


TNO innovation for life

generic simulation of a retrofit SCR

basic parameters and efficiencies

Norbert E. Ligterink

WHTC x Engine x SCR = exhaust emission

- Engine characterisation
  - generic Euro-III engine, simple fits based on IUC-programme data
- SCR characterisation
  - 3 parameter model (temperatures and efficiency)
- WHTC test
  - without torque curve
  - second-by-second: fractional speed and fractional torque
- Simulation
  - tracking: temperature, power, and accumulated NOx
  - initial temperatures of engine and SCR (cold start and hot soak)

Parameters for generic SCR simulation:

- engine characterisation
  - engine efficiency:
    - internal combustion efficiency (η_{engine} [g CO2]/[kWh])
    - speed-dependent engine loss (τ_{loss} x n_{rated} = 4% P_{rated} → idle FC)
  - engine out specific emission [NOx/CO2] (for idle a separate value)
  - engine out temperature (T_{idle}, $T_{full\ load}$)
  - engine heat capacity (heat-up time τ_{engine}(P) *e.g. 3 min at half load*)
  - engine out mass flow (load-dependent lambda: λ_{idle} , $\lambda_{full\ load}$)
- SCR characterisation:
  - SCR heat capacity (heat-up time τ_{SCR} (P) *e.g. 5 min at half load*)
  - SCR light-off temperature (T_{min} ~ 180 ^{o}C)
  - SCR maximal efficiency ($\eta_{SCR} = 80\% - 95\%$, if T > T_{op})
  - SCR operational temperature (T_{op} ~ 220 ^{o}C)

Engine out NOx

specific NOx = power-based engine map

x engine loss factor and torque (τ)

x combustion energy

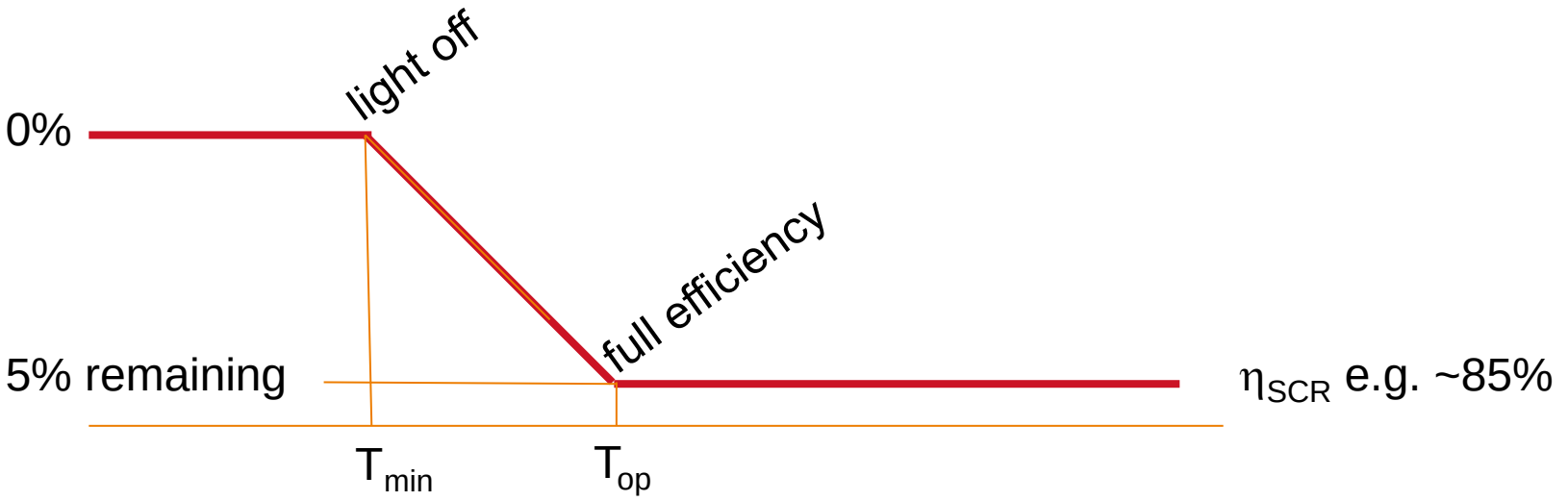
x speed (n [RPM])

/combustion efficiency

$$NOx\left[\frac{g}{s}\right] = \frac{2\pi}{60}\left[\frac{NOx}{CO2}\right] \times (\tau + \tau_{loss}) \times \left[\frac{gCO2}{Work}\right] \times \frac{n}{\eta_{engine}}$$

SCR characterisation

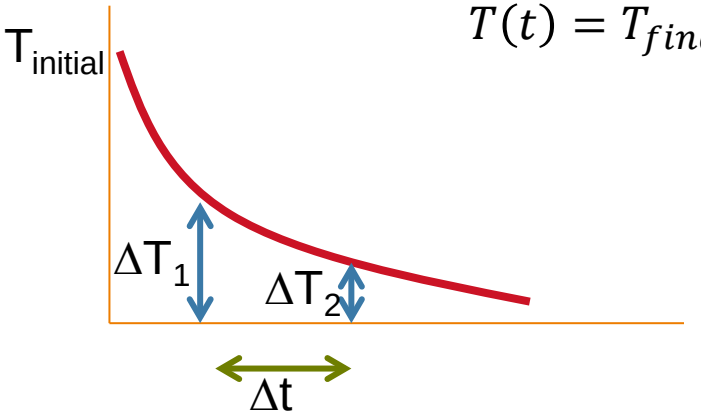
- linear profile approximation
- no space-velocity effect assumed
- maximal efficiency depends on control loop, clean-up catalyst, etc.



heat capacity: build up and retention of temperature

- Heat capacity engine and SCR at stationary engine operation

heat capacity = heat capacity gas
x mass flow gas
/ temperature change

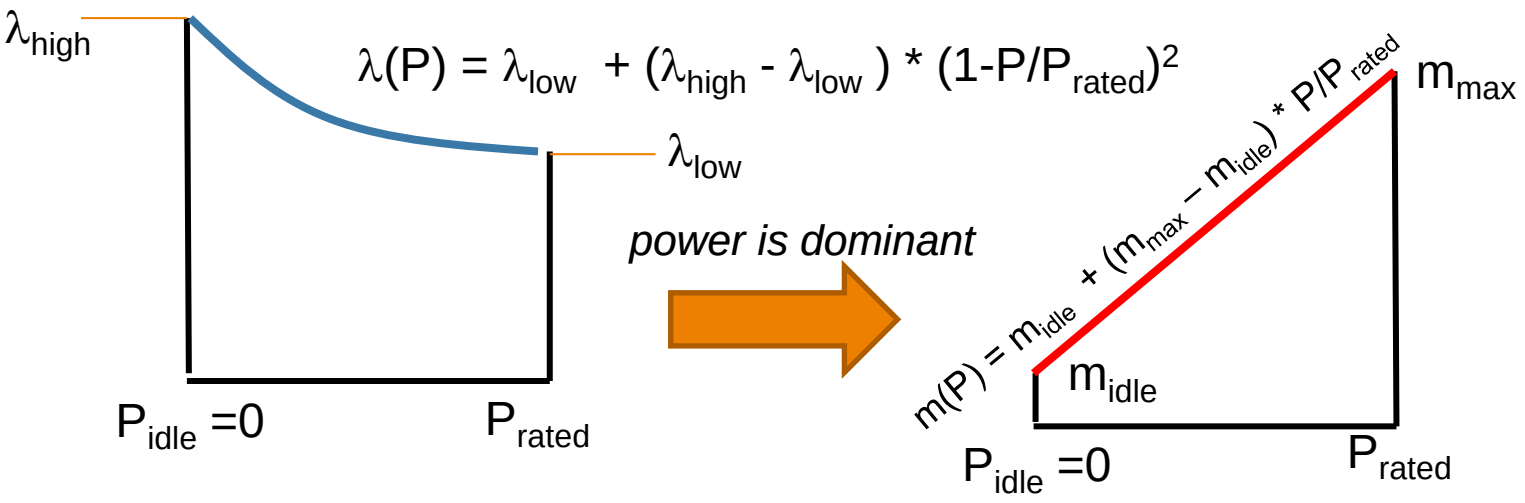


$$T(t) = T_{final} + (T_{initial} - T_{final}) \times e^{-Ct}$$

$$C = \frac{gas\ heat\ capacity\ flow}{component\ heat\ capacity}$$

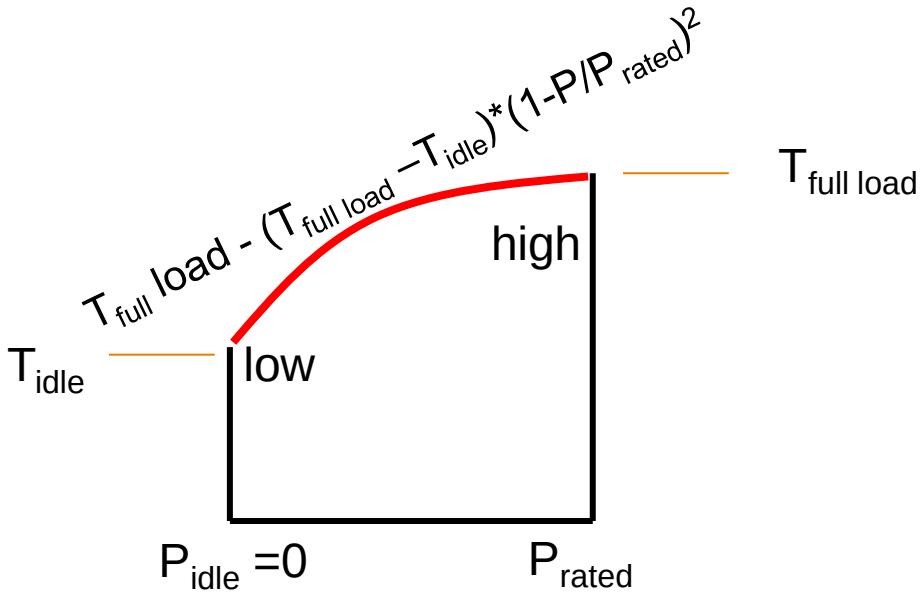
Engine mass flow

- mass flow = CO_2 * (stoch. combustion products + (1-λ) x air)



Engine out temperature

- limited speed variation: higher λ at lower power, turbo at higher

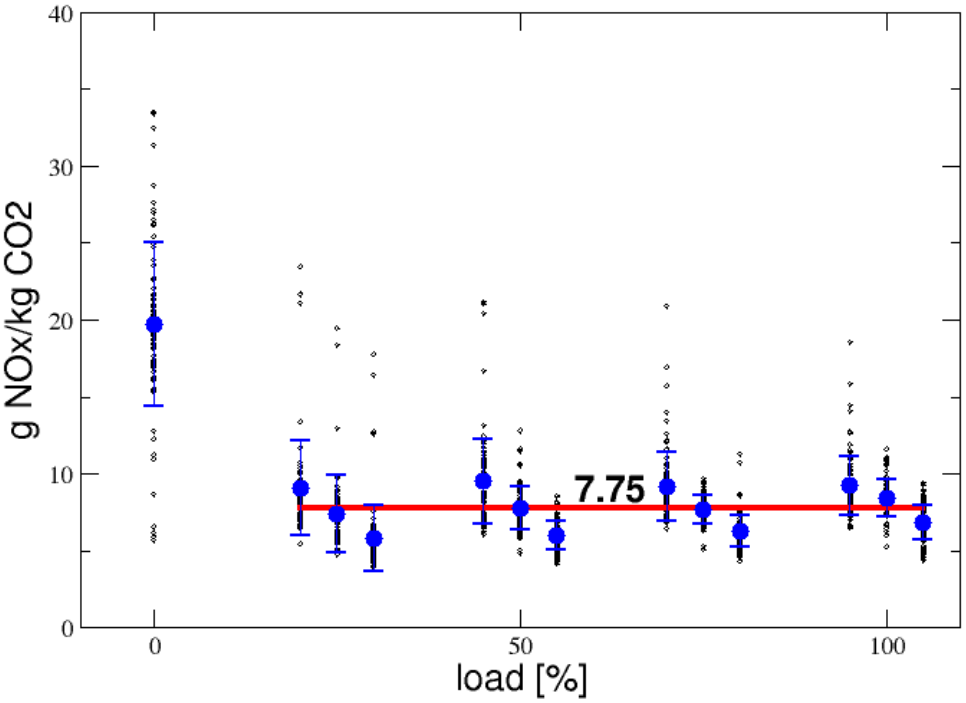


Data Euro-III from In-Use Compliance programme

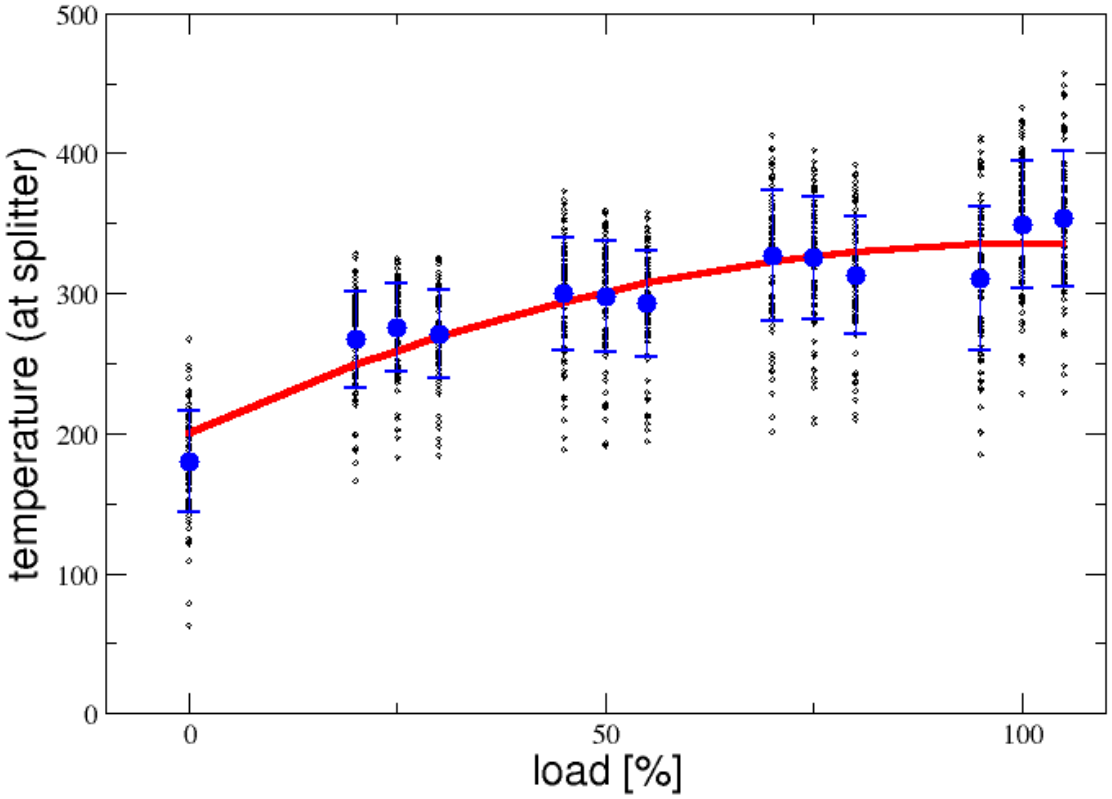
- 16 engine type tested
  - 3 vehicles per engine type
  - 7 common OEM's
  - typical 2 tests per vehicle
  - total 83 tests, 1079 stationary points analysed
- chassis-dynamometer testing
- compensation for power-train losses
- 13 mode testing (conform Euro-III)
- normalized by scaling with P_{rated} for highest speed (C-line)

Specific NOx emission, based on 13-mode (A-B-C)

16 Euro-III engines types, 3 engines per type

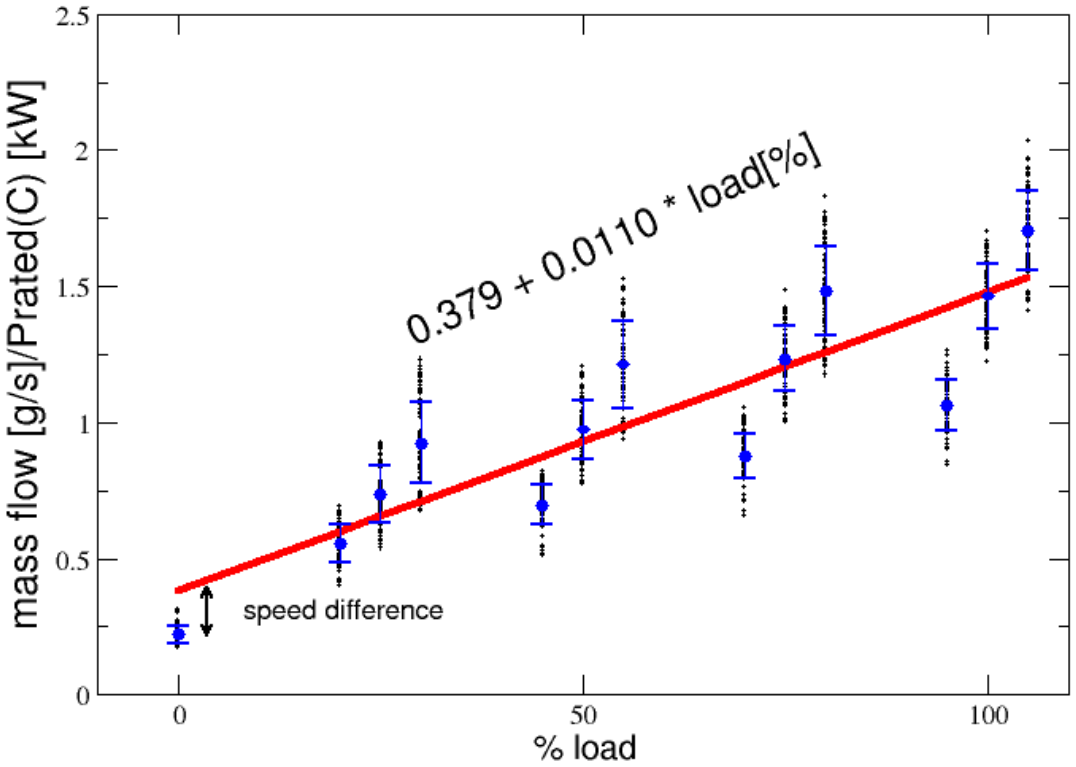


Exhaust gas temperatures (13 Mode, A-B-C)

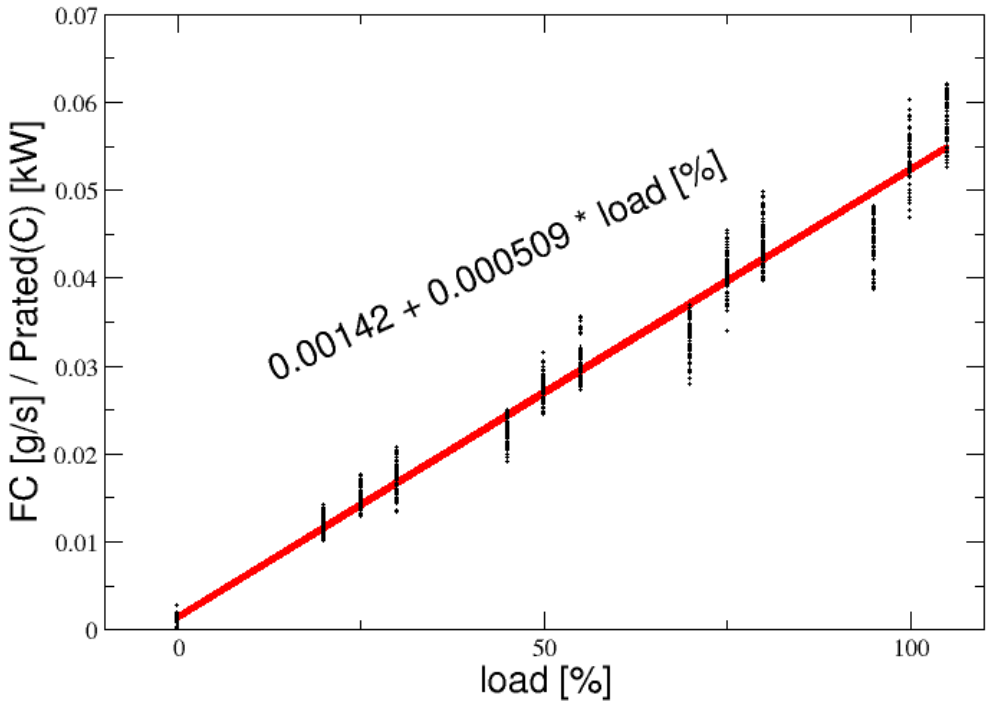


Mass flow

13-mode: A-B-C speeds



Fuel consumption *(steeper than mass flow line)*
13 mode A-B-C

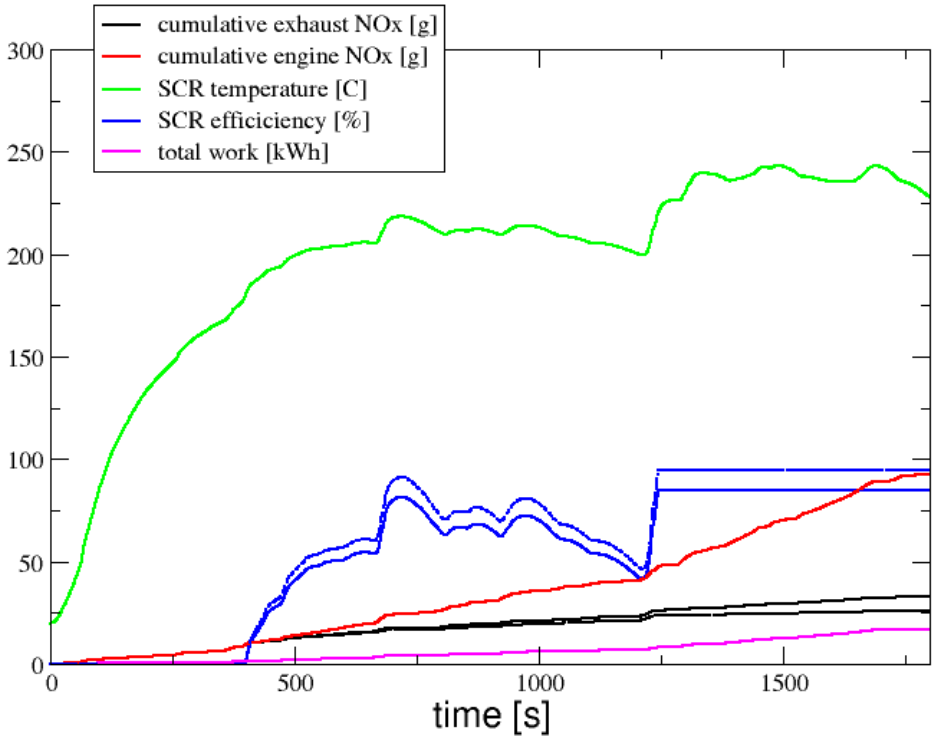


*CO2 = 3.15*FC*

Simulation results

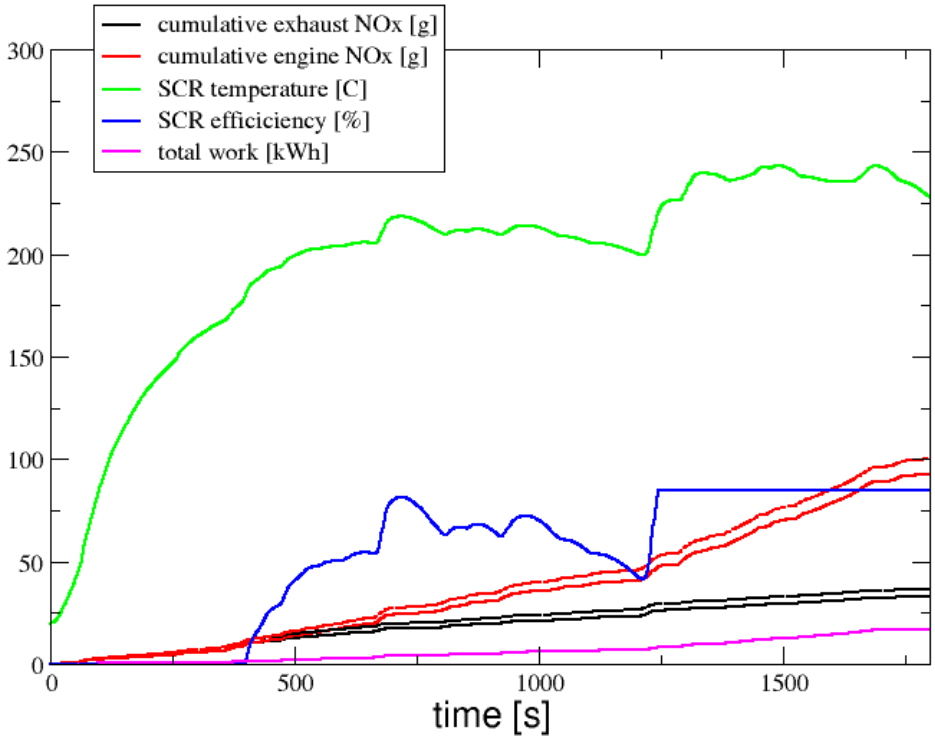
- base values:
  - engine heat-up at half load: 200 sec
  - SCR heat-up at half load: 30 sec
  - $T_{min} = 180^{o}$, $T_{op} = 220^{o}$, $\eta_{scr} = 85\%$
  - loss = 3%* P_{rated} (at operational speeds)
  - $loss_{idle}$ = loss*(600/1300)
  - idle specific NOx: $NOx_{idle} = 2.45 * NOx_{load}$
  - idle mass flow = 0.2 * rated mass flow
- WHTC test *(no torque curve given)*
  - P = %load * %speed * $P_{rated}(C)$

SCR optimal efficiency: 85% → 95%



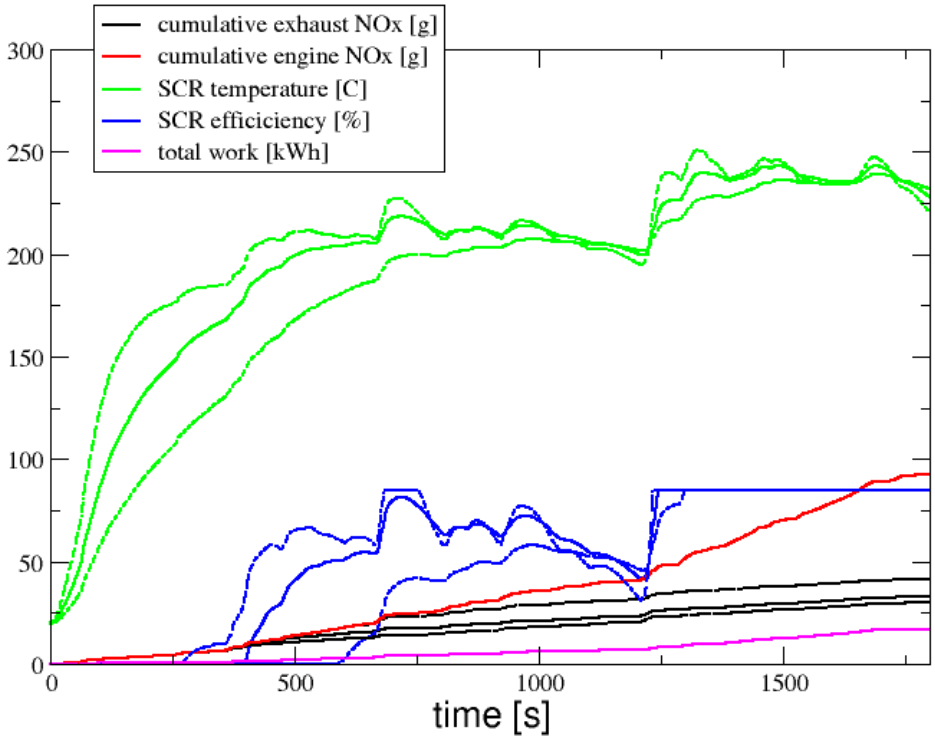
engine loss 3% → 4%

given the specific NOx a higher emission, but same reduction

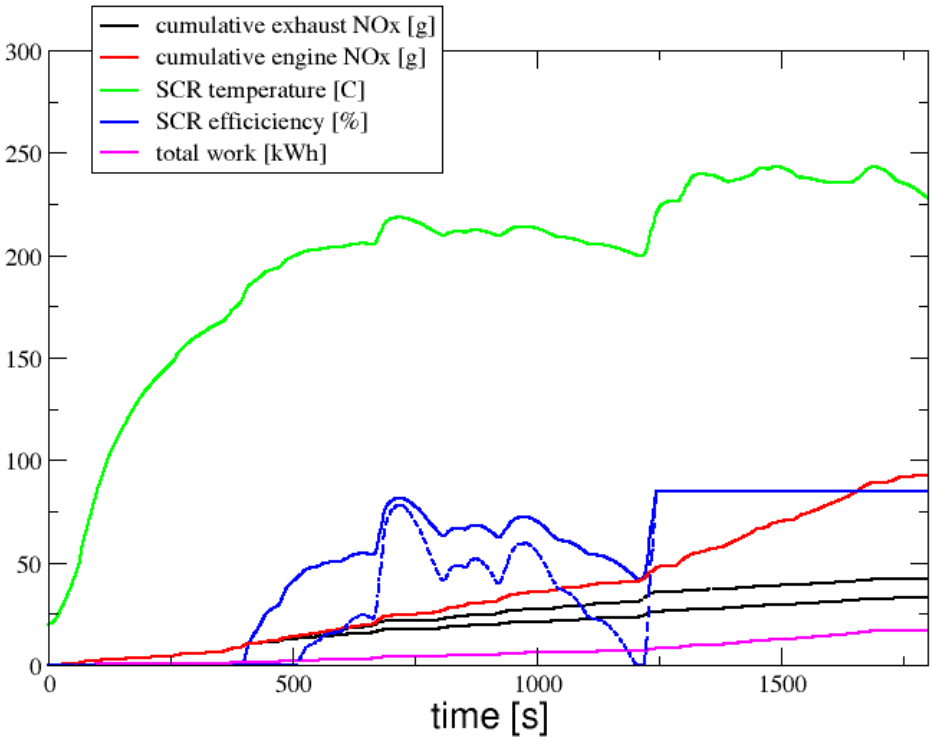


engine heat up time

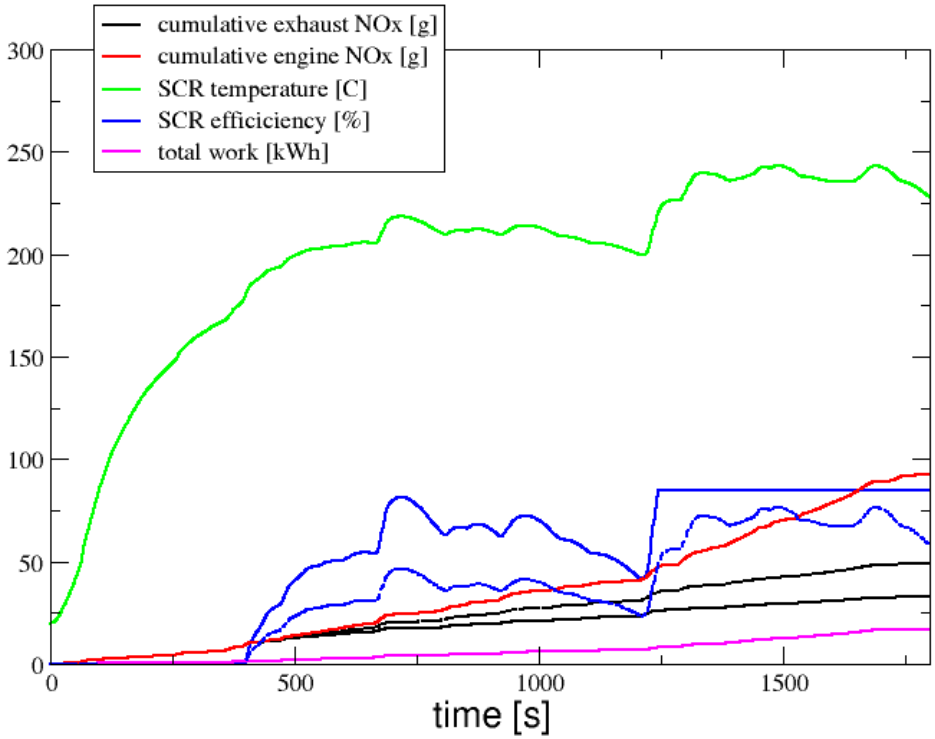
half load: 100 sec, 200 sec, 400 sec



SCR light off T_{min}: 180^o C→ 200^o C

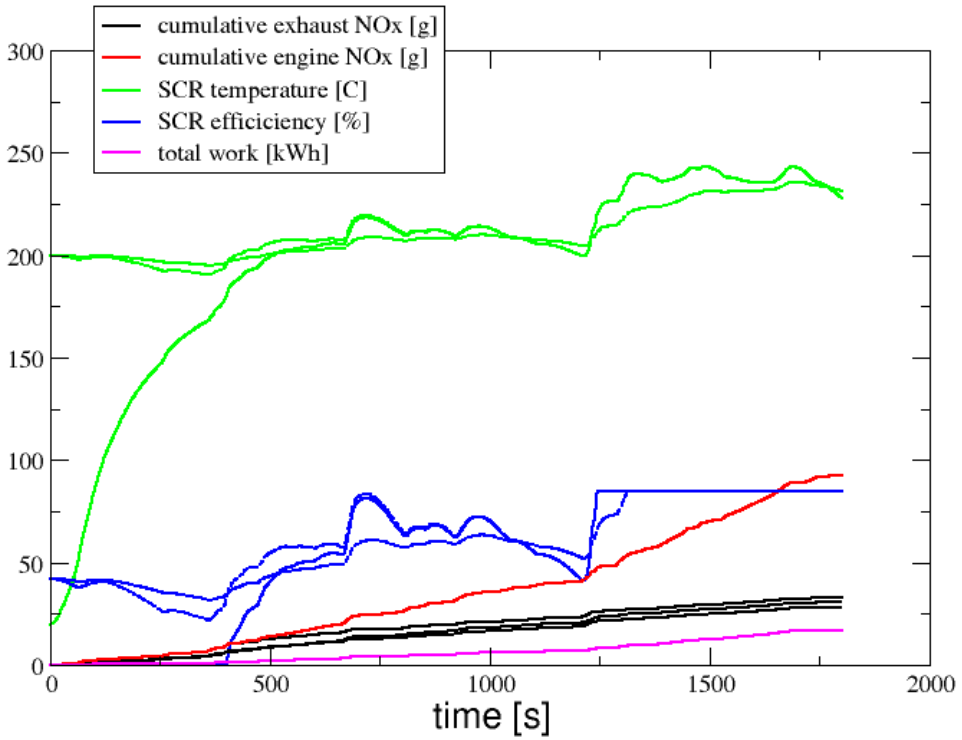


SCR operational temperature T_{op}: 220° C → 250° C



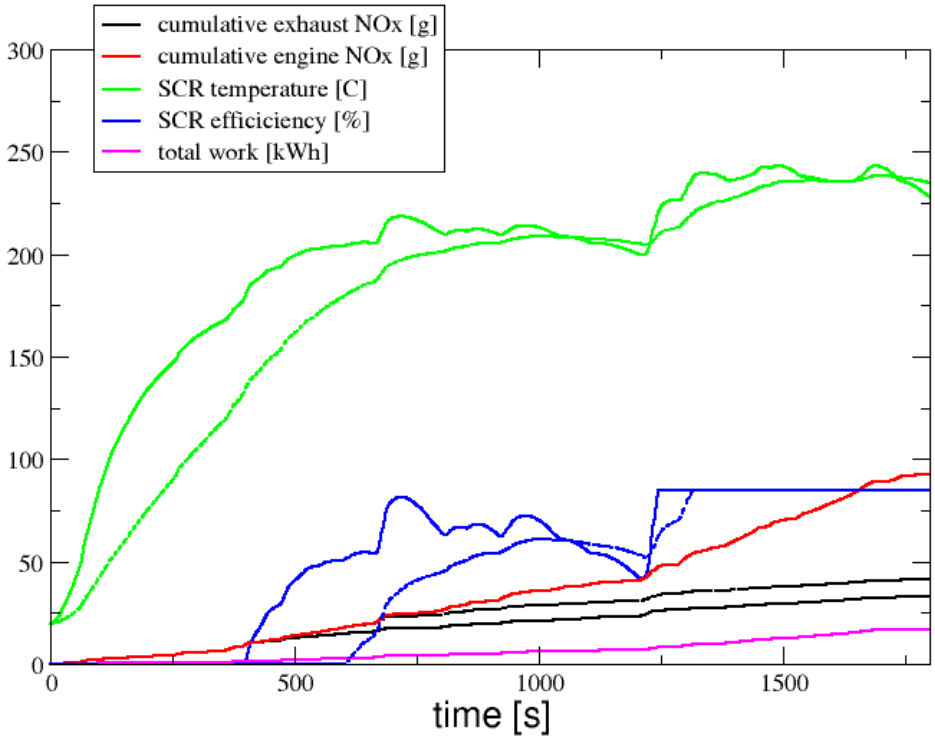
initial temperature (SCR + engine) at 200º C

(two simulations: including doubled heat-up time for sensitivity)

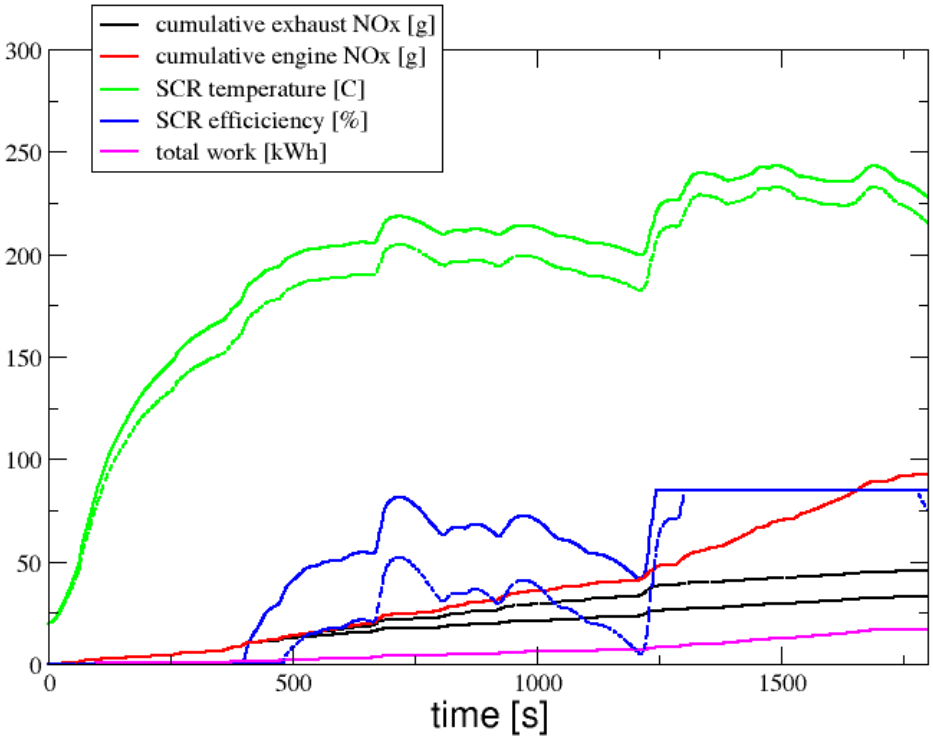


SCR heat capacity five times higher

"jumping short temperature dips"



Idle engine temperature T_{idle}: 180 → 160°C



Overview main results
(dominant effects only, g/kWh)

g/kWh	cold start 20 C		soak 200 C		ETC	
WHTC: urban = [1:1200s]	urban	all	urban	all	soak 200 C	soak 300 C
engine out	6.0	5.4	6.0	5.4	4.9	4.9
base line	3.4	1.9	2.7	1.6	0.8	0.7
SCR parameters						
SCR efficiency 85% --> 95%	3.1	1.5	2.4	1.2	0.3	0.3
Tmin 180 --> 200 C	4.5	2.5	4.3	2.4	0.9	0.8
Top 220 --> 250 C	4.5	2.9	4.1	2.7	1.4	1.1
engine sensitivity						
heat up 200 --> 100 sec	3.0	1.7	2.7	1.6	0.8	0.8
heat up 200 --> 400 sec	4.6	2.4	2.9	1.7	0.8	0.7
Tidle 180 --> 160 C	4.8	2.6	4.5	2.5	0.9	0.8

Overview main results
(reduction of engine-out emissions)

g/kWh WHTC: urban = [1:1200s]	cold start 20 C urban	 all	soak 200 C urban	 all	ETC soak 200 C	 soak 300 C
engine out	6.0	5.4	6.0	5.4	4.9	4.9
base line	43%	64%	54%	69%	84%	85%
SCR parameters						
SCR efficiency 85% --> 95%	48%	72%	60%	78%	93%	95%
Tmin 180 --> 200 C	24%	54%	28%	56%	82%	85%
Top 220 --> 250 C	24%	47%	31%	50%	72%	77%
engine sensitivity						
heat up 200 --> 100 sec	50%	68%	55%	70%	84%	84%
heat up 200 --> 400 sec	23%	55%	51%	68%	83%	85%
Tidle 180 --> 160 C	19%	51%	24%	53%	81%	83%