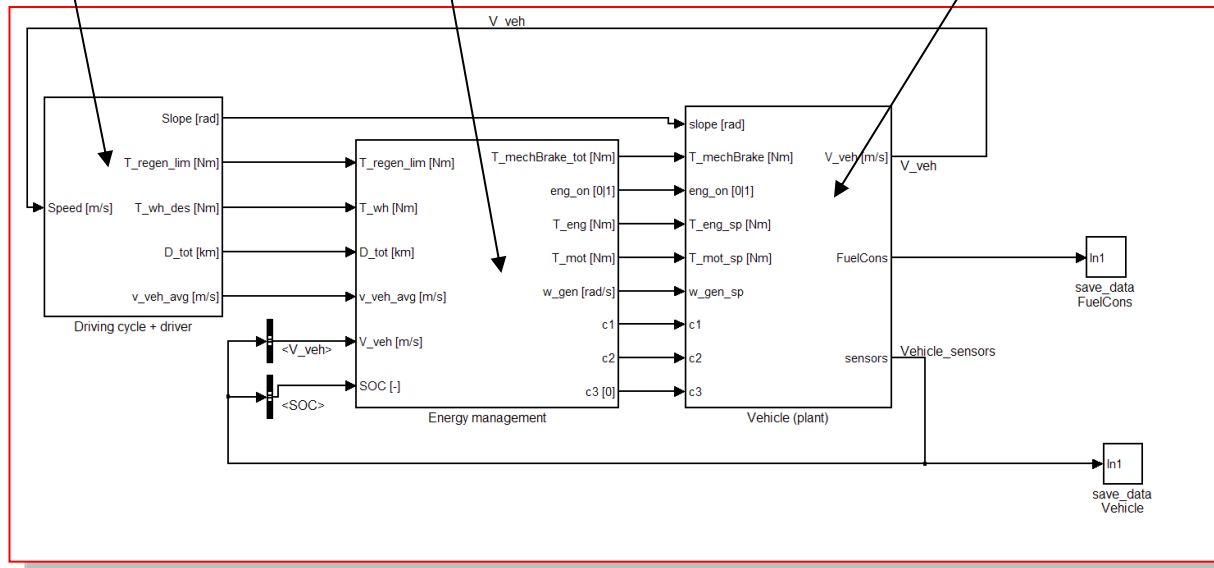


Figure 1: The Volt powertrain architecture as presented by GM [1]

Driving cycles
not known to
participants,
selected by the jury

Energy management
provided by the participants

Chevrolet Volt
simulator provided
by the organizers



Participants and scores

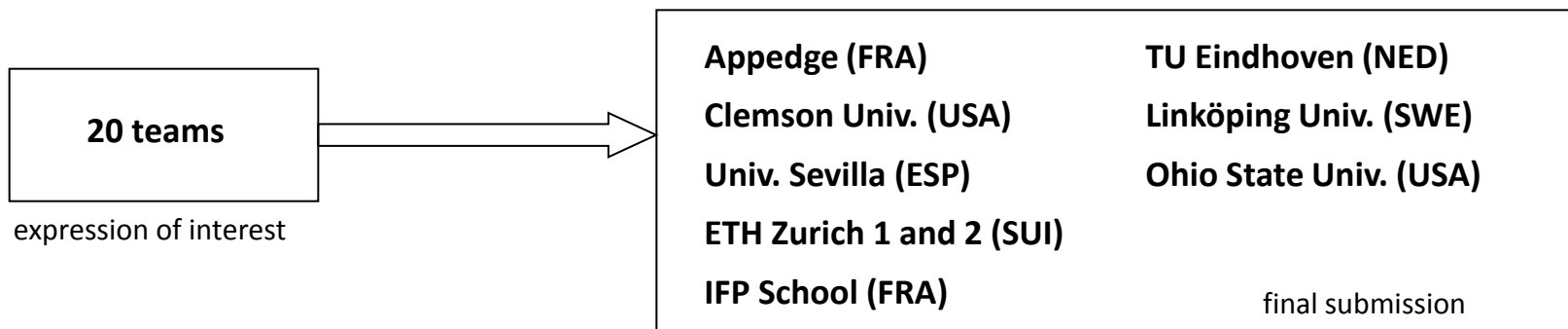
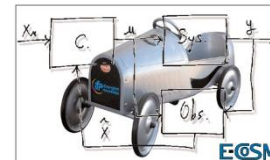
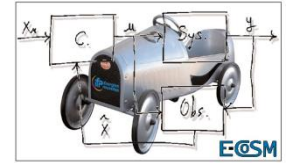


Table 3: Scoring metrics

	Metric	Weight
<i>Performance (30%)</i>	Acceleration 0-100 km/h [s]	7.5 %
	Acceleration 70-120 km/h [s]	7.5 %
	Acceleration 0-1000 m on 4% slope [s]	7.5 %
	Braking distance from 100 km/h [m]	7.5 %
<i>Energy and economy (50%)</i>	Total energy use (fuel+electricity) [MJ]	15 %
	Fuel consumption [MJ]	20 %
	Tailpipe Emissions (not modeled)	0 %
	Well-to-wheel CO ₂ emissions [kg]	15 %
<i>Computational performance (20%)</i>	Processor use [%]	10 %
	Memory use [MB]	10 %

+ physical constraints to be met for the tests to be validated

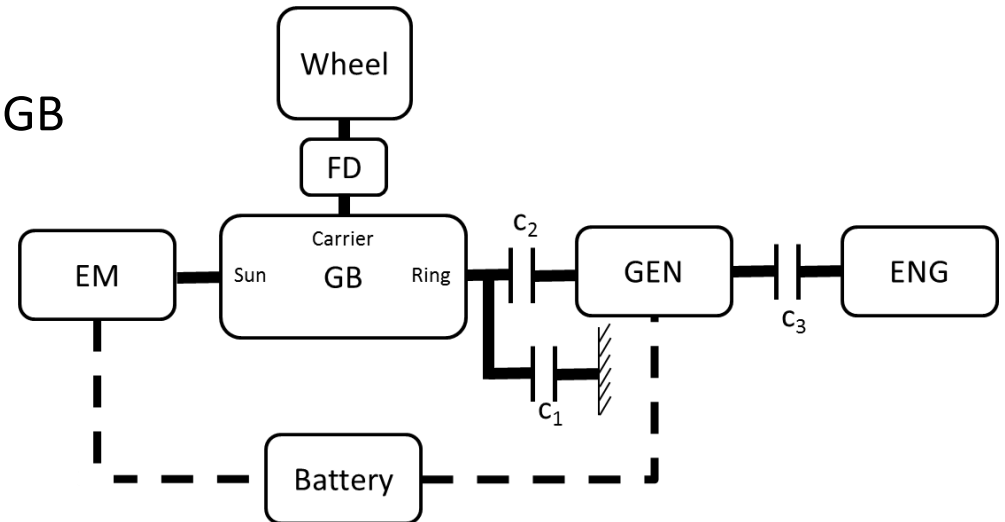
Chevrolet Volt



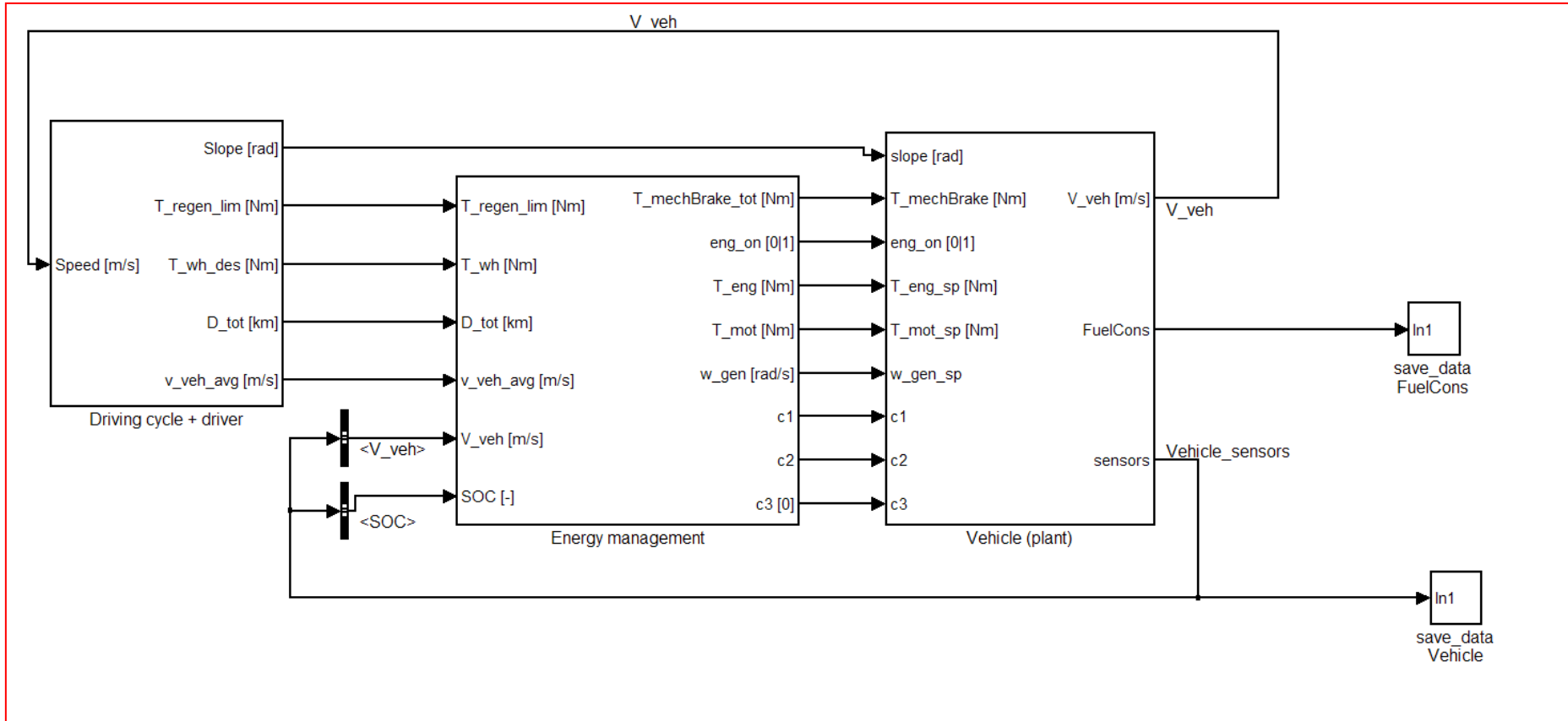
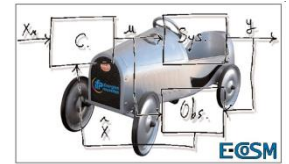
- Two electric machines
- One combustion engine
- Three clutches
- Connected through planetary GB

Four modes:

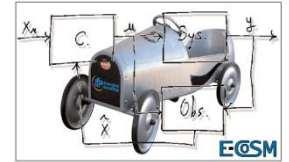
- 2 Electric modes(1/2 EMs)
- Series Hybrid mode
- Power split mode



Problem



Problem



Input:

- Requested torque: T_{req}
- Maximum regenerative torque: $T_{regen, lim}$
- Vehicle speed: V_{veh}
- Battery: SOC
- Approximate cycle length: D_{tot}
- Approximate average cycle speed: v_{avg}

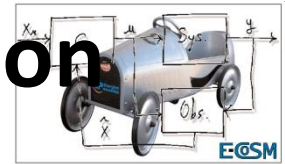
Disturbance: Slope

Output:

- Torques: T_{EM}, T_{ENG}
- Generator speed: ω_{GEN}
- Clutches: c_1, c_2, c_3
- Engine on: eng_{on}
- Mechanical brake: $T_{mech-brake}$

so that the driving cycle is followed and energy minimized.

Equivalent Consumption minimization



- Min sum of fuel and battery energy, equivalence factor λ relating the two.

$$\min (H = P_f + \lambda P_{ech})$$

$$[T_{EM}, T_{ENG}, \omega_{GEN}, Mode] = \operatorname{argmin}(H)$$

Subject to:

$$T_{wh} = T_{req}$$

$$T_{min}(\omega) \leq T \leq T_{max}(\omega)$$

$$0 \leq \omega \leq \omega_{max}$$

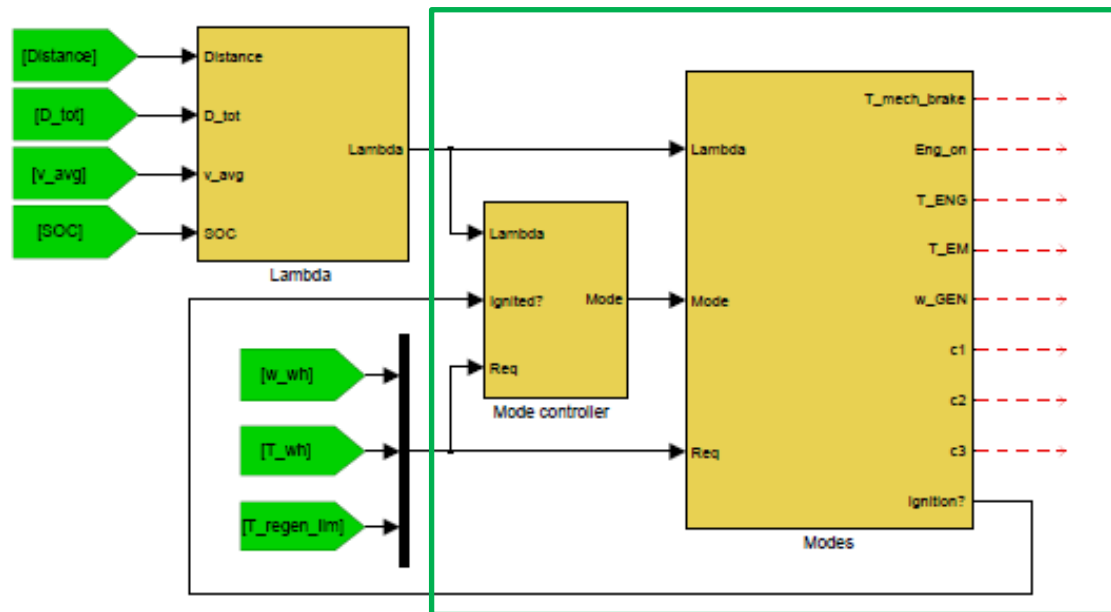
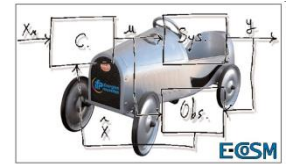
$$P_{b,min}(SOC) \leq P_b \leq P_{b,max}(SOC)$$

- For given values of T_{req} , v_{veh} and λ , the torques, generator speed and clutch positions has to be decided.

SOC is ignored due to small influence of battery efficiency.

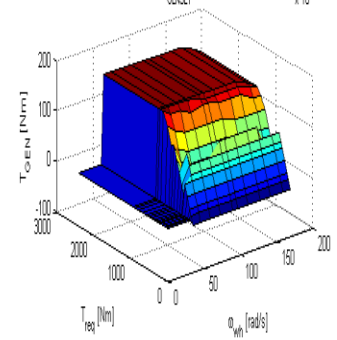
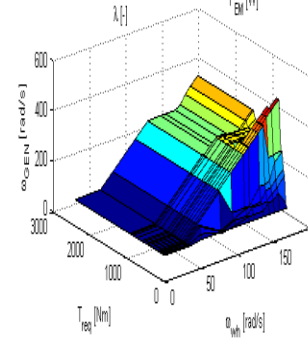
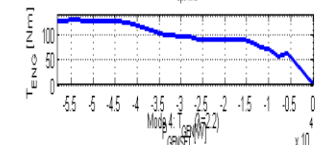
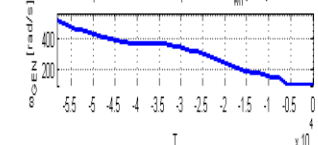
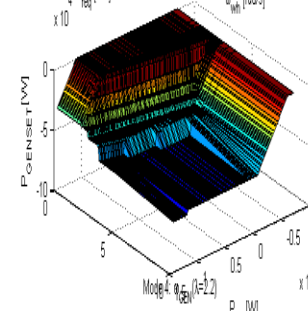
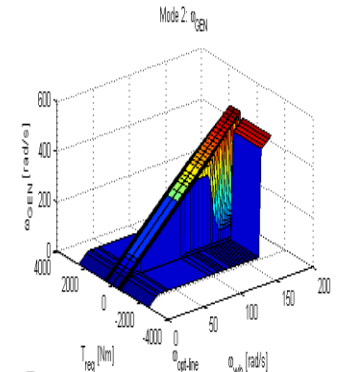
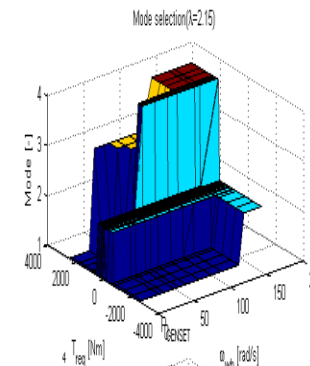
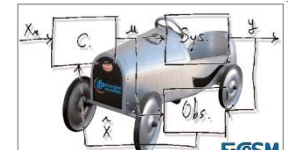
Controller structure

Three control blocks, mode, torque-split and λ

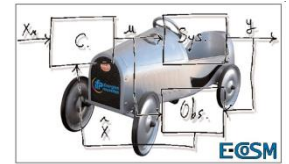


Offline optimizations

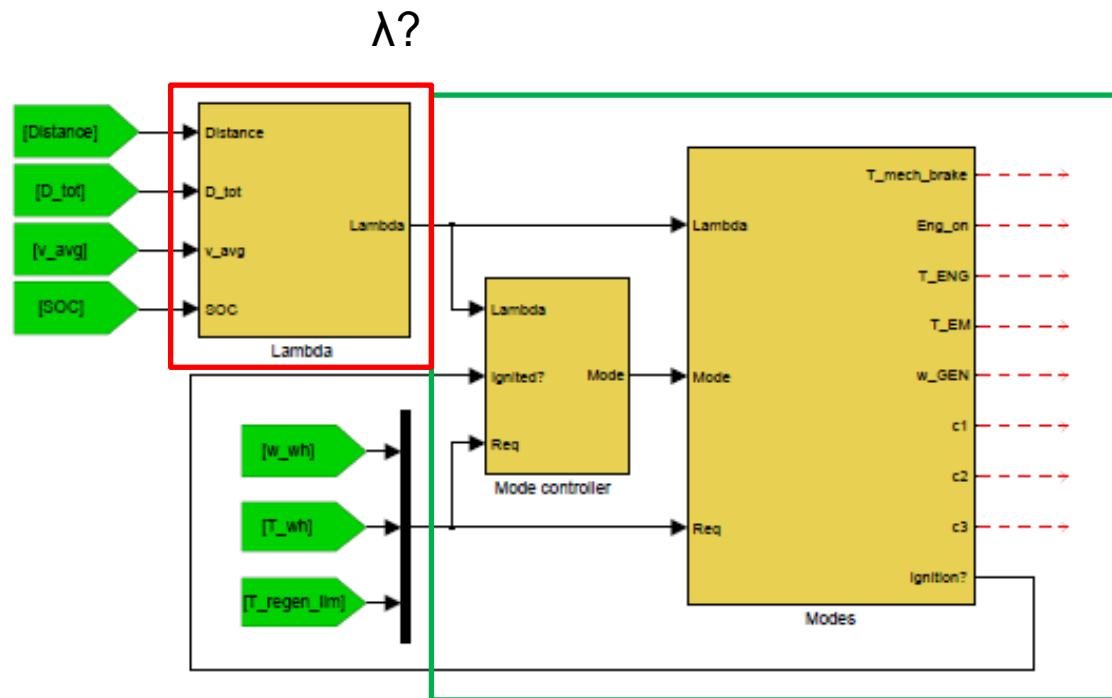
- Optimal controls calculated offline and stored in tables.
Interpolation in real-time control.
- Insights can be gained from kinematic relations
- T_{EM} can be calculated from T_{req}
- Mode 1: One EM electric, no tables
- Mode 2: T_{GEN} given from T_{req} , ω_{GEN} (2D)
- Mode 3: Series Hybrid. P_{EM} given from driver, No reason to deviate from optimal line for genset. 3 tables, P_{GENSET} (2D), $\omega_{opt-line}$ (1D) and $T_{opt-line}$ (1D)
- Mode 4: Power-split hybrid ω_{GEN} (3D) and T_{GEN} (3D)
- Mode selection(3D)



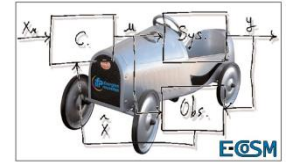
Controller



- Given λ , ω_{wh} and T_{wh} the mode is decided, and thereafter the torques and speed.
- To avoid frequent on/offs of the engine (no engine start cost in the optimization), on/off has to be requested longer than t_{on}/t_{off} to ignite/turn-off the engine.

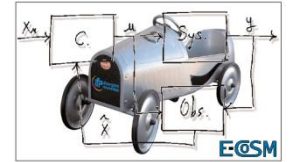


λ -control



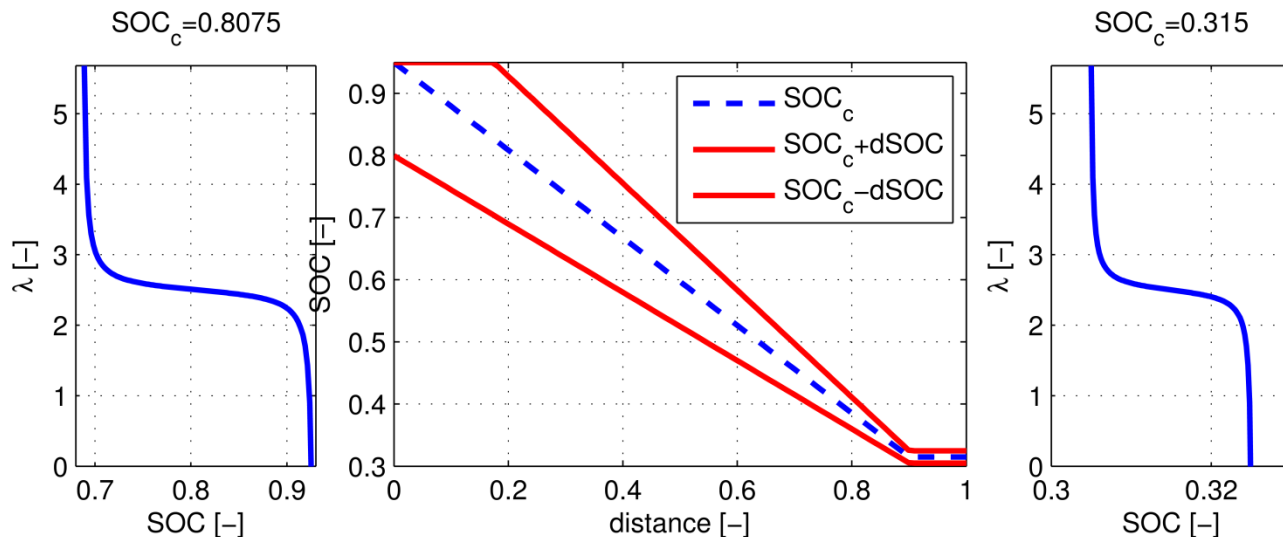
- Well established in literature that blended driving beats CDCS
- Known : Approximate driving distance (errors up to 10%)
Approximate average cycle speed.
- Idea: Use λ to achieve a discharge profile linear in distance, but undershoot the approximate distance to ensure full usage of battery.
- Ideally λ should be approximately constant due to small influence of battery efficiency.

λ -control



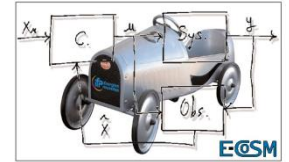
- Use tan-function to adapt λ .
- tan-function steeper near edges of SOC-window.
- Decrease SOC-window as a function of distance.
- tan-function steeper as function of distance, i.e. controller more aggressive.

$$\lambda = \lambda_c - l_1 \tan\left(\frac{l_s \pi}{2dSOC}(SOC - SOC_c)\right)$$

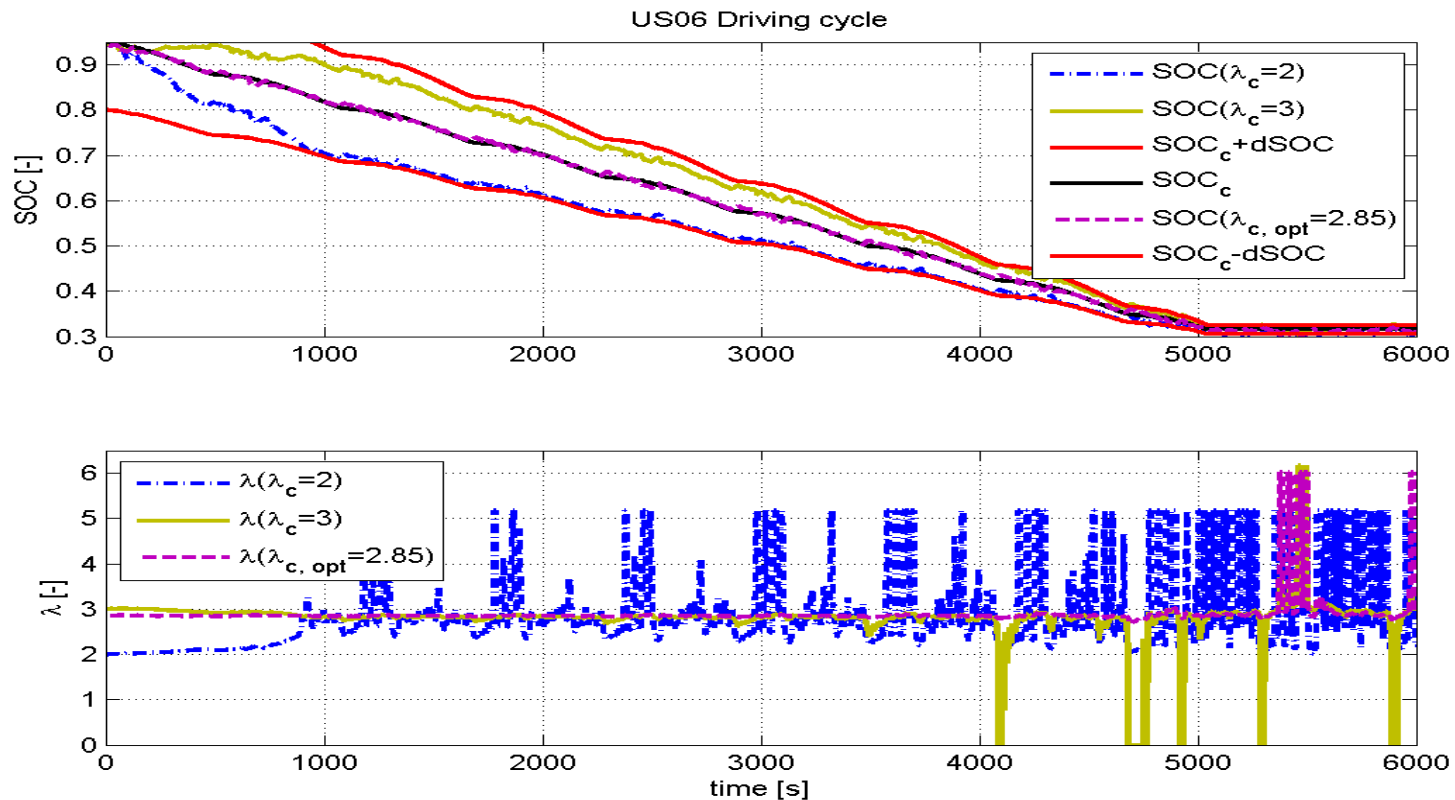


Resulting control is switching, except for optimal λ_c (drive cycle-dependent)

λ -control

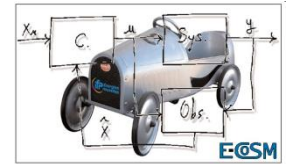


- Use tan-function to adapt λ .
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Resulting control is switching, except for optimal λ_c (drive cycle-dependent)

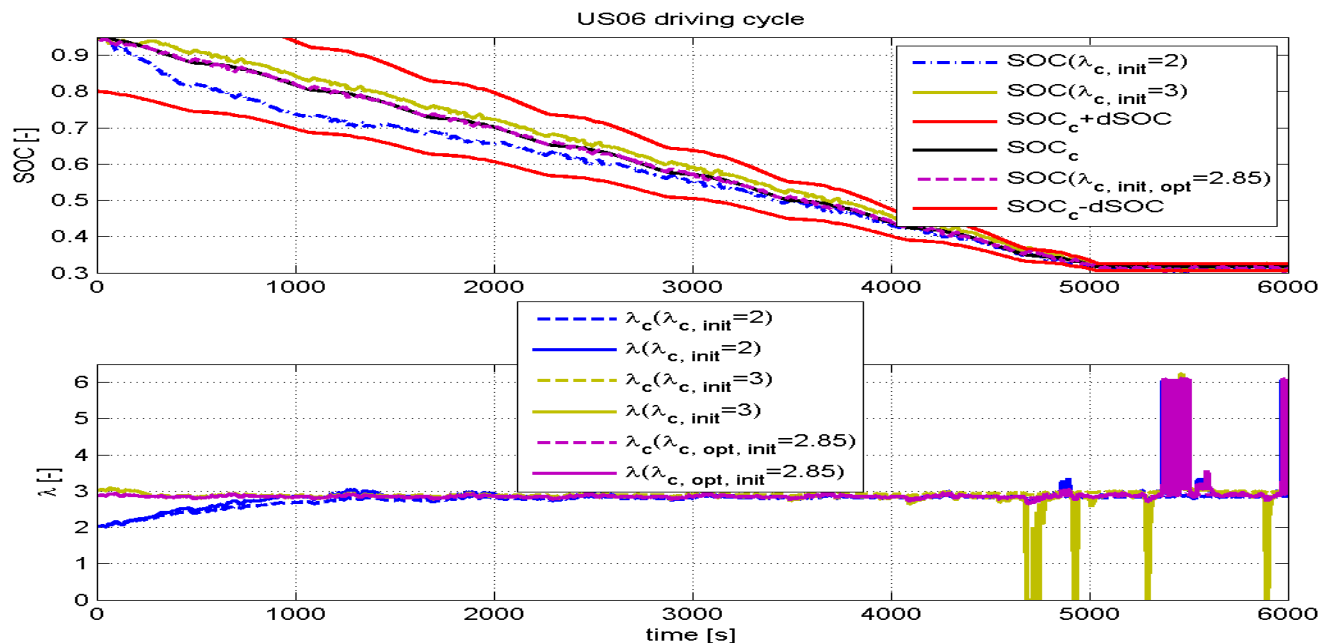
λ_c -control



- Adapt λ_c if SOC deviates too far from SOC_c , according to:

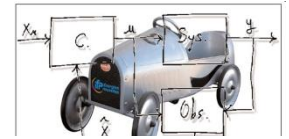
$$\lambda_c = \lambda_{c,init} + K_p(SOC_c - SOC) + K_i \int (SOC_c - SOC) dt$$

- K_p and K_i trade-off between consumption and how fast the controller is.



Performs well even for bad λ_{c-init} , but initial values affect consumption

λ_{c-init} -estimation



- $\lambda_{c-init-opt}$ seen to depend on cycle distance
- Electric range "almost linear" in mean speed
- $\lambda_{c-init-opt}$ vs corrected distance "fall" on the same curve. (Artemis Urban outlier, not used)
- Full controller:

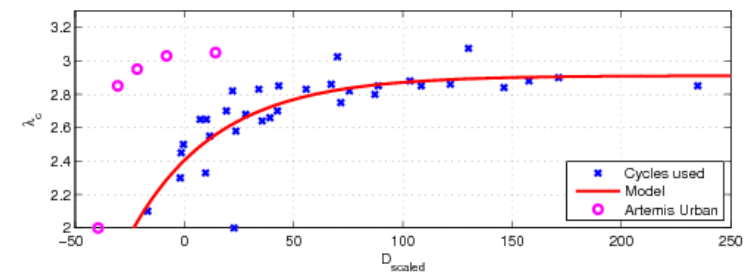
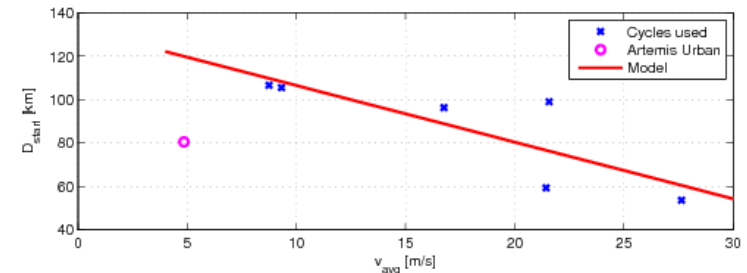
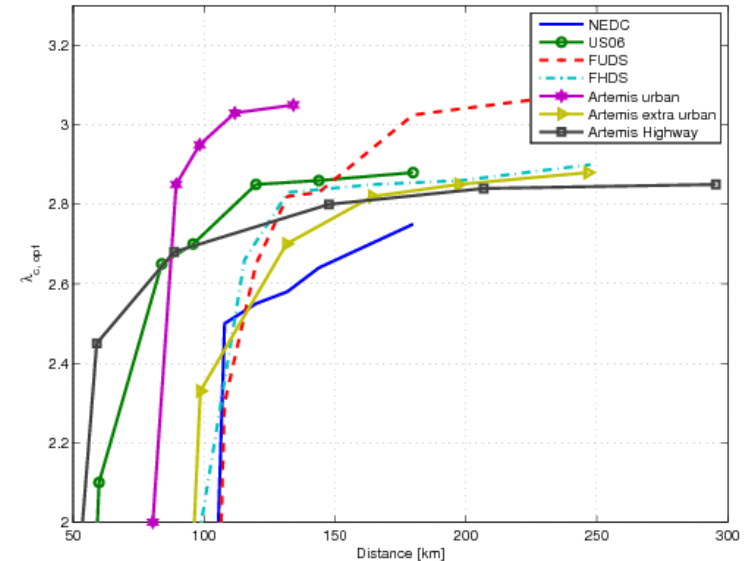
$$\Delta SOC = SOC_c - SOC$$

$$D_{corr} = D_{tot} - (k_1 v_{avg} + k_2)$$

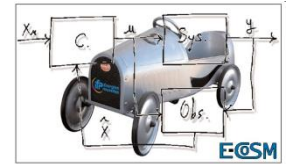
$$\lambda_{c,init} = k_3(1 - \exp(-k_4 D_{corr} + k_5))$$

$$\lambda_c = \lambda_{c,init} + K_p \Delta SOC + K_i \int \Delta SOC dt$$

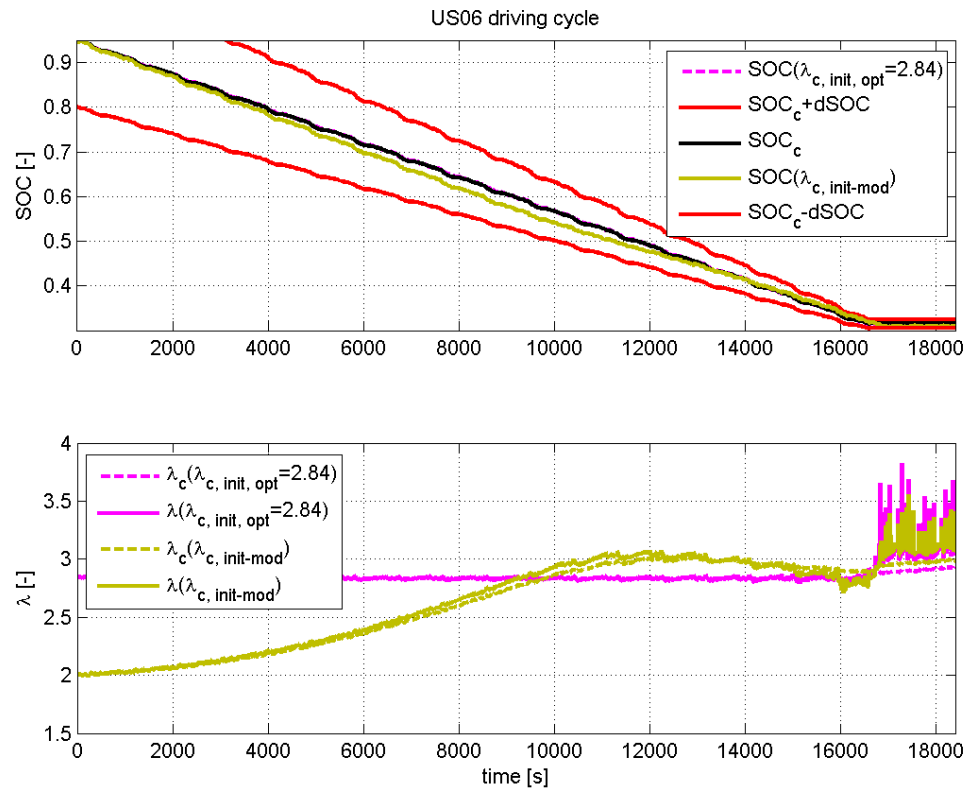
$$\lambda = \lambda_c - l_1 \tan\left(\frac{l_s \pi}{2dSOC} \Delta SOC\right)$$



Results

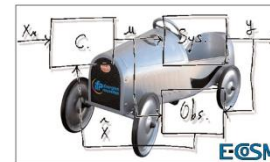


- Artemis Urban considered outlier, but how does the controller perform?



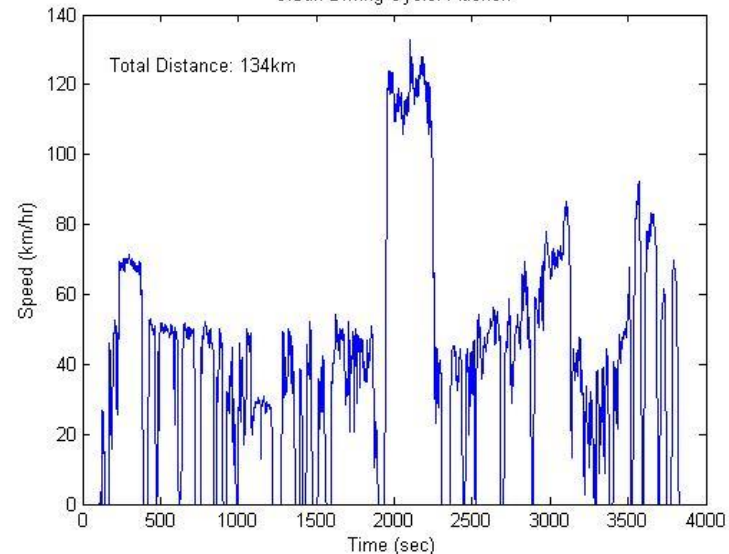
Despite poor initial value the control maintains SOC near the desired value (Side note: The consumption is actually lower!)

Test cycles

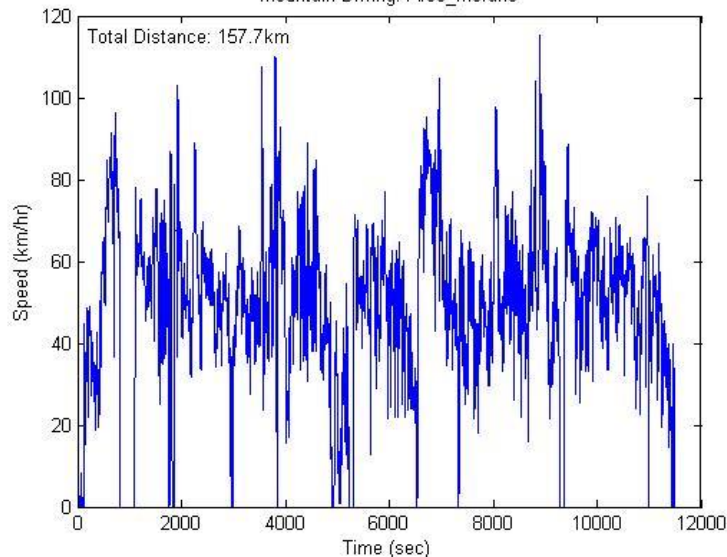


- Urban Driving
 - recorded in Aachen
 - 134 km
 - 0 elevation
- Mountain Driving
 - recorded in the Alps (Arco to Merano, ITA)
 - 157.7 km
 - severe altitude variations

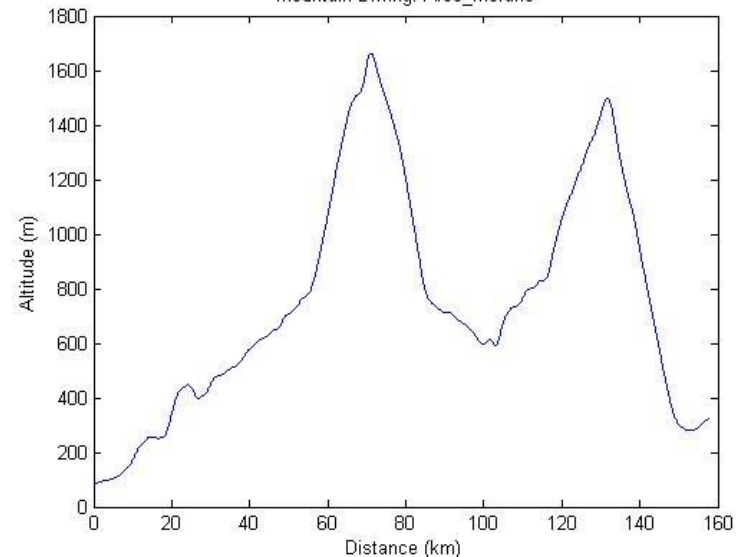
Urban Driving Cycle: Aachen



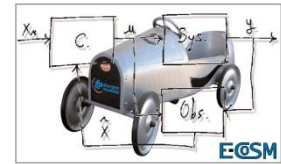
Mountain Driving: Arco_Merano



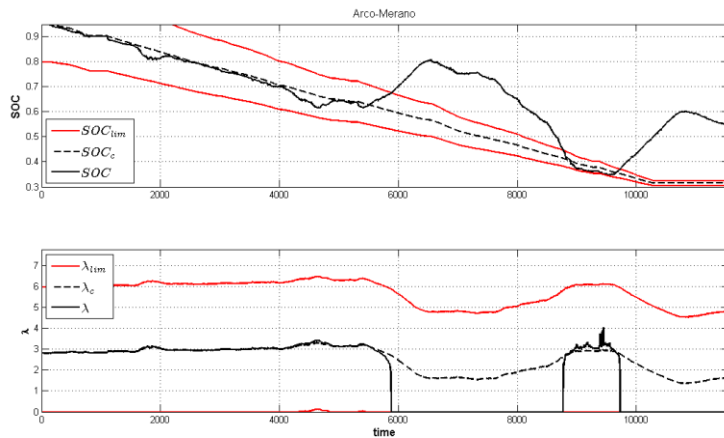
Mountain Driving: Arco_Merano



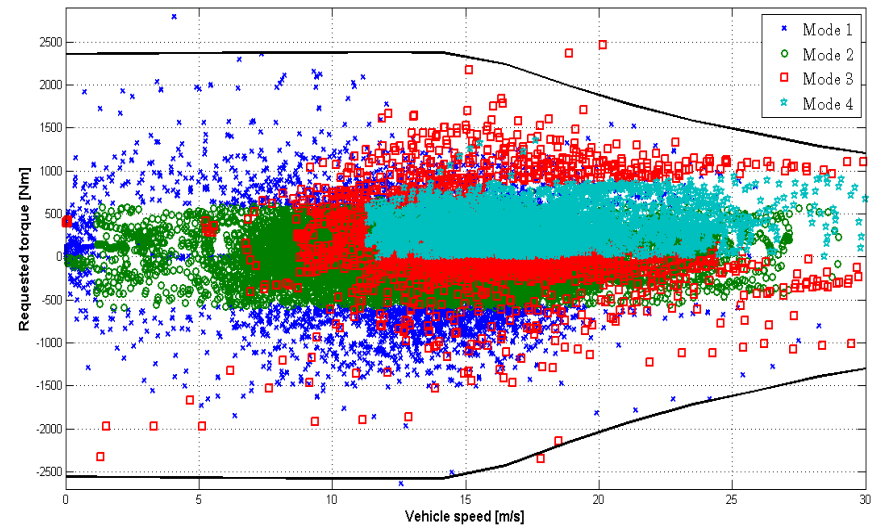
Results



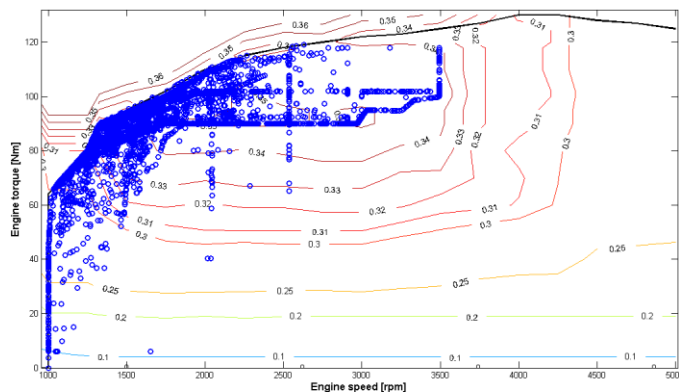
SOC profile: Cycle A (Arco-Merano)



Mode used vs Wheel Torque (Nm) vs Veh Speed (m/s)



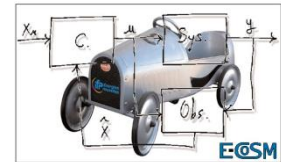
Operating points: Engine on cycle A



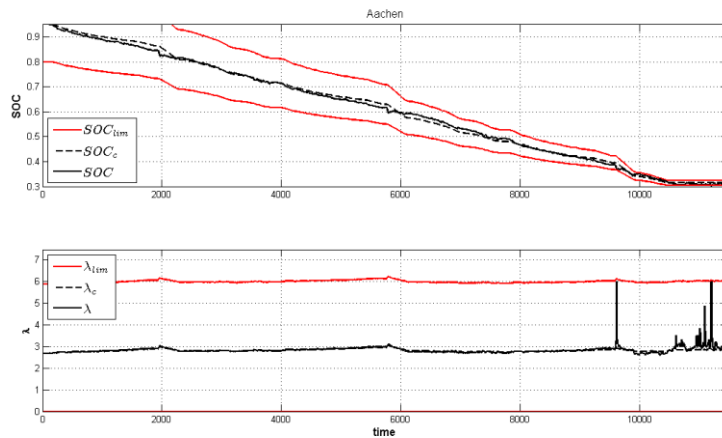
Benchmark results for the developed controller

Metric	Arco-Merano	Aachen
Total energy use (fuel+electricity) [MJ/km]	1.0809	0.8664
Fuel consumption [MJ/km]	0.9259	0.5913
Well-to-wheel CO ₂ emissions [kg/km]	0.0942	0.0768
Processor use [s]	2.9874	2.9631
Memory use [MB]	0.1535	
Acceleration 70-120km/h [s]	9.1	
Acceleration 0-100km/h [s]	7.3	
Acceleration 0-1000m on 4% slope [s]	32.6	
Braking Distance from 100km/h [m]	37.7614	

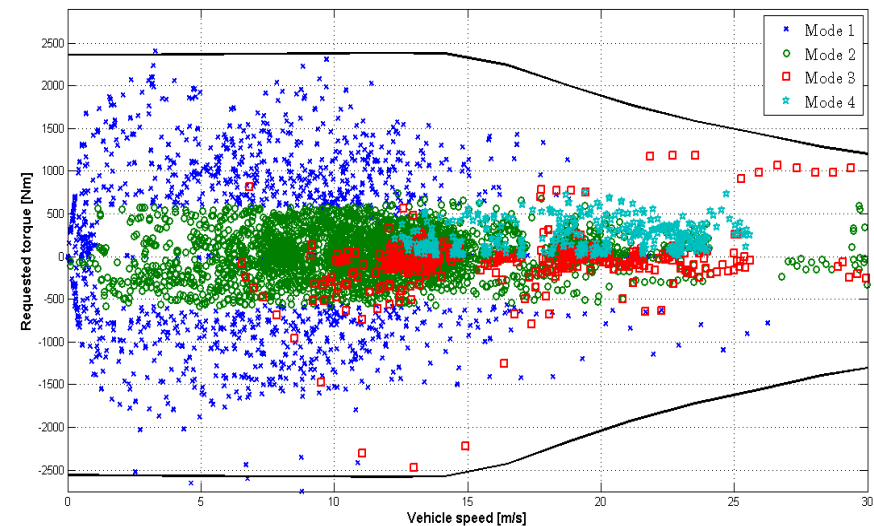
Results



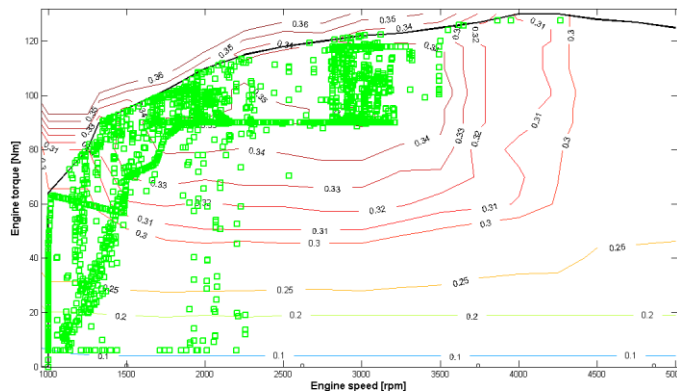
SOC profile: Cycle B (Aachen)



Mode used vs Wheel Torque (Nm) vs Veh Speed (m/s)



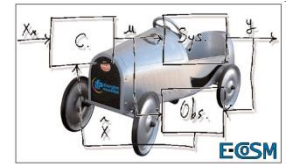
Operating points: Engine on cycle B



Benchmark results for the developed controller

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Results



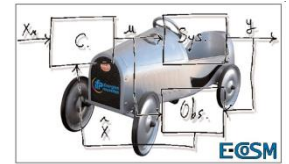
		Fuel A	Fuel B	Memory	Proc. time	SCORE
	Team	L/hkm	L/hkm	kB	100=Avg.	
4	Team 4	3,39 (4)	2,57 (5)	159 (6)	18 (4)	0,934
5	Team 5	3,66* [^]	4,60* [^]	36 (2)	13 (1)	0,993
6	Team 6	3,66 (6)	4,60 (6)	186 (7)	18 (4)	1,086
7	Team 7	3,05 (2)	1,88 (3)	298 (8)	197 (7)	1,119
8	Team 8	6,06* [^] (8)	4,99* [^] (8)	353 (9)	442 (9)	1,873
9	Team 9 [^]	NA** (9)	8,93 (9)	95 (4)	361 (8)	NA
	Optimum	2,76	1,77			

* test disqualified due to constraints not met, result set to maximum valid if lower

** test invalid, cycle not entirely driven

[^] entry or test not considered for average calculation

Results



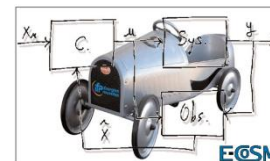
		Fuel A	Fuel B	Memory	Proc. time	SCORE
	Team	L/hkm	L/hkm	kB	100=Avg.	
1	Linköping	2,86 (1)	1,83 (1)	153 (5)	16 (3)	0,836
2	Eindhoven	3,18 (3)	2,27 (4)	81 (3)	14 (2)	0,850
3	Zürich A	3,56 (5)	1,86 (2)	24 (1)	84 (6)	0,877
4	Team 4	3,39 (4)	2,57 (5)	159 (6)	18 (4)	0,934
5	Team 5	3,66*^	4,60*^	36 (2)	13 (1)	0,993
6	Team 6	3,66 (6)	4,60 (6)	186 (7)	18 (4)	1,086
7	Team 7	3,05 (2)	1,88 (3)	298 (8)	197 (7)	1,119
8	Team 8	6,06*^ (8)	4,99*^ (8)	353 (9)	442 (9)	1,873
9	Team 9^	NA** (9)	8,93 (9)	95 (4)	361 (8)	NA
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Results



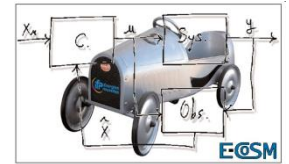
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3	Zürich A	3,56 (5)	1,86 (2)	24 (1)	84 (6)	0,877
4	Team 4	3,39 (4)	Consumption vs optimal for each cycle LiU: +3.6% (A), +3.4% (B) 2nd: +10.5% (Team 7), +5.1% (Team 3) 3rd: +15.2% (Team 2), +6.2% (Team 7) 4th: +22.8% (Team 4), +28.2% (Team 2)			
5	Team 5	3,66* [^]				
6	Team 6	3,66 (6)				
7	Team 7	3,05 (2)				
8	Team 8	6,06* [^] (8)				
9	Team 9 [^]	NA** (9)				
	Optimum	2,76	1,77			

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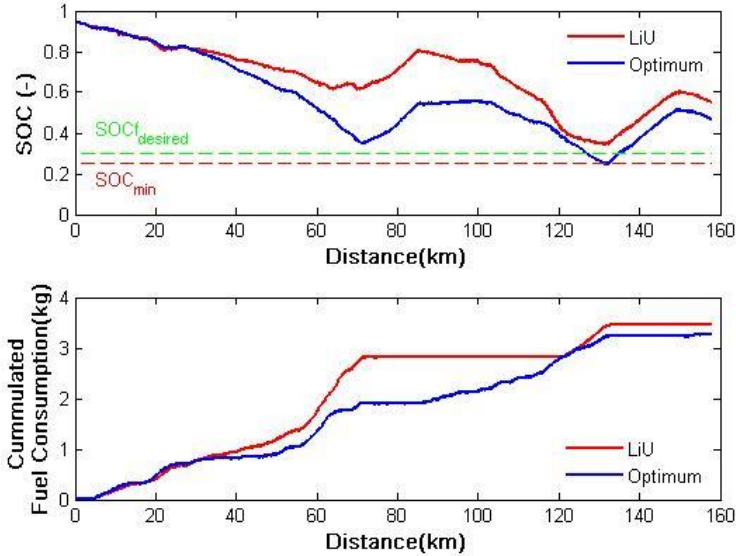
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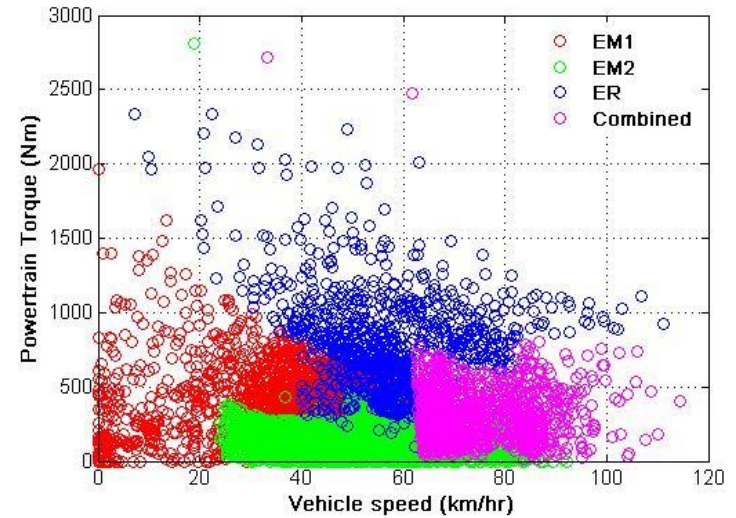
Winner vs. optimal



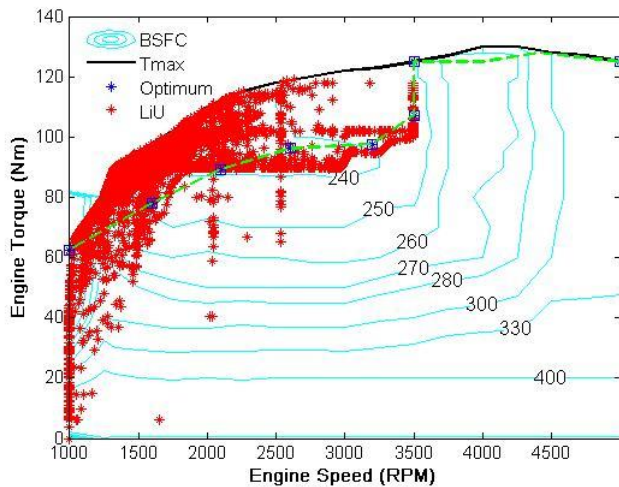
SOC profile:



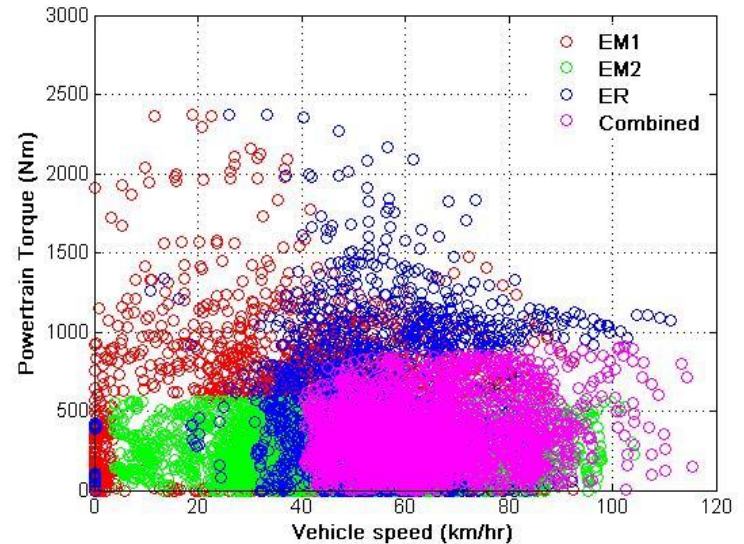
Optimum Modes vs Wheel Torque (Nm) vs Veh Speed (m/s)



Operating points: Engine on Arco-Merano



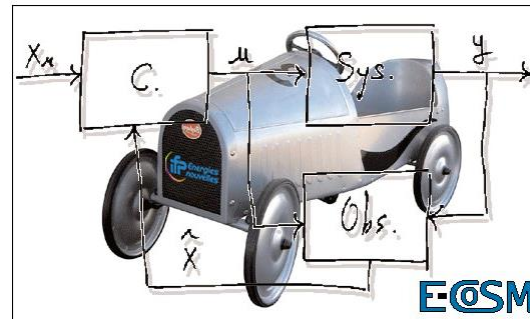
Modes (LiU) vs Wheel Torque (Nm) vs Veh Speed (m/s)





The PHEV Control Benchmark – ECOSM12 – 24/10/2012

Team: Linköping university



The PHEV Control Benchmark

Team: LiU

Martin Sivertsson



Linköping University