Downsized and Supercharged Hybrid Pneumatic Engine

Higher efficiency and good drivability at relatively low cost

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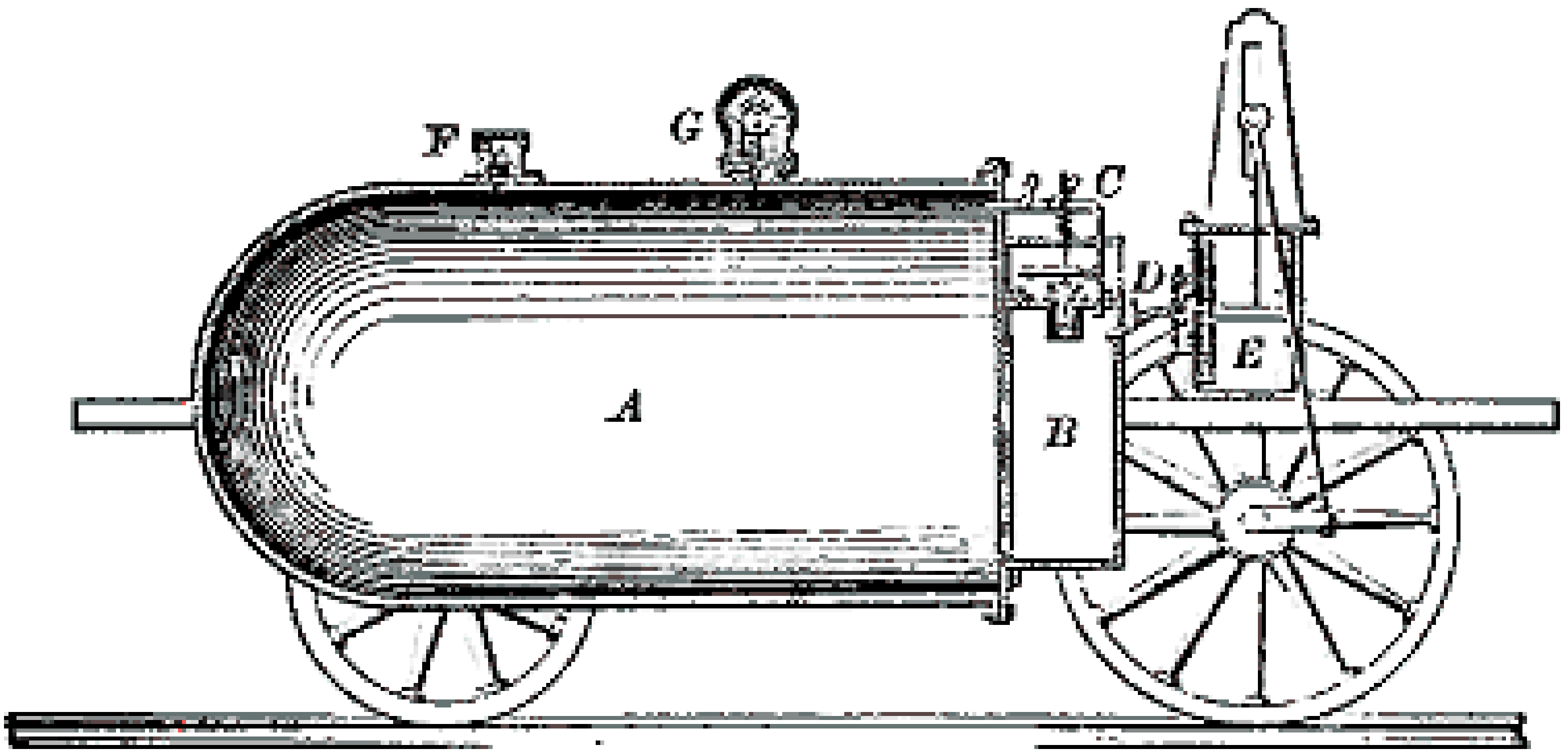
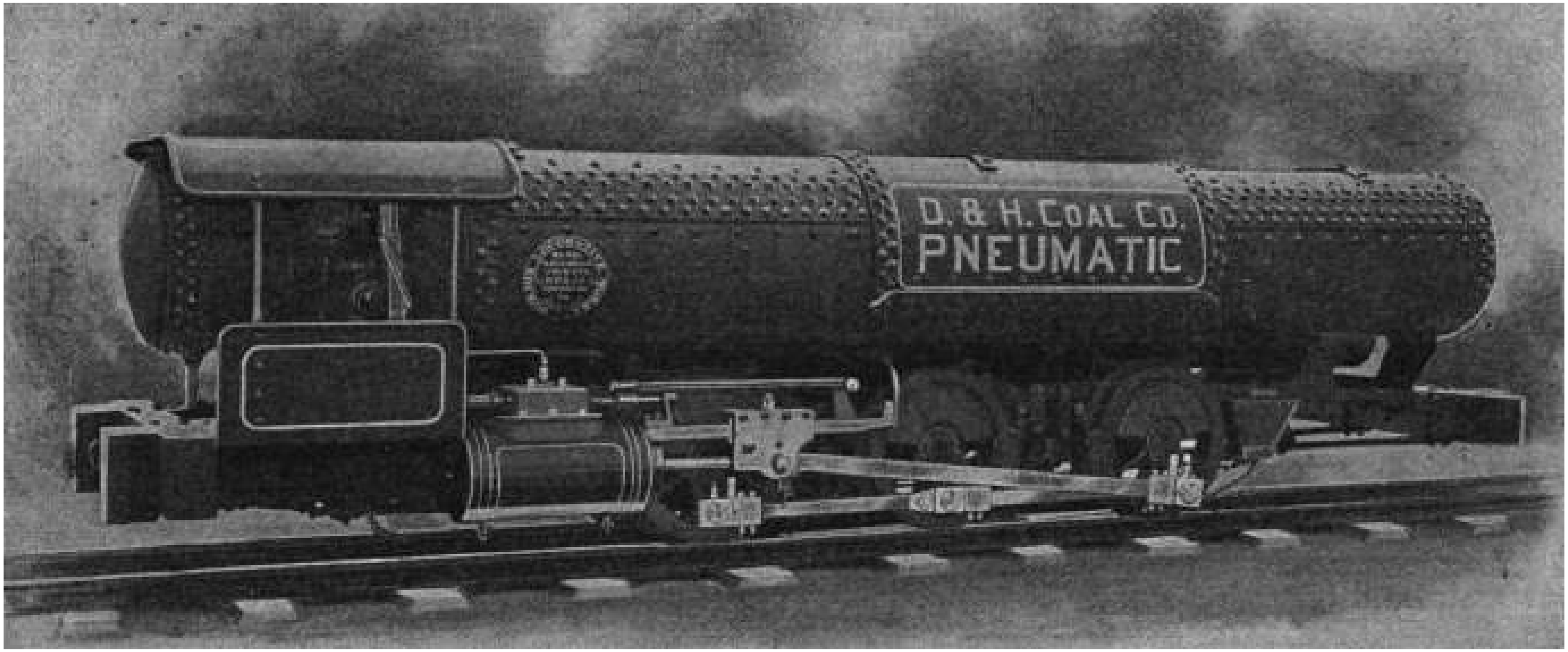
Nothing New (the Parsey Locomotive, 1847)



Parsey's Compressed-Air Engine.

Source: http://www.dself.dsl.pipex.com/MUSEUM/TRANSPORT/comprair/comprair.htm

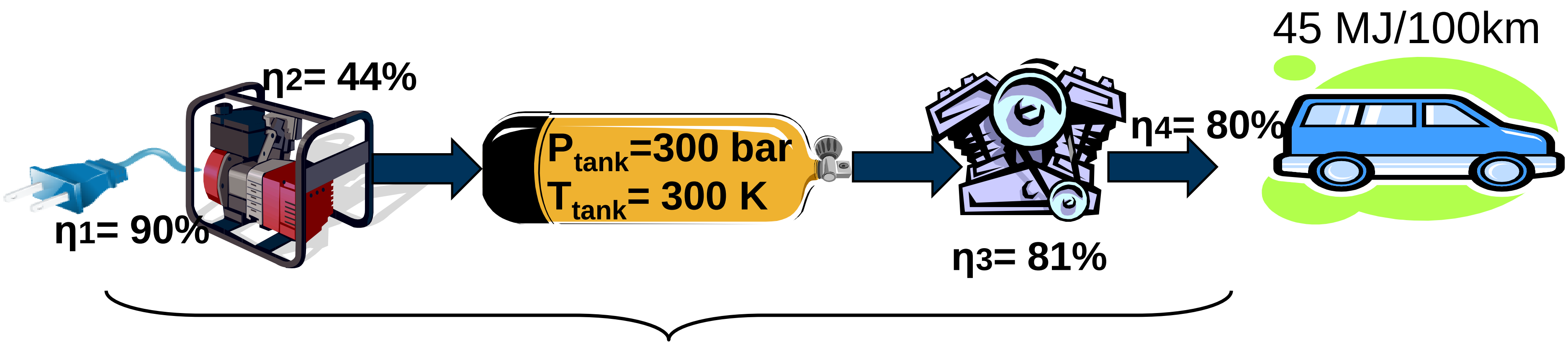
Dickson Locomotive, 1899



Mass 16t, storage 40 bar, working 10 bar, volume 4.8m^3

Source: http://www.dself.dsl.pipex.com/MUSEUM/TRANSPORT/comprair/comprair.htm

Compressed Air as Fuel?

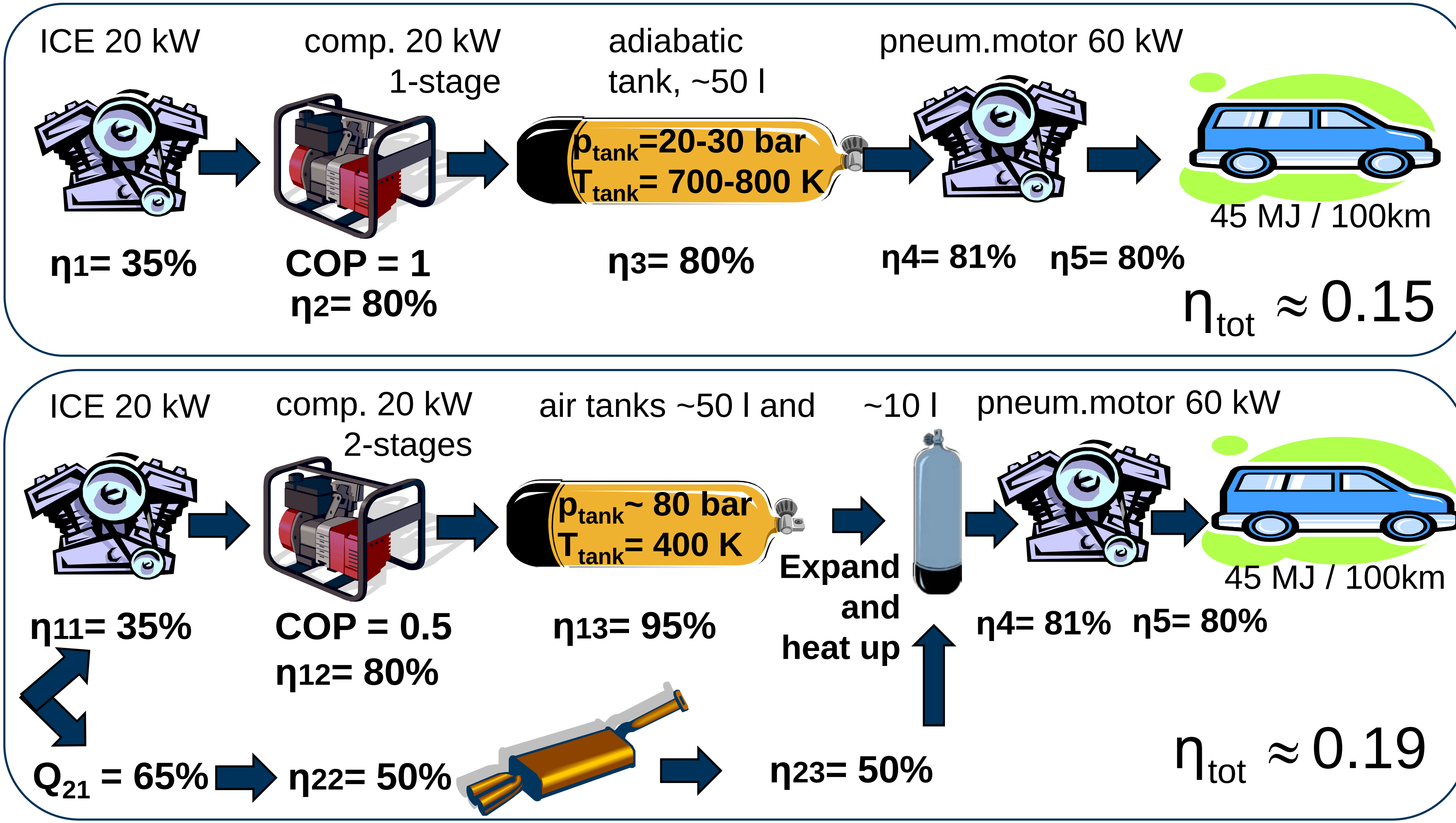


$$\eta_{tot} \approx 0.25$$

Necessary energy in air tank 70 MJ, which corresponds to 250 kg air mass and 200 kg tank mass (kevlar composite) and 700 l tank volume.

Compared that to BEV: plug-to-wheel efficiency of η_{tot}= 0.75 and 130 kg battery mass (Li-ion batteries with 125 Wh/kg useful energy density).

Compressed Air in a Series Hybrid?



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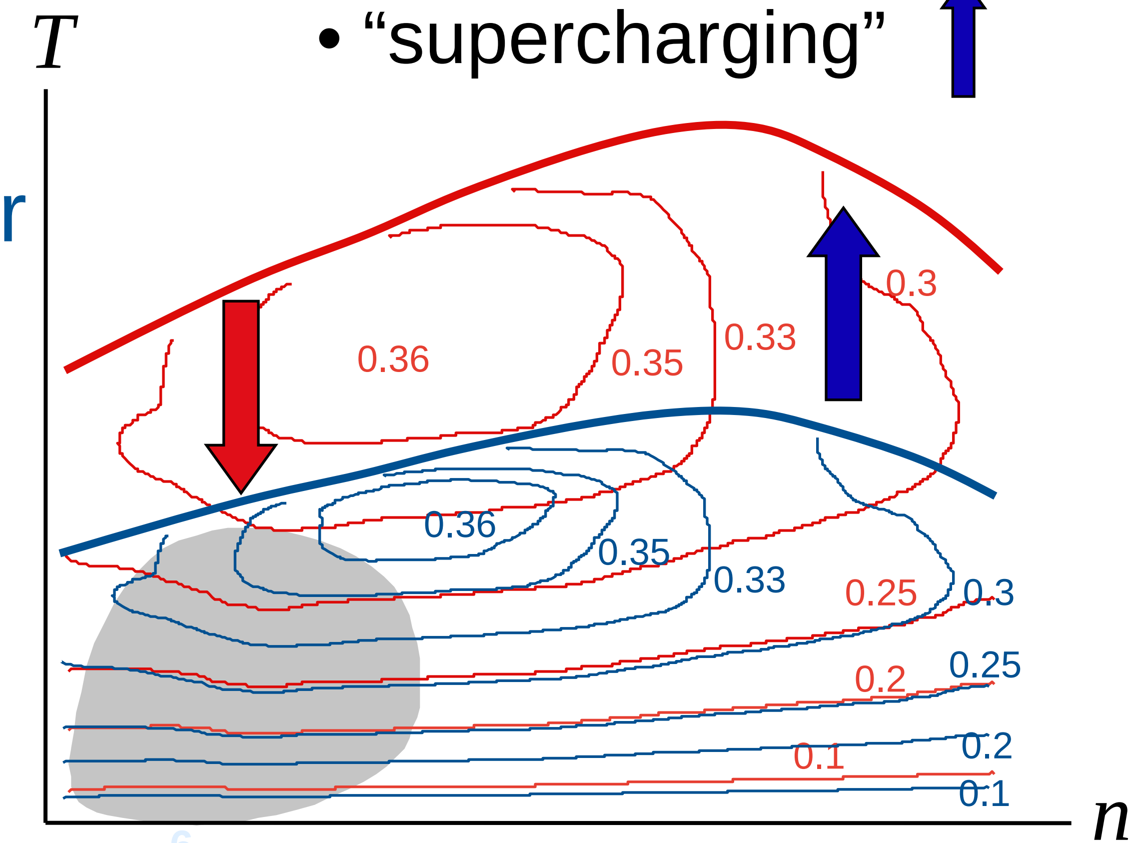
Downsizing and Supercharging (DSC)

replace A V-6
by an R-3
with turbocharger

- “downsizing” V-6 ↓ I-3
- “supercharging” ↑



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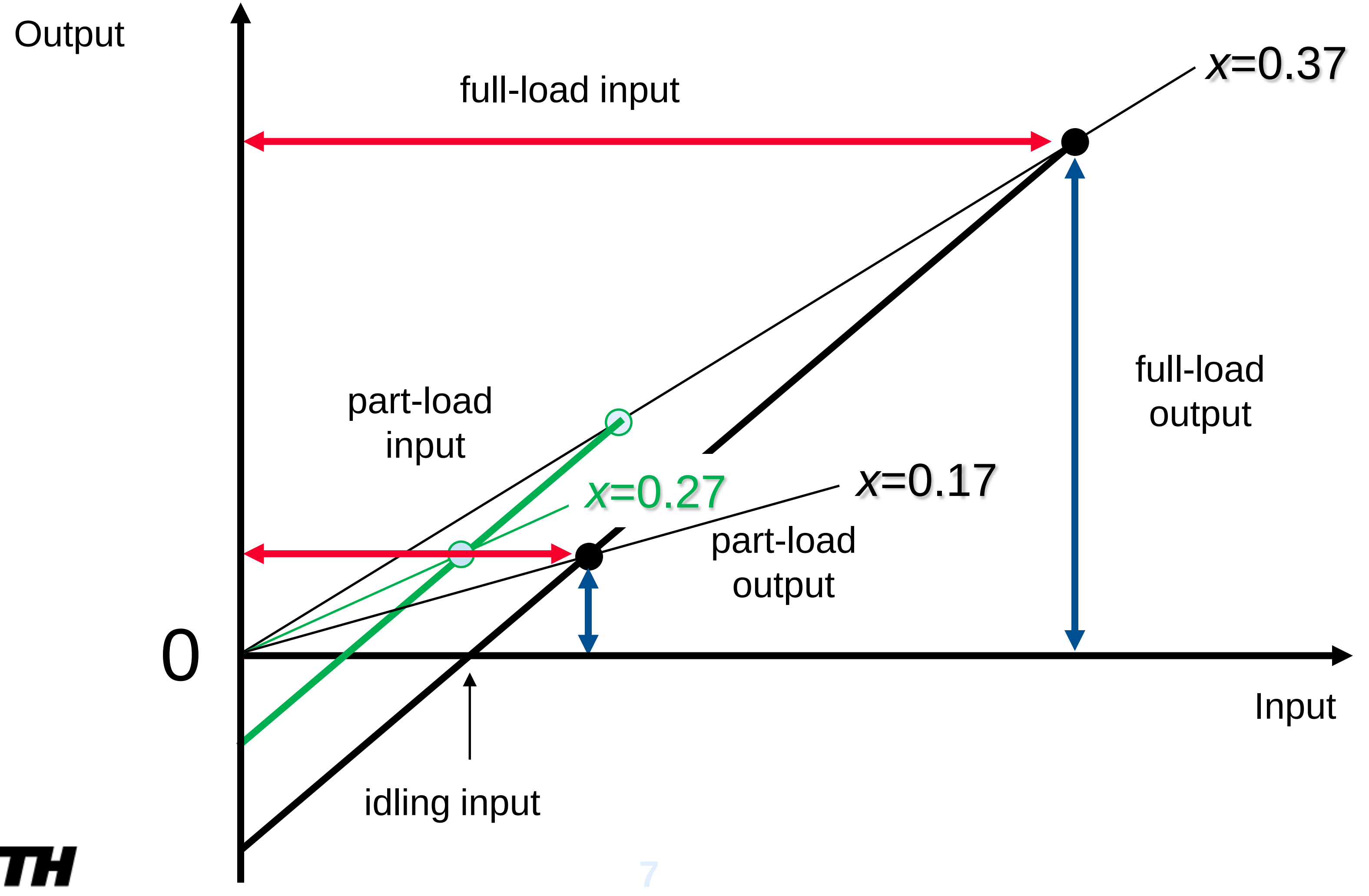
Explanation DSC



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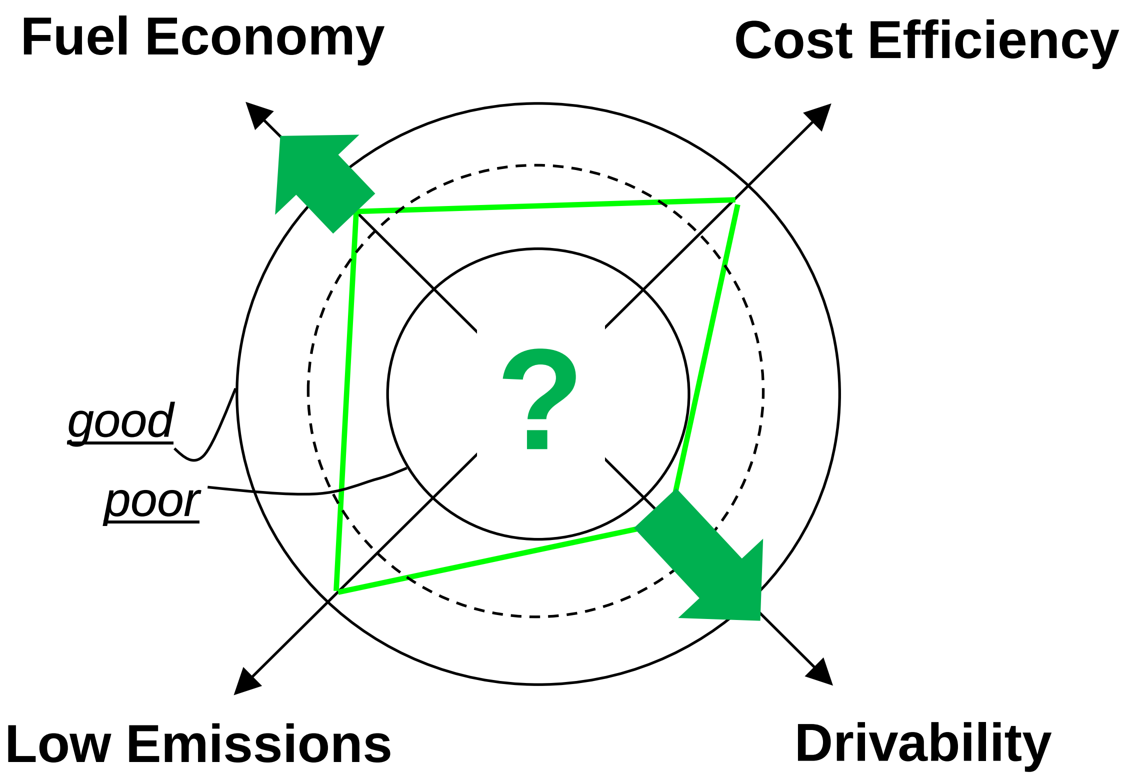
DSC Problems



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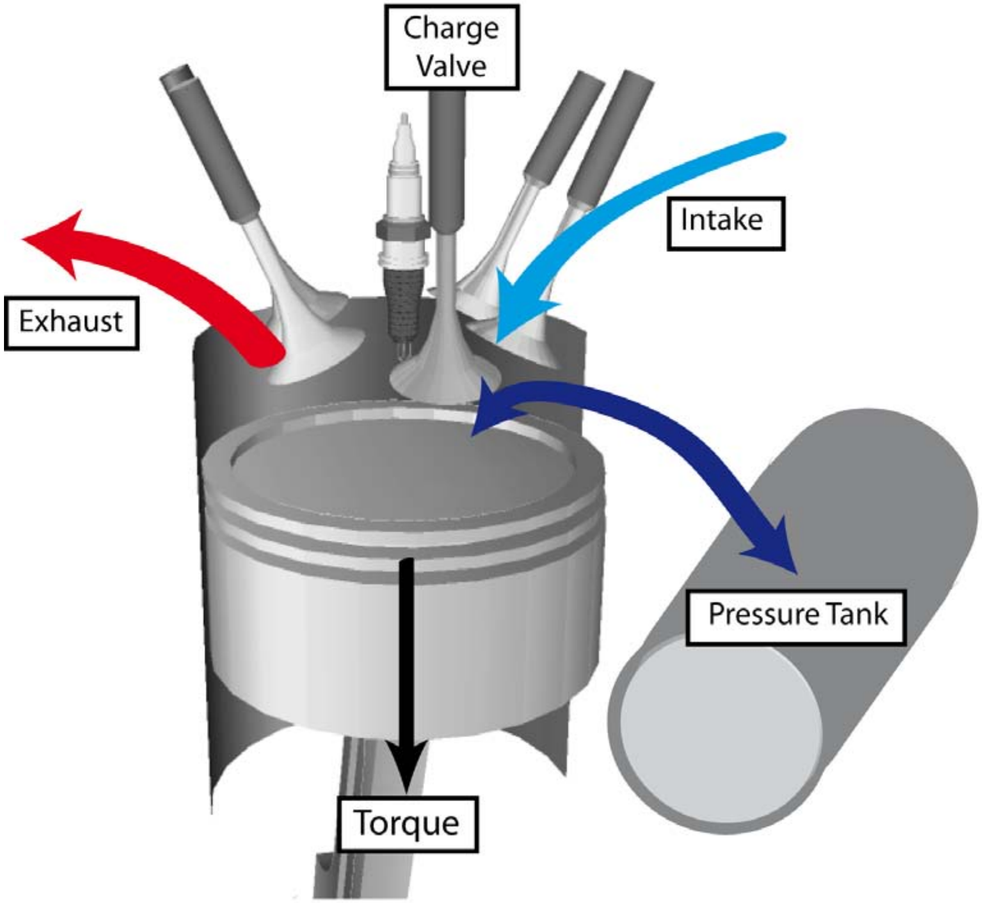
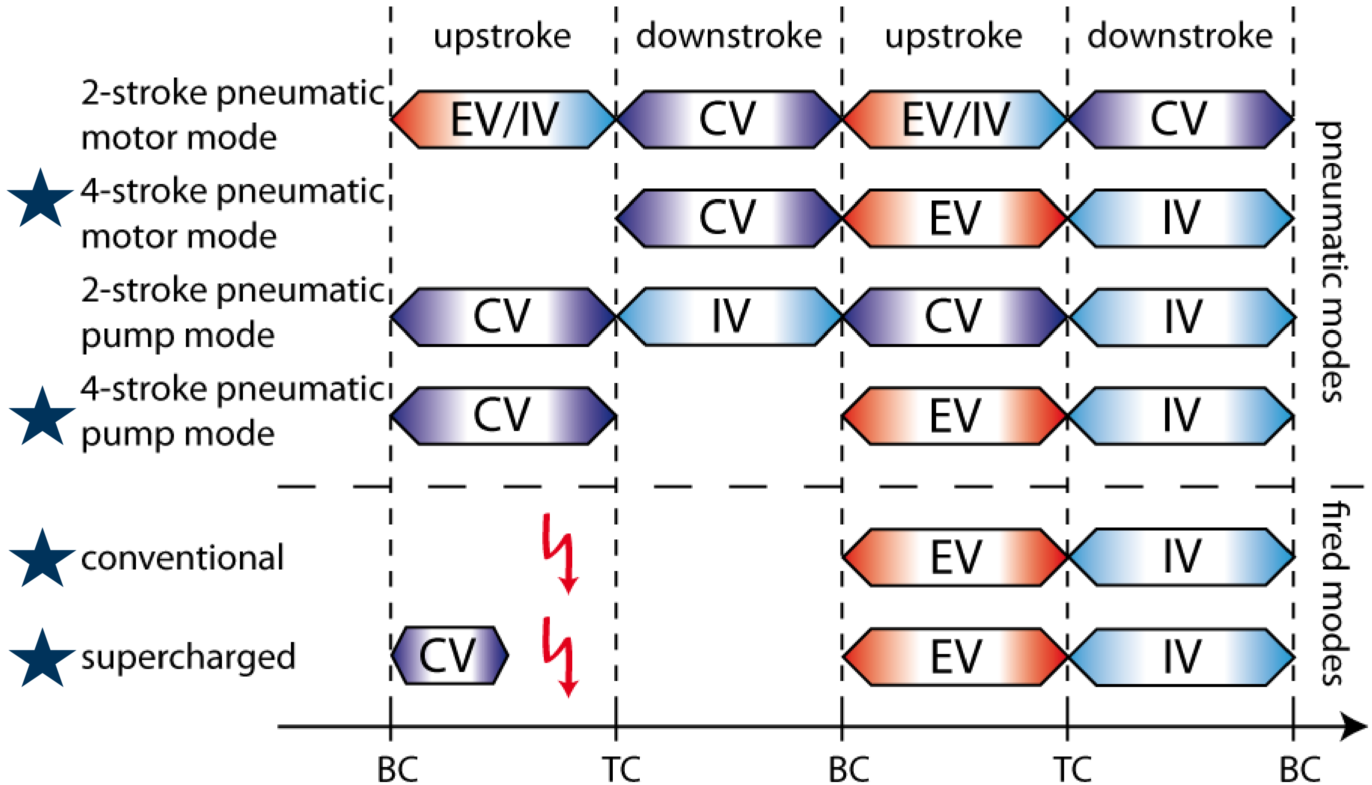
The Hybrid Pneumatic Engine (HPE) Idea

- Previous work by Herrera (1998), Schechter (1999) and Higelin (2001)
- Air tank as energy buffer
- Recuperation and pneumatic driving
- Pneumatic modes are 2-stroke based, all valves variable



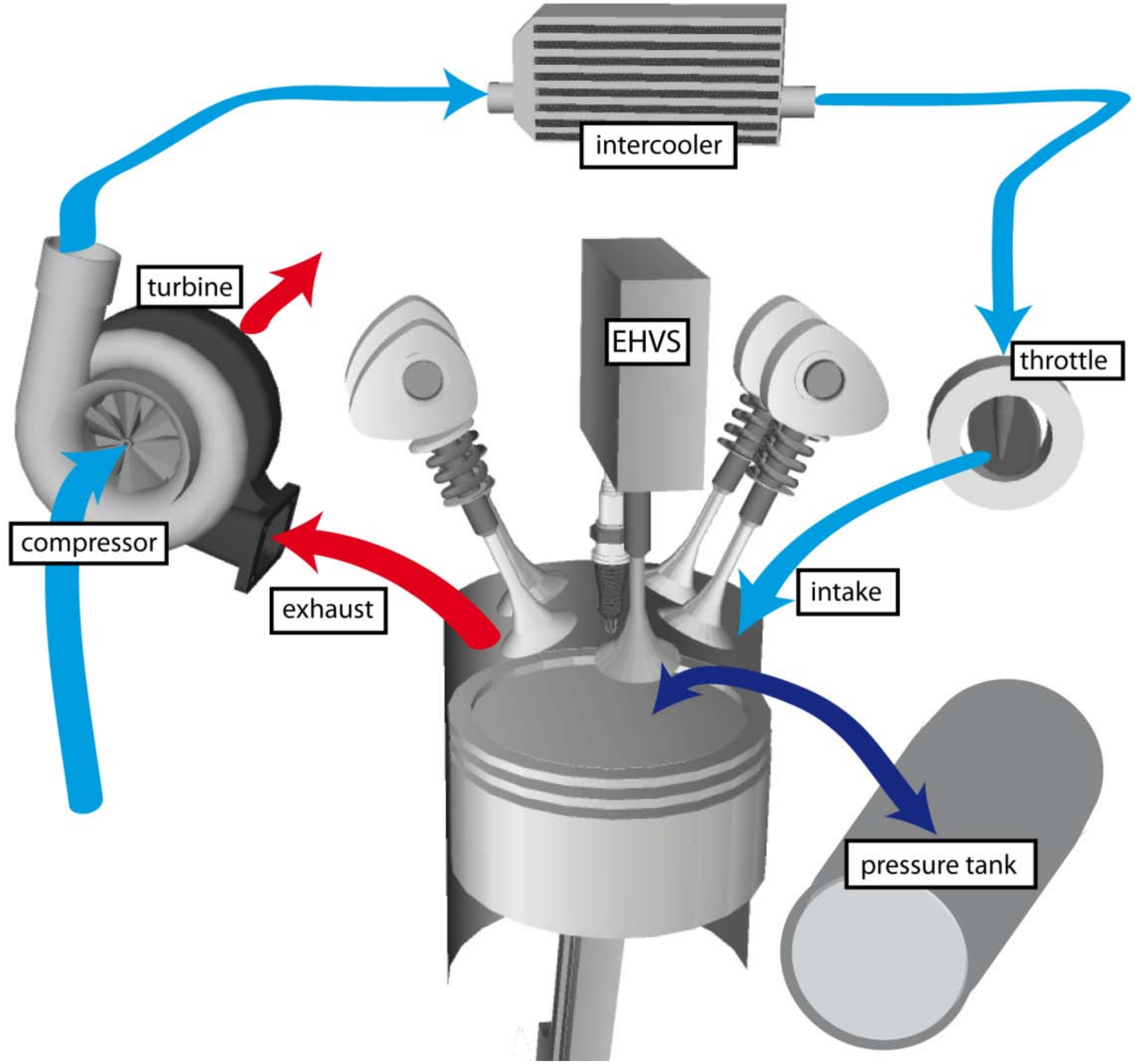
Concept (1): Valve Actuation Comparison



IV – Intake Valve
EV – Exhaust Valve
CV – Charge Valve
★ – ETH Modes

- 4-stroke concept is cheaper and less complex

Concept (2): The ETH DSC HPE Concept



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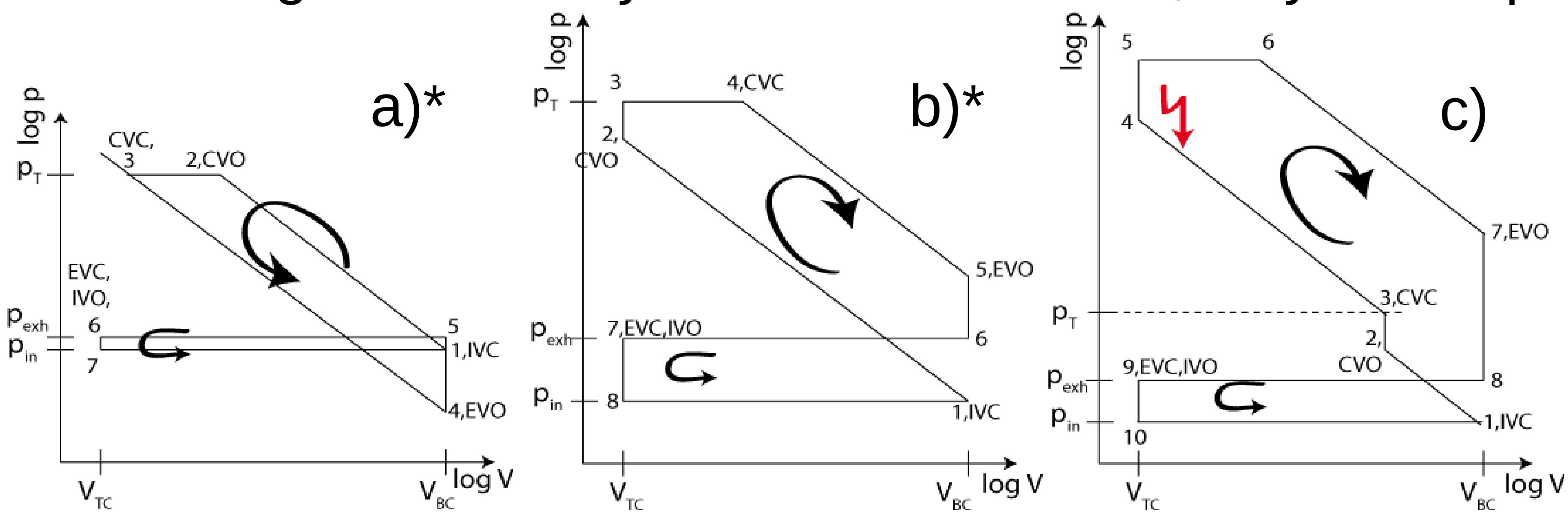
Concept (3): The Additional Engine Modes

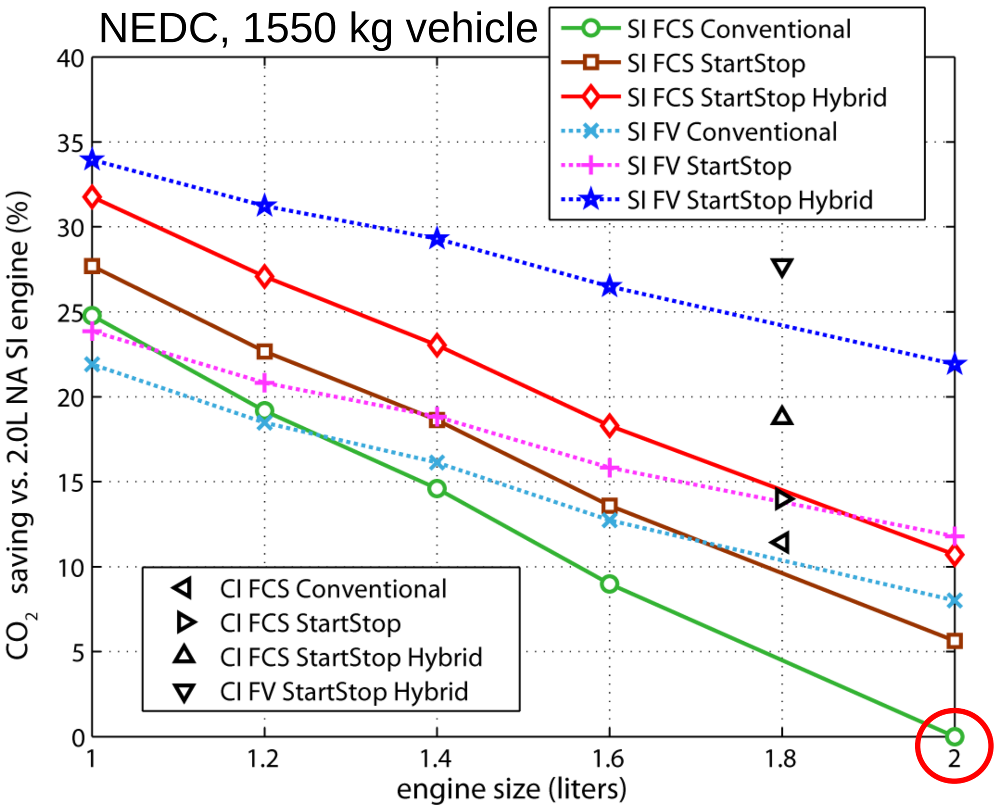
a) Pump mode*: throttle always open
b) Pneumatic motor mode*: uses throttle for higher torque
c) Supercharged mode: air injection at start of compression

- Recharge mode: 2 cylinders conventional, 2 cylinders pump



* Dönitz et al., “Modelling and optimizing two- and four-stroke hybrid pneumatic engines,” Proc.IMechE, Part D: J. Automobile Engineering, vol. 223, no. 2, pp. 255–280, 2009.

Simulations (1): Fuel Economy



FV – all valves fully variable
FCS – fixed camshaft for intake and exhaust valves
QSS – quasi-static simulation
DP – dynamic programming

- All engines with same rated power (100 kW), baseline (O) is 2.0 l NA SI engine.
- Most important effect: downsizing, hybridization is downsizing enabler
- 2-stroke modes: No significant advantage
- CI engines: cannot be downsized further
- Results obtained with QSS + DP

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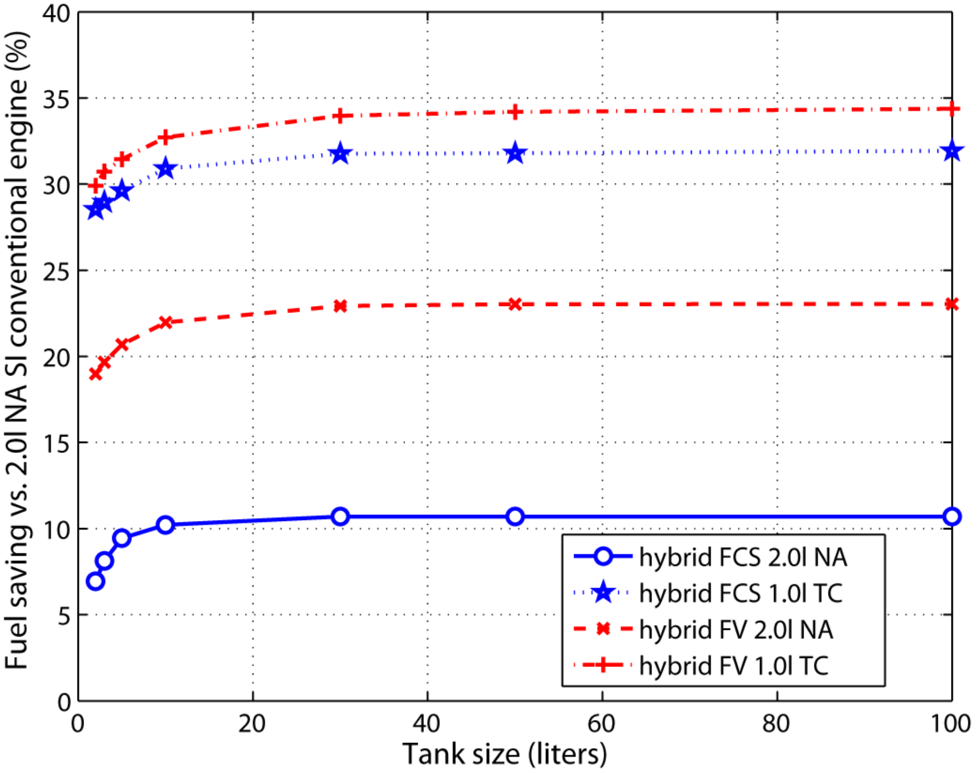
Simulations (2): Influence Tank Volume

- 20-liter tank is sufficient for a 1-liter engine
- Calculation based on optimal control strategy
- Can choose tank size according to number of subsequent pneumatic starts or supercharge-boosts



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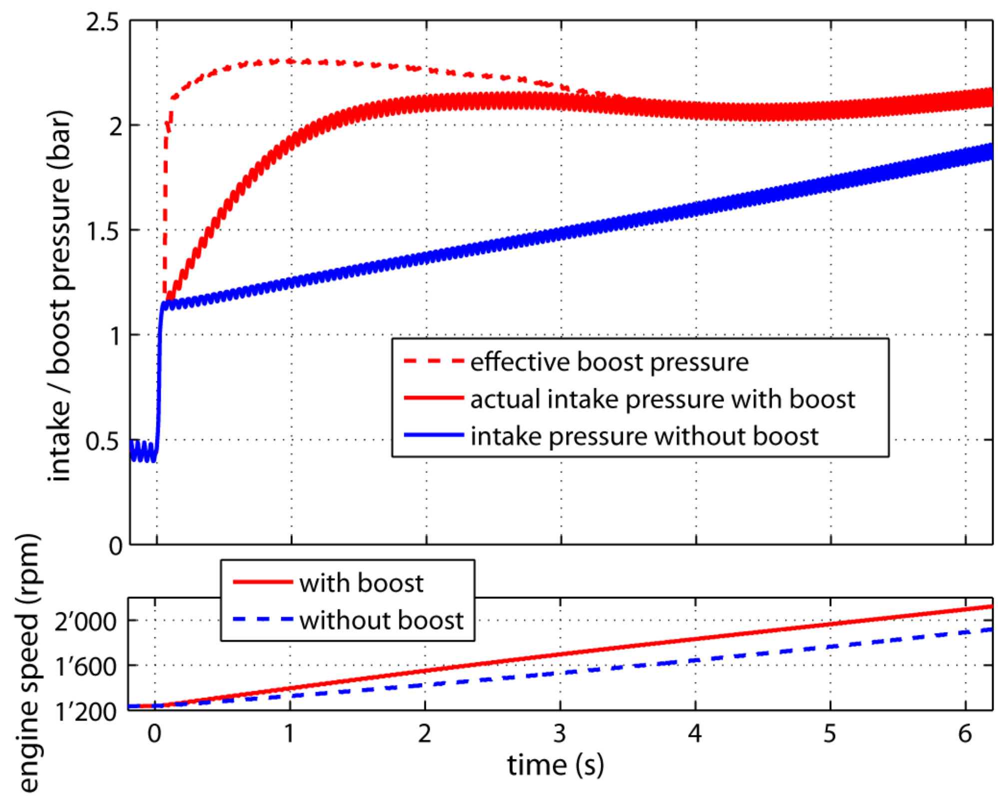
Simulations (3): Overcoming the Turbo-lag

- Engine “sees” effective intake pressure (---)
- Turbocharger accelerates rapidly
- Additional air only necessary for a short period.
- With full 30 liter tank, up to 30 boosts are possible (energy comes from fuel)

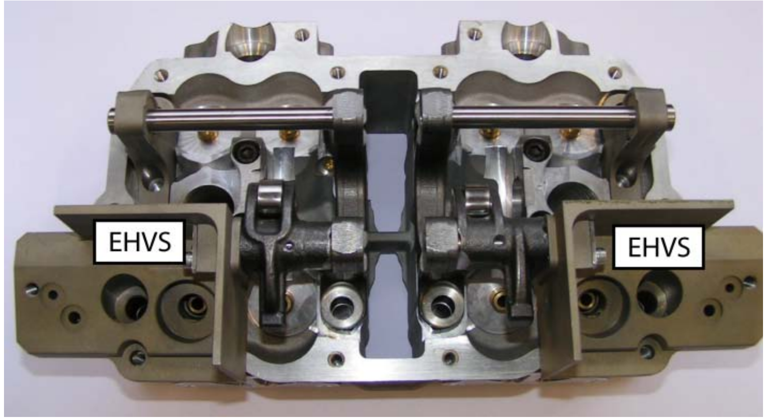


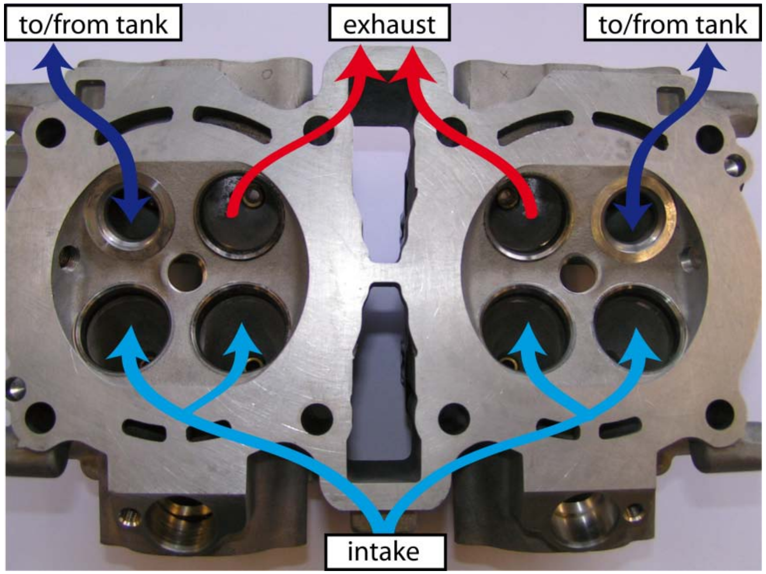
Simulation for 1500 kg vehicle in 4th gear with 0.75 liter engine

Hardware (1) : Modified Engine MPE750

original engine data	
manufacturer	Weber Automotive GmbH
displaced volume	0.75 liter
# cylinders	2, parallel twin 360°
compression ratio	9.0
fuel	gasoline port fuel injection
# valves	2 IV, 2 EV per cylinder
turbocharger	Garrett GT 12
rated power	61 kW

- 1 EV per cylinder replaced by charge valve actuated by the Bosch electro-hydraulic valve system (EHVS)





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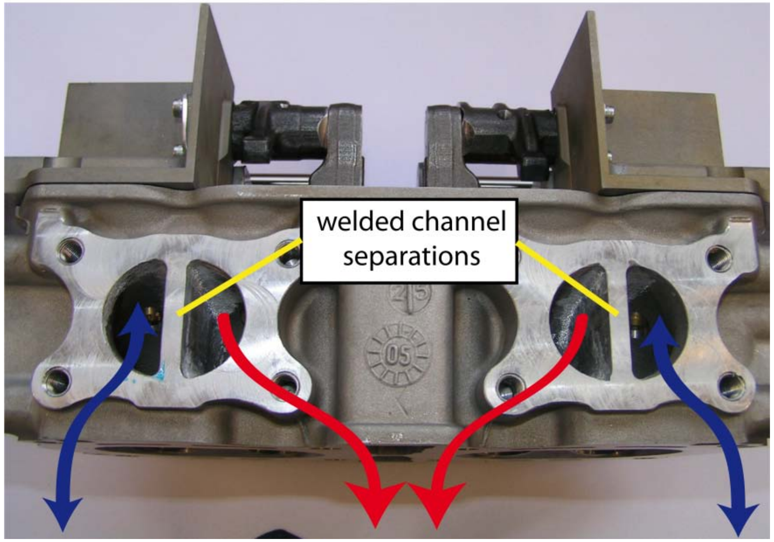

- Separation of exhaust and compressed air ducts
- Original engine design & modifications: Wenko AG

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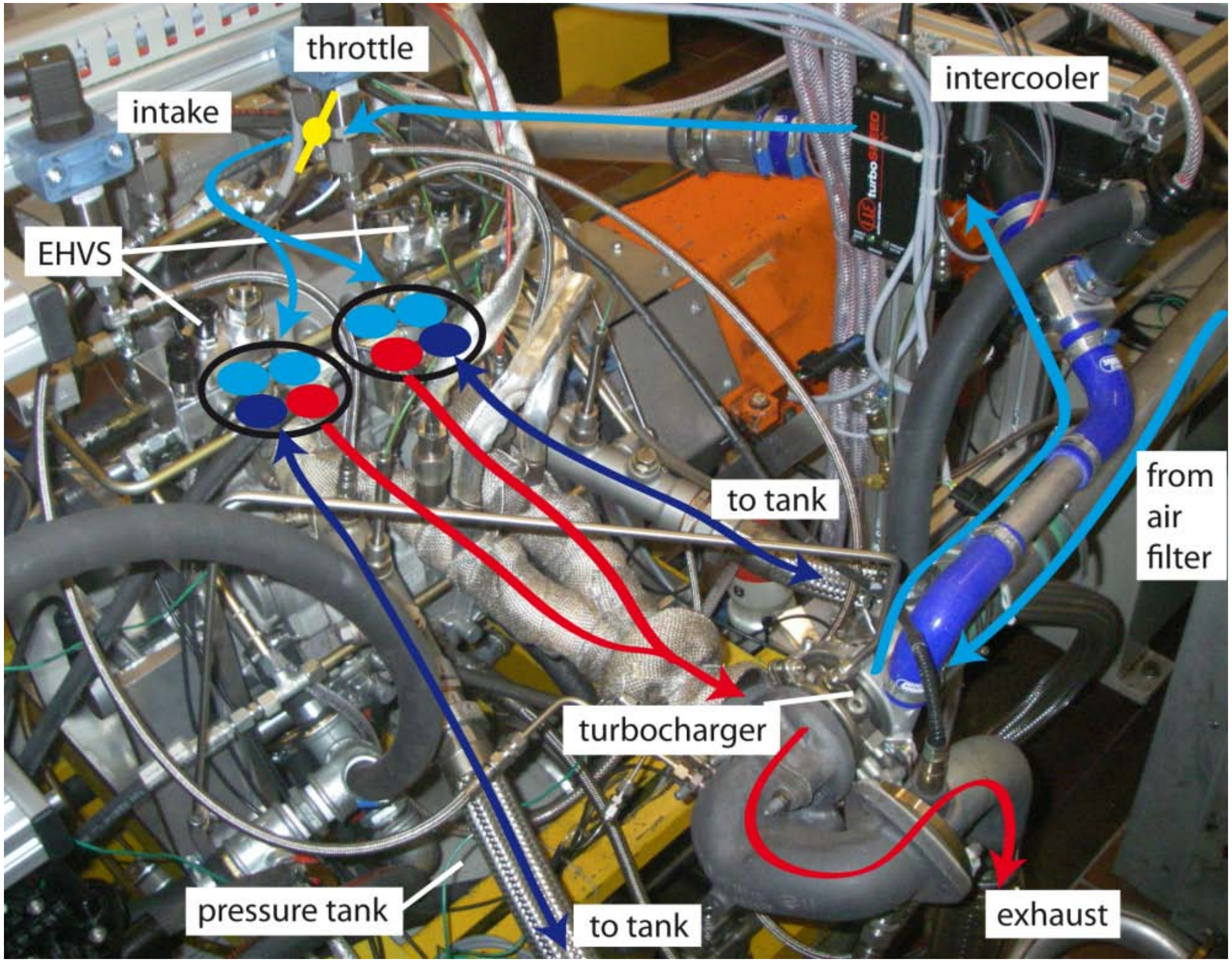
Hardware (3): Engine on testbench



- Air tank 30 liters, steel, not insulated for cold-tank strategy
- Engine equipped with GT12 compressor & GT14 turbine, variable wastegate actuator

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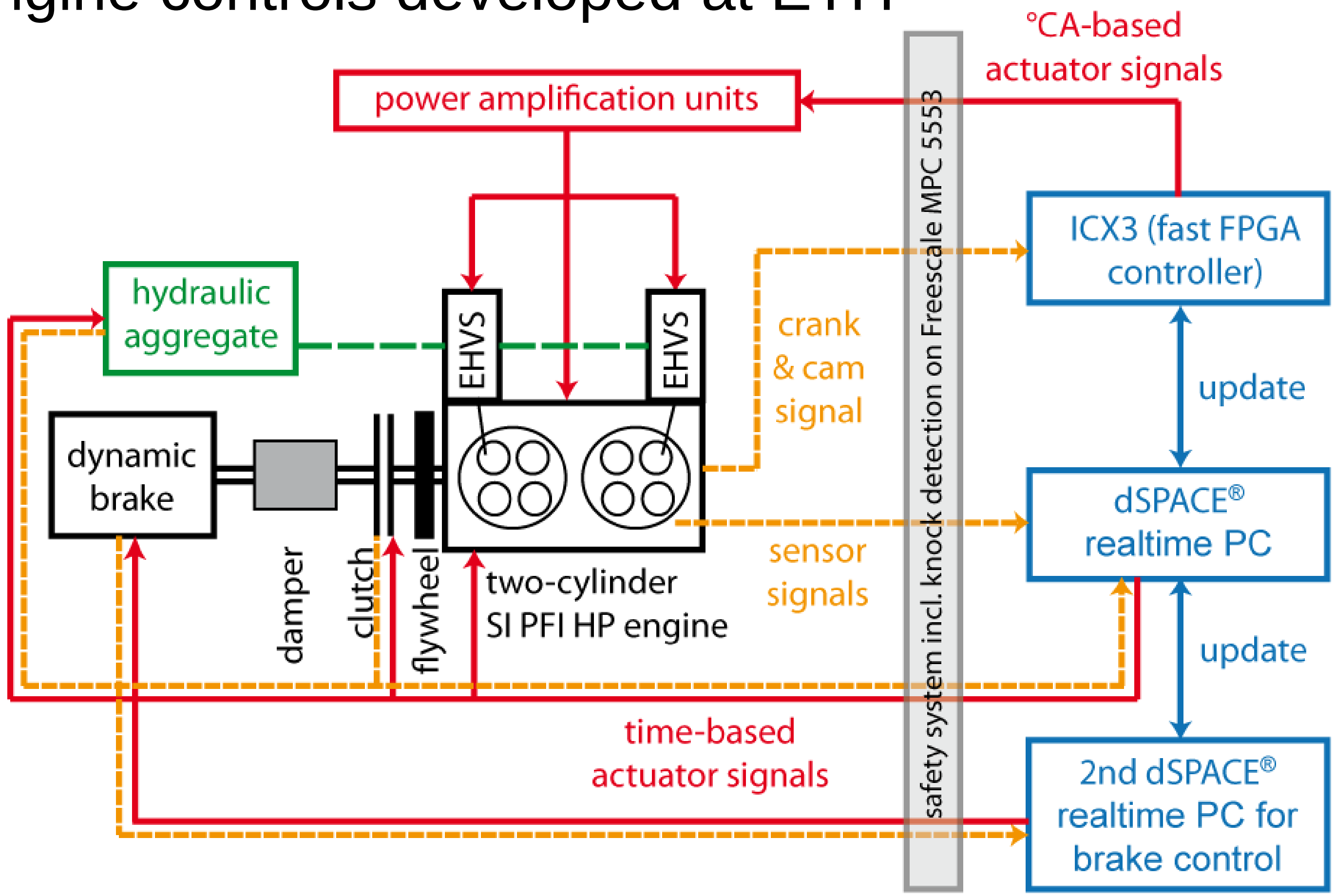
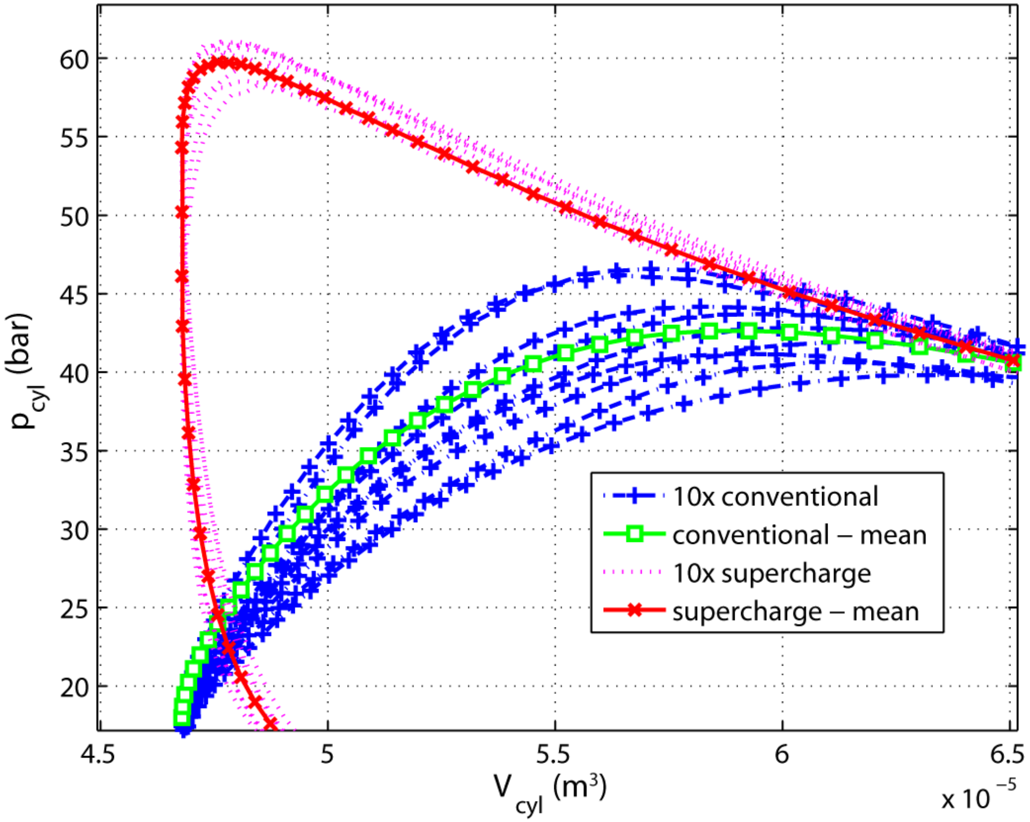
Hardware (4): Engine Control Systems

- All engine controls developed at ETH



Measurements (1): The Supercharged Mode

- Injected air provides high turbulence
- Results in stable and reproducible combustion
- **But**: Supercharged Mode only for transients!



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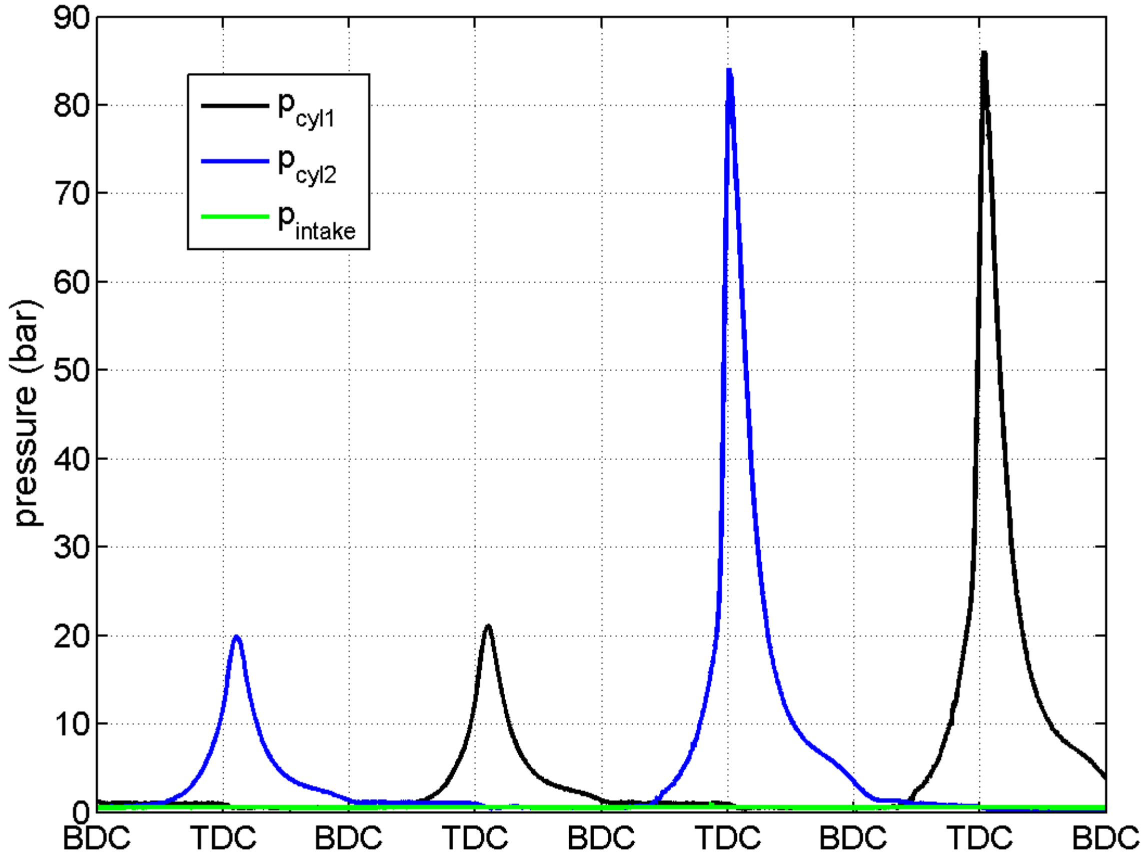
Measurements (2): The Supercharged Mode

- Instantaneous torque step
- Fastest dynamic response possible using air path
- Dynamics comparable with electric motor



Test at constant intake pressure (550 mbar)

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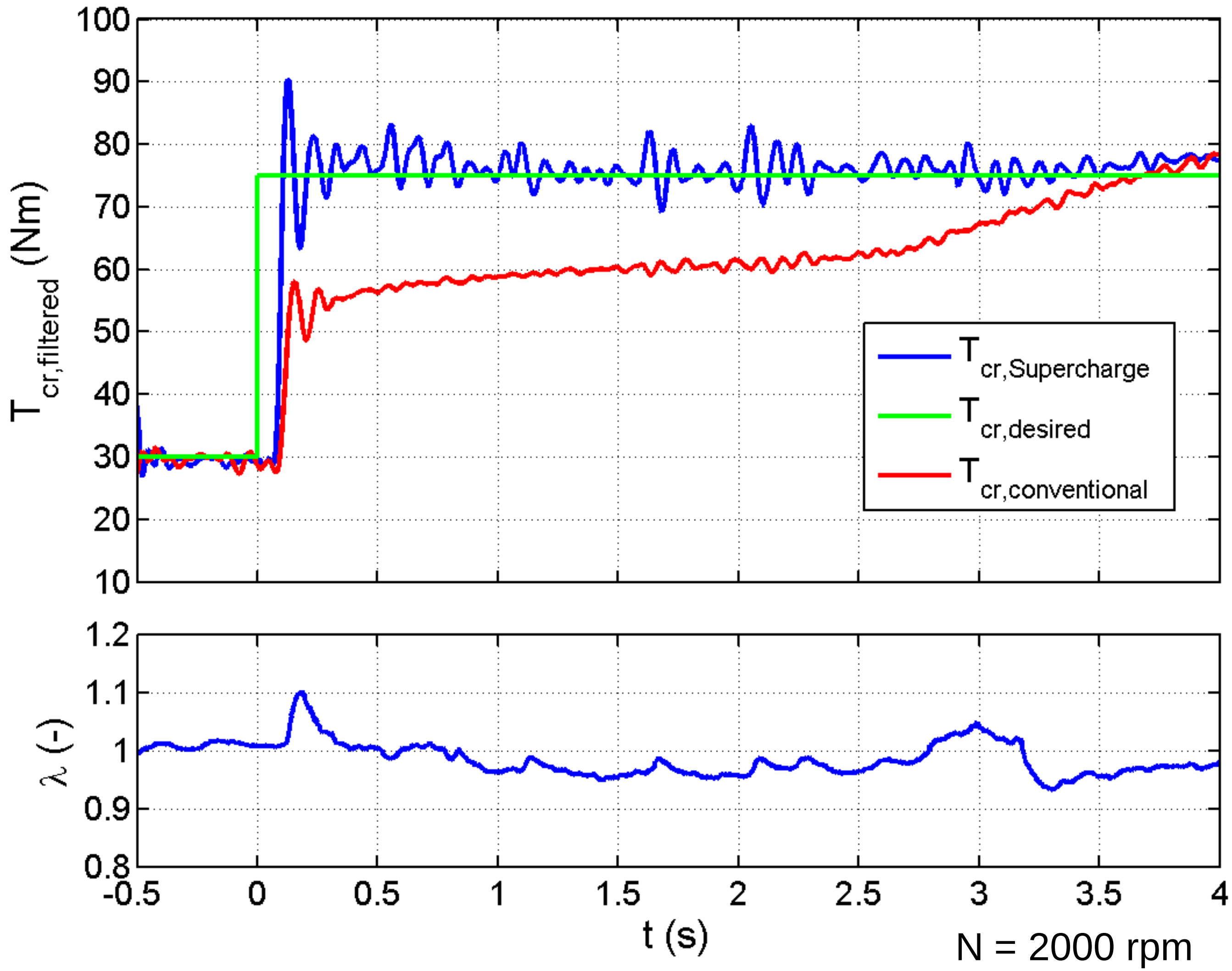
Measurement (3): Overcoming the Turbolag

- Good lambda trajectory for torque step
- Model based control:
  - Intake air path observer
  - EHVS air path observer
  - Torque model (Willans)
  - Fuel path model



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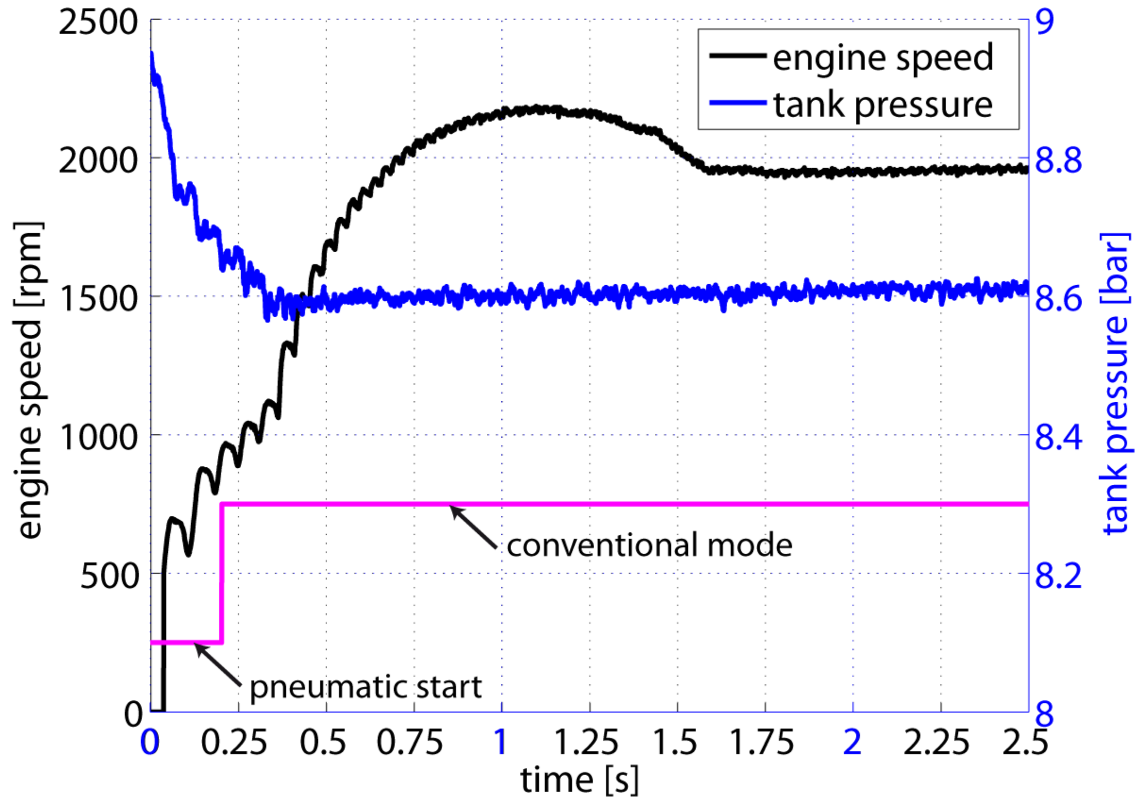
Measurements (4): Rapid Pneumatic Start

- Within 3-4 revolutions, idling speed is reached
- A pneumatic start consumes ~350 mbar of air when using a 30 liter tank
- 25 subsequent starts possible without recharging (15 -> 6 bar)



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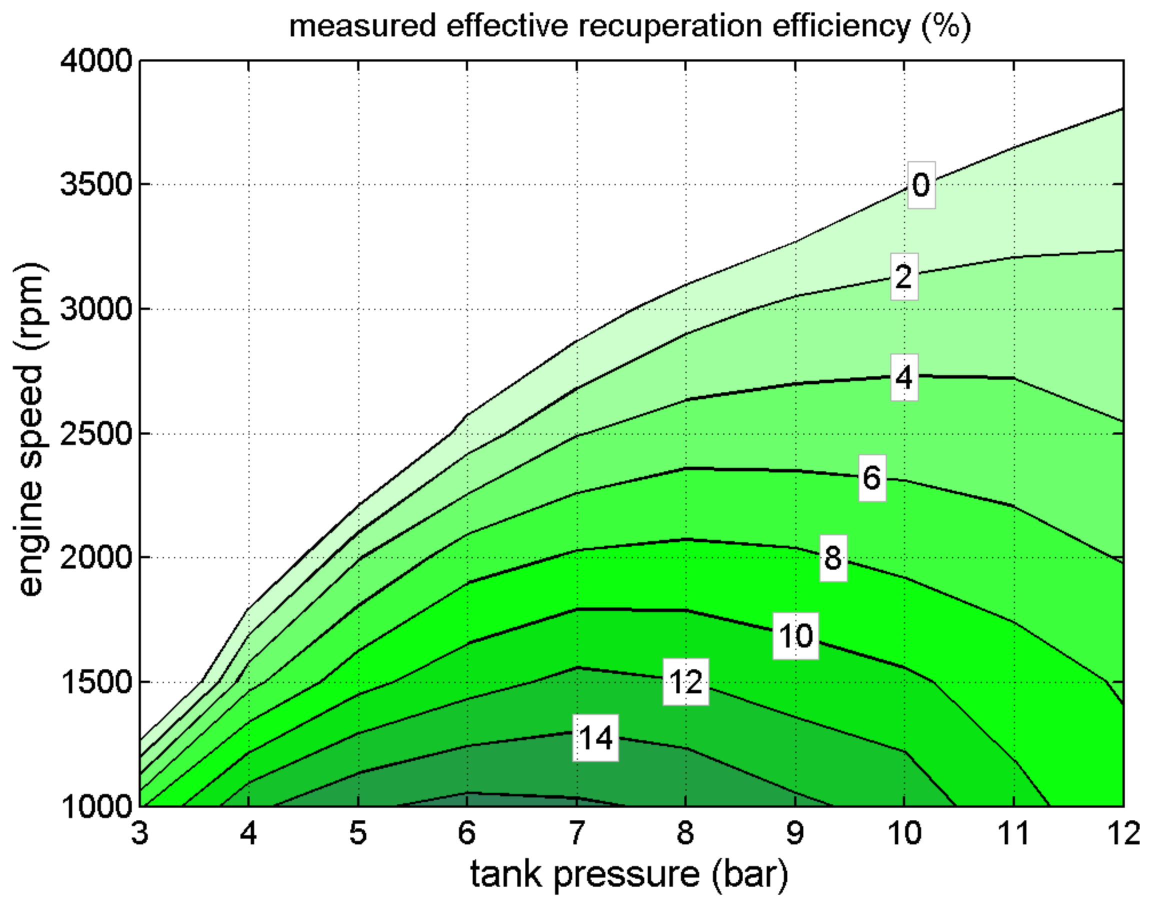
Measurements (4): Recuperation Efficiency

- Recuperation is not the main idea, but downsizing
- Recuperated air mainly used for boosting & rapid pneumatic start
- Pneumatic modes optimized for air mass (cold tank)



For every data point (N, p_{tank}):

$$\max\left(\frac{T_{eff}}{\Delta m_{air}}\right)_{p.mot} \cdot \max\left(\frac{\Delta m_{air}}{T_{eff}}\right)_{pump}$$

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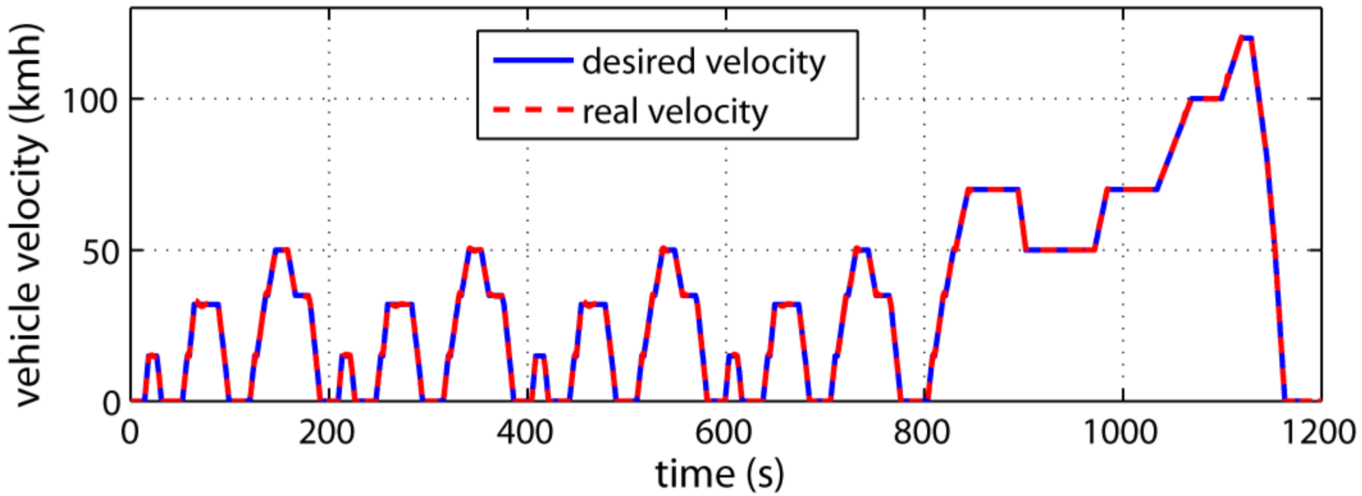
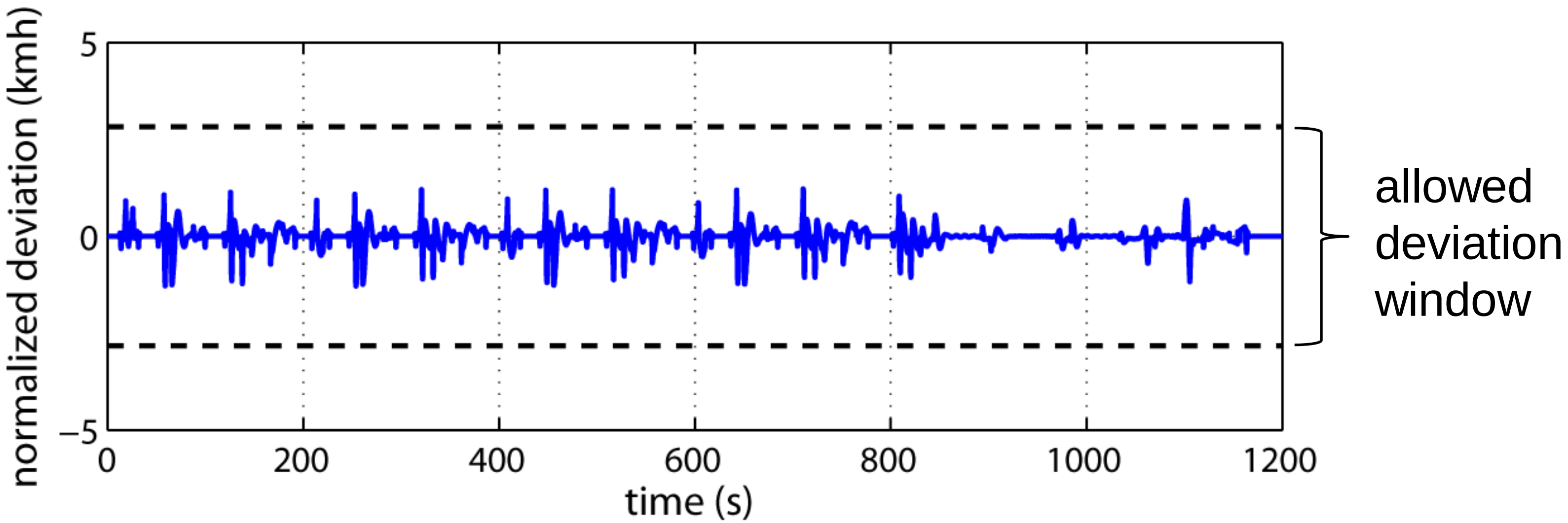
Remark: Recuperation Using Alternator

- Recuperation: pumping is limited (4 - stroke)
- NEDC: **~500 kJ** cannot be recuperated by pumping air
- Excess energy not recuperated using pumping in braking phases can be used for:
  - EHVS actuation: **104 kJ** needed to drive NEDC (assuming 60% efficiency for the alternator & 60% efficiency for an electric hydraulic pump)
  - Electric auxiliaries: Using 300 W at the crankshaft for 1200 s, **360 kJ** are needed for the drive cycle

→ Fuel consumption can be further reduced

Experiment: VW Polo, NEDC





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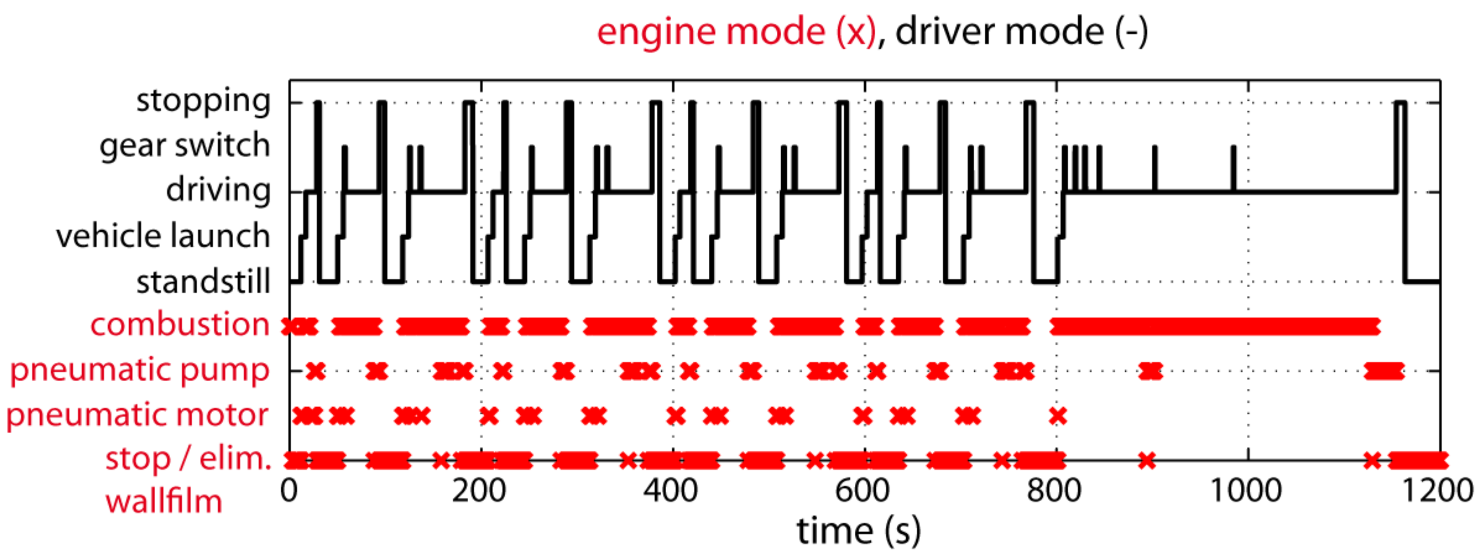
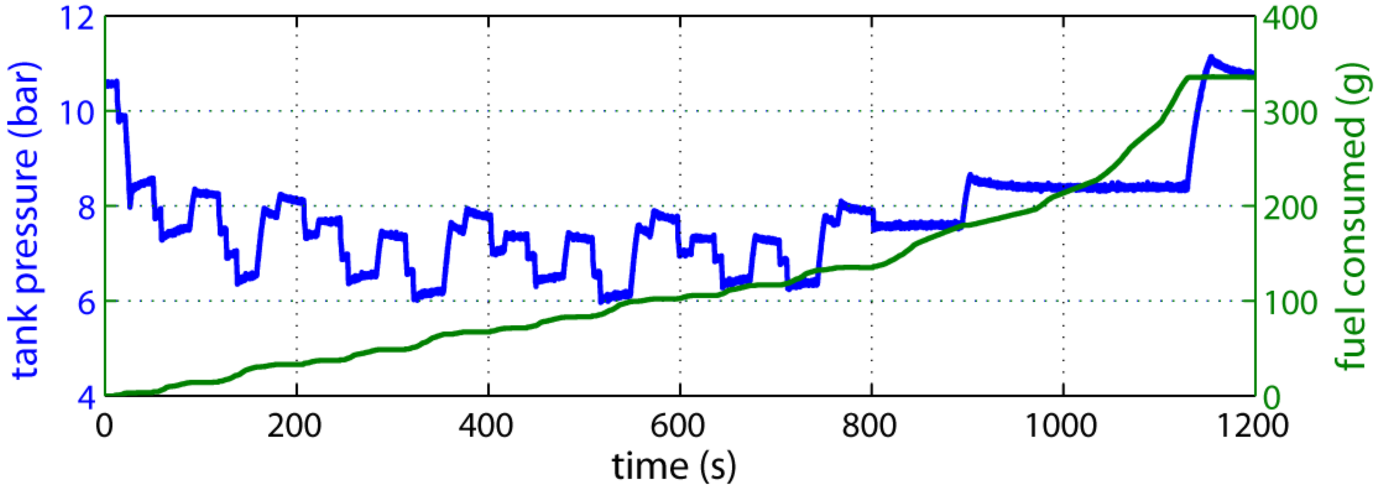
Engine Mode Determined Using DP



- Charge sustenance guaranteed by DP



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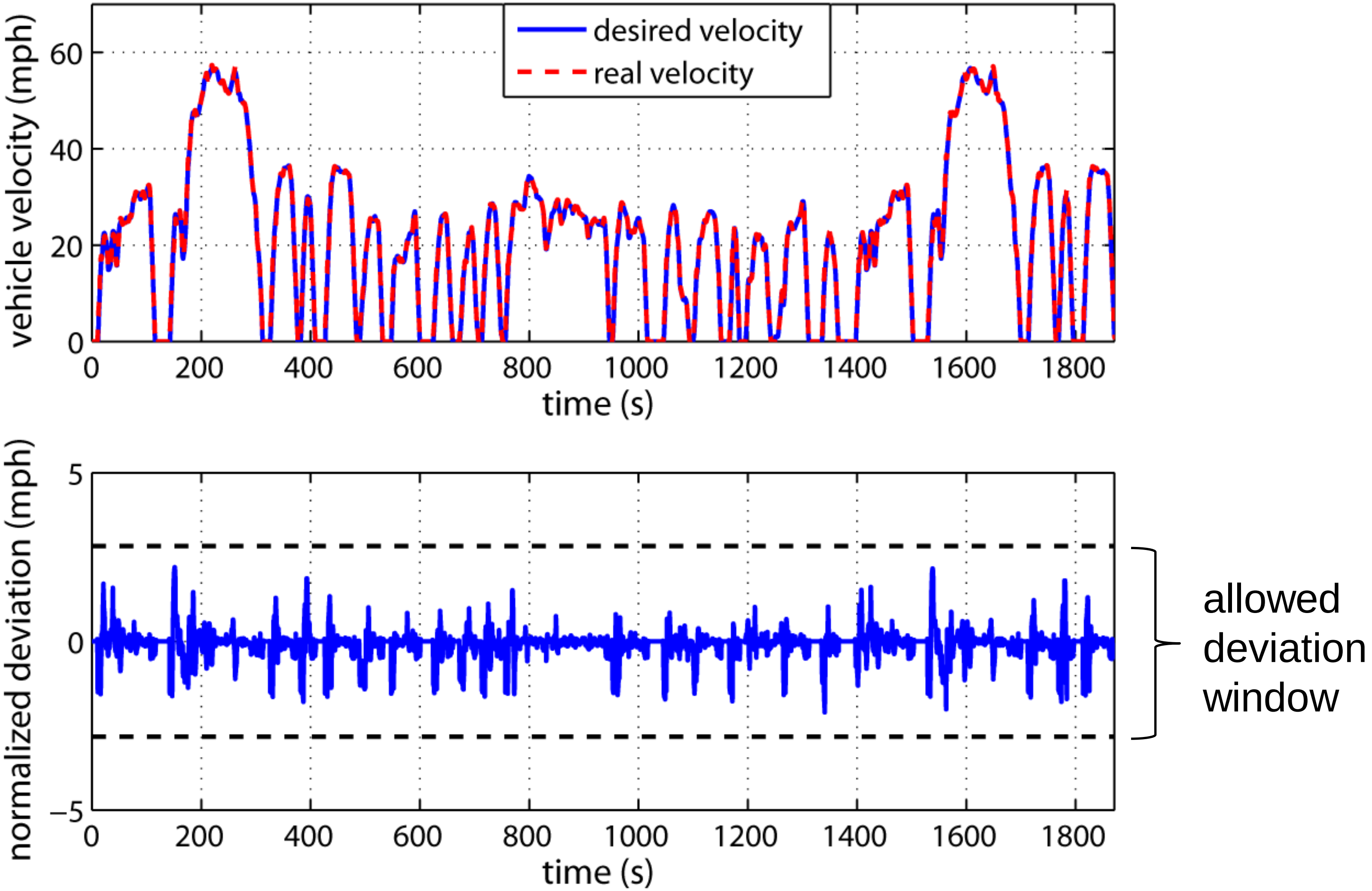
Experiment: Nissan Micra, FTP



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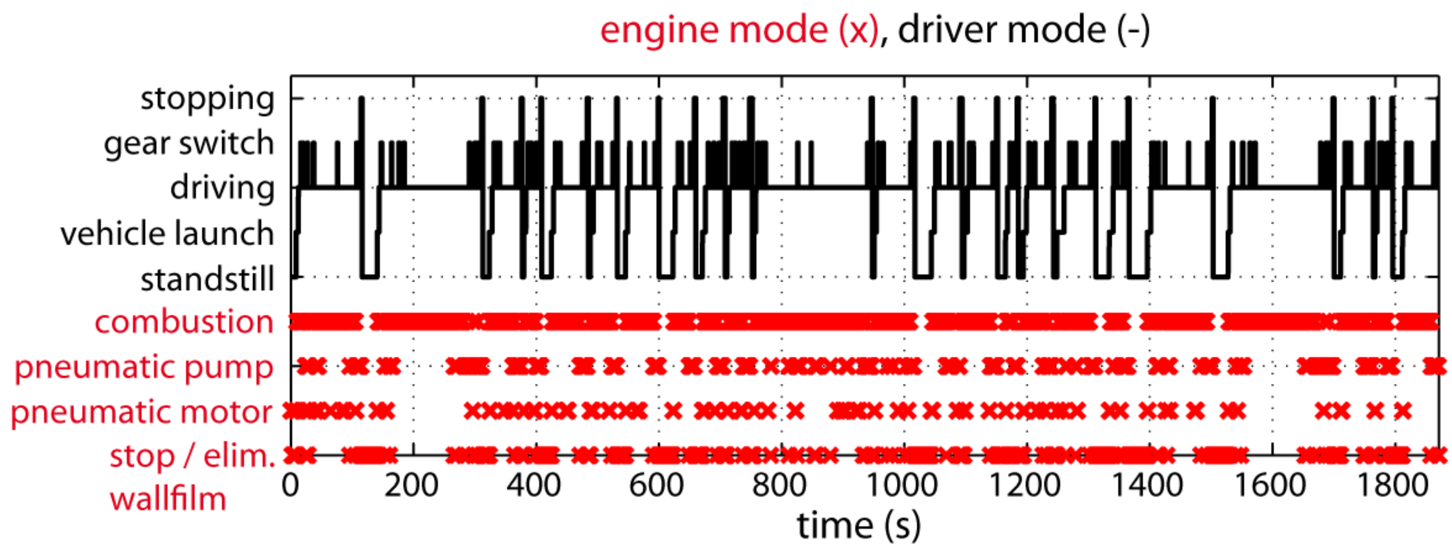

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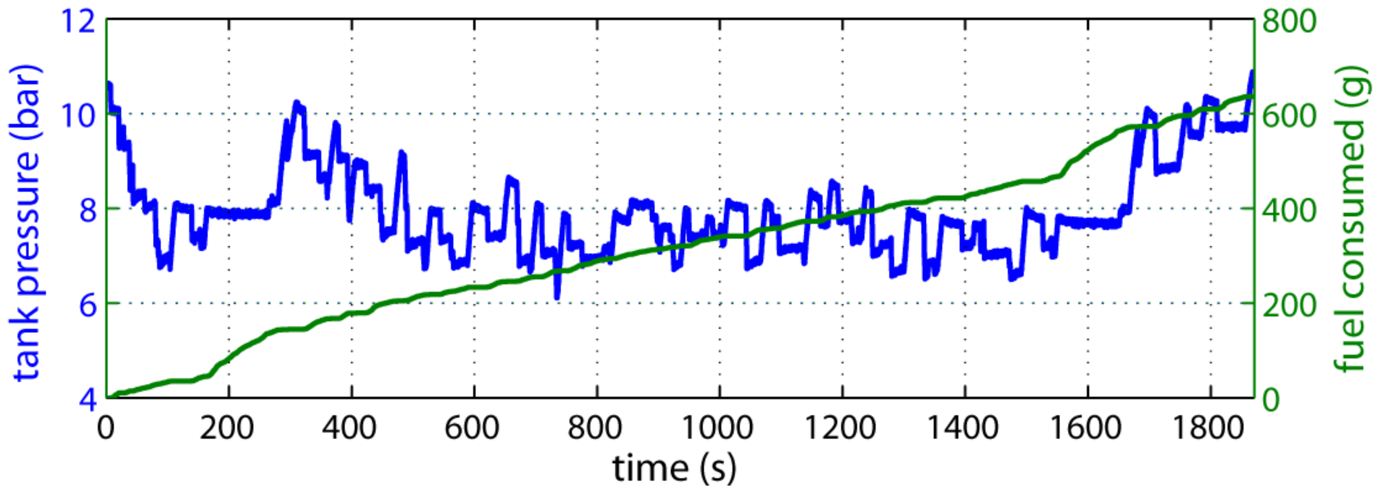

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Result Table, NEDC

Vehicle	VW Polo (2005)	VW Polo (2009)	Nissan Micra	Nissan Micra	Toyota Prius II
Engine V_d	1390 ccm	1390 ccm	1240 ccm	1386 ccm	1497 ccm
Rated power	59 kW	63 kW	59 kW	65 kW	57 kW
Weight	1088 kg	1070 kg	1065 kg	1075 kg	1400 kg**
Cost (CHF)	19’770	22’600	16’897	20’090	38’950
ECE / EUDC / NEDC (l/100km)	8.3 / 5.2 / **6.3**	8.0 / 4.7 / **5.9**	7.4 / 5.1 / **5.9**	7.9 / 5.4 / **6.3**	5.0 / 4.2 / **4.3**

Vehicles Above Emulated With Hybrid Pneumatic MPE750 (61kW), 30l Air Tank					
ECE / EUDC / NEDC (l/100 km)	4.2 / 4.0 / **4.1**	(4.2 / 3.9 / **4.0**)*	4.3 / 4.6 / **4.4**	4.2 / 4.5 / **4.4**	(4.5 / 4.4 / **4.5)****
Fuel savings	- 49.4 % / - 23.2 % / **- 35.4 %**	(- 47.2 % / - 17.5 % / **- 31.9 %**)*	- 42.6 % / - 10.5 % / **- 24.6 %**	- 46.3 % / - 16.2 % / **- 29.8 %**	(- 9.1 % / + 5.0 % / **+ 3.7 %)****
Δ rated power	+ 3.4 %	- 3.2 %	+ 3.4 %	- 6.2 %	+ 7.0 %**

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Result for FTP, Nissan Micra

Vehicle	Nissan Micra (visia)
Engine V_d	1240 ccm
Rated Power	59 kW
Weight	1065 kg
Cost (CHF)	16’897
FTP part 1 / 2 / 3 / comb.	6.2 / 6.5 / 5.6 / **6.1** (l/100km)

Vehicle Emulated With Hybrid Pneumatic MPE750 (61kW), 30l Air Tank	
FTP part 1 / 2 / 3 / comb.	4.8 / 4.4 / 4.6 / **4.6** (l/100km)
Fuel Savings	- 22.4 % / - 32.7 % / - 17.9 % / **- 24.9 %**

Data sources: Touring Club Switzerland
www.tcs.ch, EMPA Switzerland, OEM webpages

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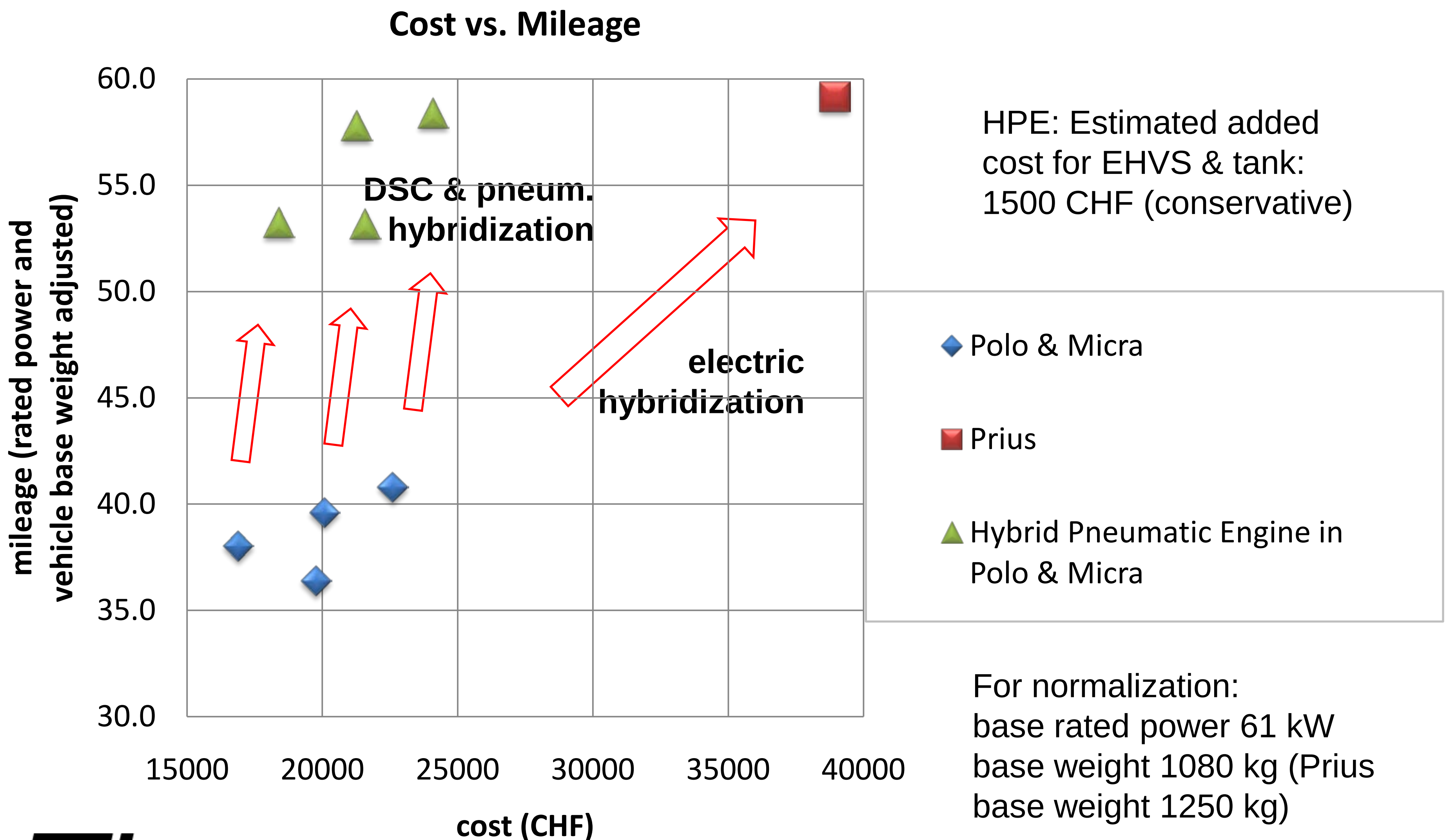
Electric Hybridization vs. DSC HPE Concept



HPE: Estimated added cost for EHVS & tank: 1500 CHF (conservative)

For normalization:
base rated power 61 kW
base weight 1080 kg (Prius base weight 1250 kg)

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Thank you for your attention!

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