Modeling & Control of Diesel Aftertreatment Systems

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Contents

Modeling & Control of Diesel Aftertreatment Systems

Exercise 10 – Map-based SCR control

For a Euro-V application, we consider a 9 liter non-EGR diesel engine. This engine is equipped with an aftertreatment system, which consists of an 18.5 liter Vanadium SCR catalyst (no DPF, DOC or AMOX).

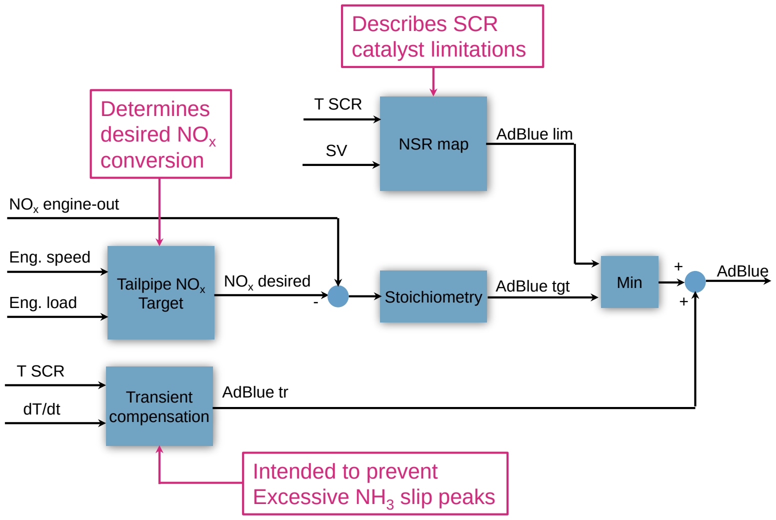

Figure 1: Outline Euro-V map-based urea dosing control strategy

This exercise concentrates on the calibration of a map-based urea dosing control strategy, such that the studied application meets Euro-V targets over the European Steady-state Cycle (ESC) and European Transient Cycle (ETC). The control strategy is given by (see Figure 1):

$$\dot{m}_{AdBlue} = \min(\dot{m}_{AdBlue,lim}, \dot{m}_{AdBlue,tgt}) + \dot{m}_{AdBlue,tr}$$

This open-loop, map-based control strategy comprises the following modules:

1. Stoichiometric urea dosing based on desired NOx conversion (in g/h), assuming 1:1 for NOx:NH3 stoichiometry (SR=1):
$$\dot{m}_{AdBlue,tgt} = \frac{M_{Urea}}{MF_{AdBlue}} \cdot \frac{\boldsymbol{SR}}{2 \cdot M_{NO2}} \cdot \Delta NOx = 2.0067 \cdot \Delta NOx$$
2. NSR map limit:
$$\dot{m}_{AdBlue,lim} = \frac{M_{Urea}}{MF_{AdBlue}} \cdot \frac{NSR(T_{SCR}, sv)}{2 \cdot M_{NO2}} \cdot \Delta NOx$$
3. Transient compensation:
$$\dot{m}_{AdBlue,tr} = g(T_{SCR}, \frac{dT_{SCR}}{dt})$$
4. Tailpipe NOx target (in g/h): engine map with desired values as function of engine speed and load.

In this exercise, we focus on the calibration of the NSR map limit (so tailpipe NOx target and function *g* are both set to zero):

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$$\dot{m}_{AdBlue} = \min(\dot{m}_{AdBlue,lim}, \dot{m}_{AdBlue,tgt})$$

Open Matlab[1] and go to the directory were the material is implemented. In the Matlab command window, run `Caldemo_EUROV.m` to start the Graphical User Interface (GUI). This GUI is the main menu and displays four buttons:

1. <u>Calibration</u>: NSR map, tailpipe NOx target (ppm), transient compensation (g/h)
2. <u>ETC</u>: determine result over ETC
3. <u>ESC</u>: determine result over ESC
4. <u>ESC modes</u>: ANR calibration of specific ESC mode (for NSR map calibration)

Select the `calibration` button. Now a new GUI opens, which shows 3 calibration maps:

1. NSR map as a function of SCR temperature and space velocity (with initial calibration)
2. Tailpipe NOx target (ppm) as function of engine speed and load
3. Transient AdBlue dosing compensation as a function of SCR temperature and temperature rise.

Here, we will focus on NSR map calibration; the other two maps are default set to zero.

ESC mode calibration

To fill this map, for every catalyst operating point (SCR temperature, space velocity), the desired ammonia-to-NOx (ANR) value has to be determined. Here, this will be done for two ESC modes: A100 and B25. First, go to main menu and select `ESC modes` button. A new window will open, which allows you to select ESC mode and ANR value. For each selection, a detailed SCR model can be run by selecting the button `Simulate ESC mode`. Fill the table below by varying ANR values for the two specified ESC modes.

Table 1: ANR sweep results

	A100		B25	
ANR	Tailpipe NOx (g/h)	NH3 (ppm)	Tailpipe NOx (g/h)	NH3 (ppm)
0.4				
0.5				
0.7				
0.8				
0.9				
1.0				

For both engine operating points, plot the ANR sweep results and determine the ANR value that corresponds to 10 ppm NH3 slip level by linear interpolation. Check if this corresponds with the values in the NSR map (in the `Calibration` window).

[1] Matlab R2011b, 32 bits version is used for Windows software

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Calibration of NSR map

With the given initial NSR map, we start with checking the performance over the European Steady-state Cycle (ESC). Go to the main menu and select `ESC` button. A new window opens: select `Simulate ESC` button to run SCR model for this homologation cycle. The figures and maps will be updated when the simulation is finished. Similar to ESC case, ETC results can be generated by using the `ETC` button in the main menu.

For both ESC and ETC, fill Table 2 and check whether the Euro-V tailpipe targets for NOx and NH3 emissions are met. Tune the NSR map to improve ESC and ETC results, such that Euro-V targets are met.

Hint: start with ESC. For each mode, the individual emission results are given. By using `ESC mode`, the calibration for a specific mode can be fine tuned; for a specified NH3 slip level, the target ANR values and NOx tailpipe emission can be determined with corresponding SCR temperature and space velocity values. Check and further refine your NSR map calibration for ETC.

What emission levels can you achieve? What makes it difficult to control NH3 slip?

Calibration of transient compensation

If you have additional time, calibrate also tailpipe NOx target map and transient compensation to limit NH3 slip peaks, especially in ETC. In summary, a typical calibration sequence comprises the following steps:

1. Determine ANR that gives approx. 10 ppm NH3 slip for ESC modes;
2. Fill NSR map;
3. Calibrate tailpipe NOx target map (using `ESC mode` for initial calibration), such that emission targets are approx. accomplished over ESC and ETC, starting with ESC;
4. Tune transient compensation to limit NH3 slip peaks by focusing on ETC;
5. Fine tune tailpipe NOx target map and transient compensation to minimize AdBlue consumption;

What is the purpose of tailpipe NOx target map? Who achieves lowest AdBlue consumption over ETC?

Table 2: ESC and ETC results for different NSR map calibrations

	Euro-V	*Initial NSR*	*Initial NSR*	*Re-calibration*	*Re-calibration*
	target	*ESC*	*ETC*	*ESC*	*ETC*
Engine out NOx (g/kWh)					
Tailpipe NOx (g/kWh)	2.0				
NOx conversion (%)					
Average NH3 slip (ppm)	10				
Max. NH3 slip (ppm)	25				
AdBlue consumption (ml)					

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Appendix A– solutions

A.1 Open-loop SCR control

A.1.1Test cycles

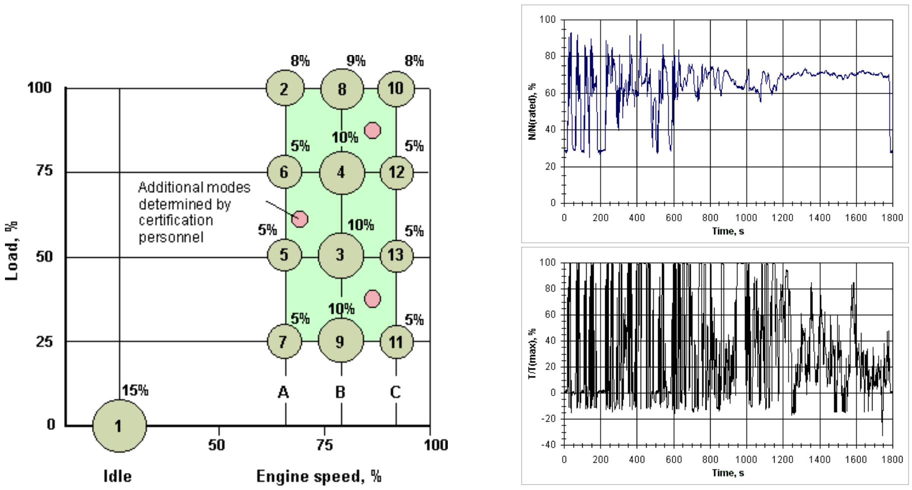

Figure 2: European Steady-state Cycle (ESC) and European Transient Cycle (ETC, right)

A.1.2 Implemented control models

In `EuroV_model.mdl`, the model is implemented that is used for simulations of the cases that can be selected in the GUI. An overview of the feedforward SCR control is shown in Figure 3.

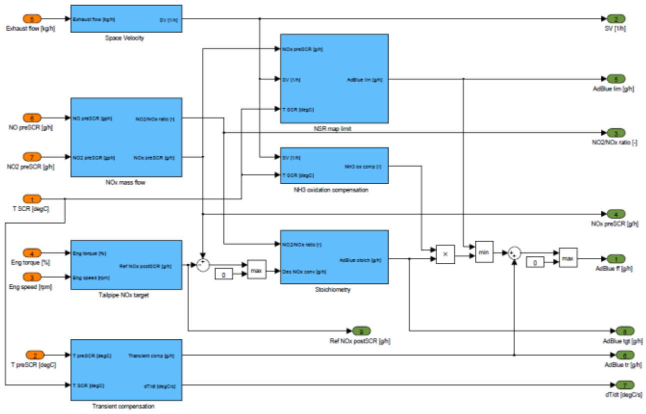

Figure 3: Overview feedforward SCR control

Based on the difference between actual and target tailpipe NOx (in g/h), the required urea dosing (in g/h) is determined based on stoichiometric dosing:

$$\dot{m}_{AdBlue,stoch} = \frac{M_{Urea}}{MF_{AdBlue}} \cdot \frac{SR_{NO2}}{2\cdot M_{NO2}} \cdot \Delta NOx = 2.0067 \cdot \Delta NOx \qquad (1)$$

Where M_{urea}=60, M_{NO2}=46, mass fraction urea MF_{AdBlue}=0.325. Depending on NO2/NOx ratio, SR_{NO2}=1 if NO2/NOx<0.5. In addition, NH3 oxidation and transient compensation (which is limited between -7500 and 7500 g/h) is available:

$$FF_{NH3oxid} = f(T_{SCR,} sv) + 1 \quad (2)$$

$$\dot{m}_{AdBlue,transient} = g(T_{SCR,} \frac{dT_{SCR}}{dt}) \quad (3)$$

The actual dosing is limited by the ANR map:

$$\dot{m}_{AdBlue,ANR} = \frac{M_{Urea}}{MF_{AdBlue}} \cdot \frac{NSR(T_{SCR}, sv)}{2 \cdot M_{NO2}} \cdot \Delta NOx \quad (4)$$

In summary, actual AdBlue dosing is determined from:

$$\dot{m}_{AdBlue} = \min(\dot{m}_{AdBlue,ANR}, \dot{m}_{AdBlue,stoch} \cdot FF_{NH3oxid}) + \dot{m}_{AdBlue,transient} \quad (5)$$

A.1.3 SCR model

For calculations, SIMCAT SCR model is available, which consists of a urea decomposition element and Vanadium SCR catalyst module (no DOC and AMOX). Specifications of the catalyst are given in the table below. Engine out data is from a 9 liter non EGR engine.

Table 3: Specification of Vanadium SCR catalyst

Quantity	*Unit*	*Default value*
Length `L`	m	0.2540 (10 inch)
Diameter `D`	m	0.3048 (12 inch)
Volume `Vcat`	m3	0.0185
Cell density	cpsi	300
Wall thickness	mil	5.5

Note: check when `L` and `D` are varied in catalyst parameter file, if `V_scr_m3` in SCR control parameter file has corresponding value.

A.1.4 Calibration NSR map

For default NSR map with all values equal to 1 and tailpipe NOx target and transient compensation, first ESC results are determined, see Figure 6. Note that urea dosing starts if T_{SCR}>200°C (see also `../parameterfiles/ControlParams.m`).

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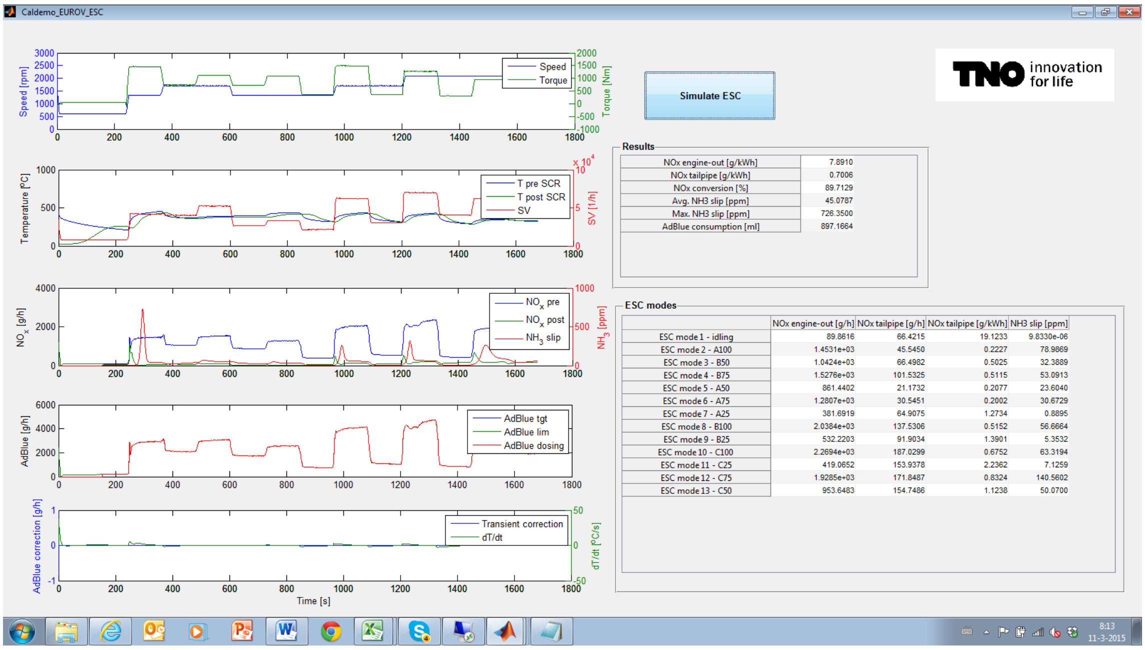


Figure 4: ESC results for NSR=1, tailpipe NOx and transient compensation set to zero

From this figure, it is observed that tailpipe NOx emission (g/kWh) is easily meeting Euro-V target: 2.0 g/kWh. Over ESC, 89.7% NOx conversion is realized. The weighted cycle NOx result is determined using:

$$NOx\left(\frac{g}{kWh}\right) = \frac{\sum_{i=1}^{13} W_i \cdot NOx_i\left(\frac{g}{h}\right)}{\sum_{i=1}^{13} W_i \cdot P_i(kW)} \qquad (6)$$

where the various modes and corresponding values for W_i can be found in Figure 2. For each mode, the 60s average of the corresponding values is determined (including tailpipe NOx). As ANR=1 across whole operating range, AdBlue dosing is not limited (as illustrated in subplot(514) in Figure 4). However, average and peak NH3 slip are above desired values: 10 and 25 ppm respectively.

Table 4: Overview of ESC points and weighting

Mode	Operating point (speed,torque)	Weighting W_i	TSCR (degC)	sv (1/h)
1	Idling	0.15		
2	A100	0.08	442.6	41912
3	B50	0.10	362.5	40138
4	B75	0.10	383.9	52321
5	A50	0.05	386.6	26518
6	A75	0.05	430.0	33223
7	A25	0.05	313.8	21559
8	B100	0.09	430.4	61934
9	B25	0.10	312.4	30458
10	C100	0.08	424.7	69819
11	C25	0.05	289.2	40268
12	C75	0.05	350.9	62167
13	C50	0.05	324.8	51852
Total		**1.0**		

A.1.4.1 ESC mode calibration

To improve calibration, let us focus now on Mode 2 - A100. Select ESC mode calibration in GUI to further analyse performance. Make sure that you are in the right directory `..\Exercise 10 map-based SCR control`. Select the A100 operating point. For this point, we perform ANR sweep to analyse performance: fill in the table below. Repeat this for B25 point In both cases, select ANR value that corresponds to 10 ppm NH3 slip:

- A100(with TSCR=442.6 °C and sv=41912 1/h): ANR=0.9002
- B25 (with TSCR=312.4 °C and sv=30458 1/h) : ANR=0.8055

Table 5: ANR sweep results for A100 and B25

	A100		B25	
ANR	Tailpipe NOx (g/h)	NH3 (ppm)	Tailpipe NOx (g/h)	NH3 (ppm)
0.4	871.1724	0.5484	314.2097	0.3916
0.5	726.6895	0.8366	262.0016	0.7885
0.7	438.4653	2.0690	159.8331	3.6433
0.8	296.1922	3.9144	113.2823	9.2280
0.9	160.2549	9.9470	76.0431	23.3777
1.0	52.3201	34.5830	52.8262	50.4390

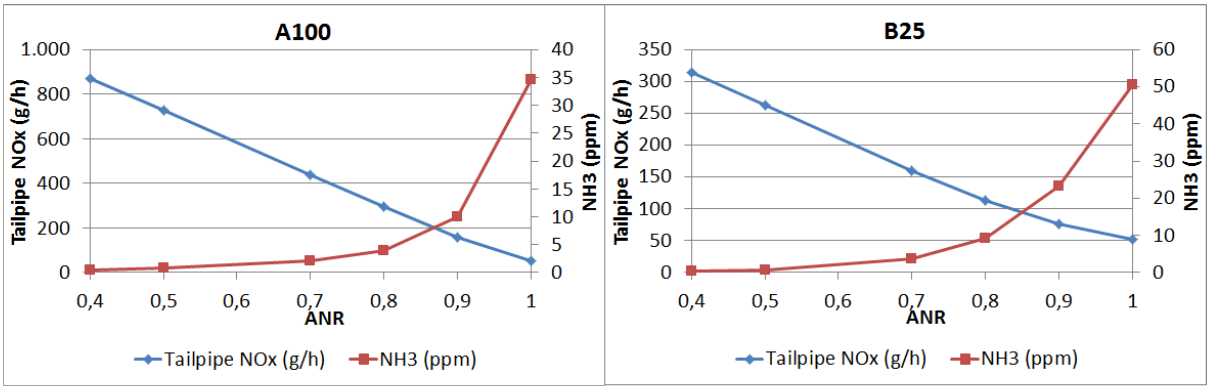
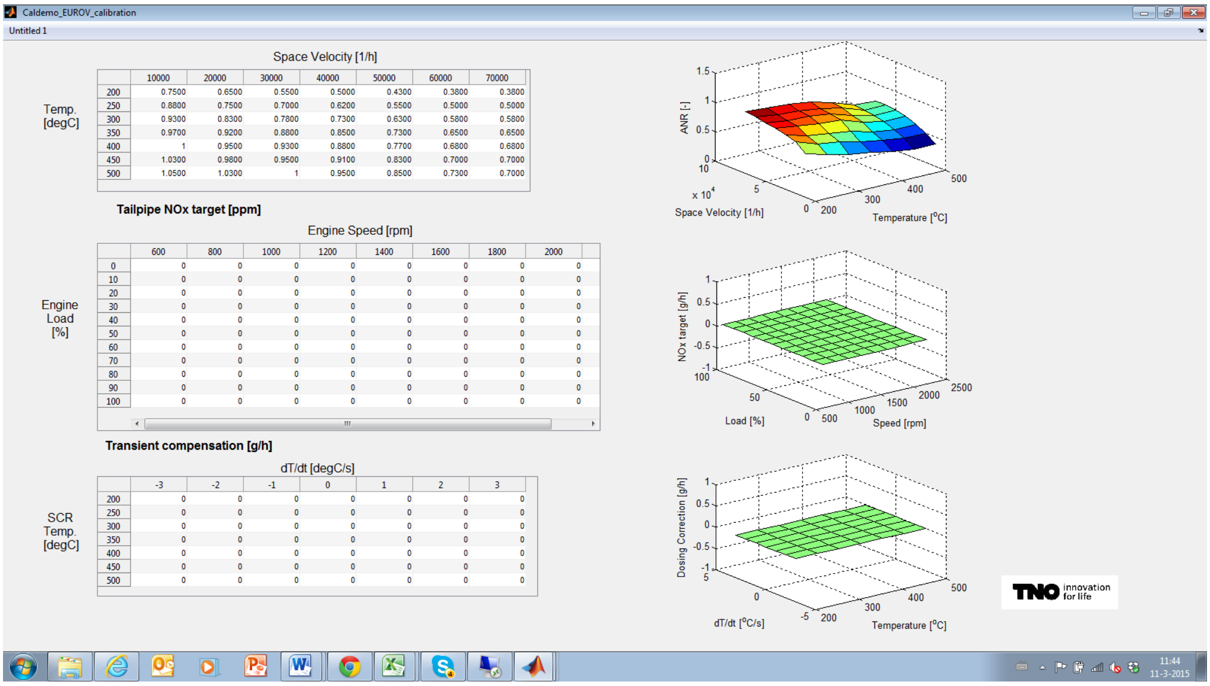


Figure 5: ANR sweep result for A100 and B25

1.4.2 NSR map calibration

In the exercise, an initial NSR map is given to meet Euro-V targets, see Table 6. The corresponding ESC and result is shown in Figure 6 and Figure 8, respectively. For this calibration, weighted tailpipe NOx emission is 2,12 g/kWh over ESC; NH3 slip reduced compared to NSR=1 case in Figure 4 due to AdBlue dosing limitation (see subplot(514) in Figure 6). However, a tailpipe NH3 target is not met yet.

Further analysis of the detailed ESC results in Figure 7 learned that NH3 slip was mainly caused by NH3 storage built up in time before NH3 slip event. In these periods, SCR temperature decreases and catalyst is storing more NH3 on its surface and through the catalyst towards the back. In the following, temperature increase ammonia is released from surface, which results in NH3 slip. Similar results can be observed in Figure 9. These results are the main motivation for NH3 storage control. This holds even more for high performance catalyst with high storage capabilities (such as Zeolite catalysts)



Space Velocity [1/h]

Temp. [degC]	10000	20000	30000	40000	50000	60000	70000
200	0.7500	0.6500	0.5500	0.5000	0.4300	0.3800	0.3800
250	0.8800	0.7500	0.7000	0.6200	0.5500	0.5000	0.5000
300	0.9300	0.8300	0.7800	0.7300	0.6300	0.5800	0.5800
350	0.9700	0.9200	0.8800	0.8500	0.7300	0.6500	0.6500
400	1	0.9500	0.9300	0.8800	0.7700	0.6800	0.6800
450	1.0300	0.9800	0.9500	0.9100	0.8300	0.7000	0.7000
500	1.0500	1.0300	1	0.9500	0.8500	0.7300	0.7000

Tailpipe NOx target [ppm]

Engine Speed [rpm]

Engine Load [%]	600	800	1000	1200	1400	1600	1800	2000
0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0

Transient compensation [g/h]

dT/dt [degC/s]

SCR Temp. [degC]	-3	-2	-1	0	1	2	3
200	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0
350	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0
450	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0

Table 6: Initial NSR map calibration

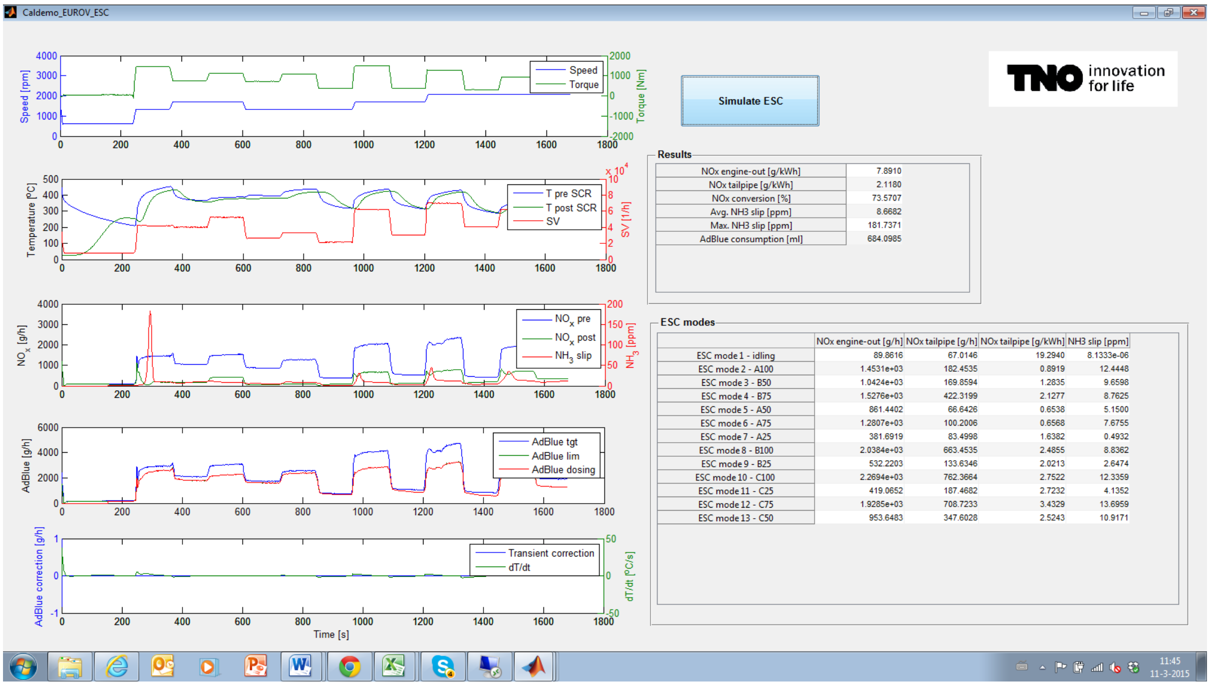


Figure 6: ESC results with initial NSR calibration (default catalyst dimensions)

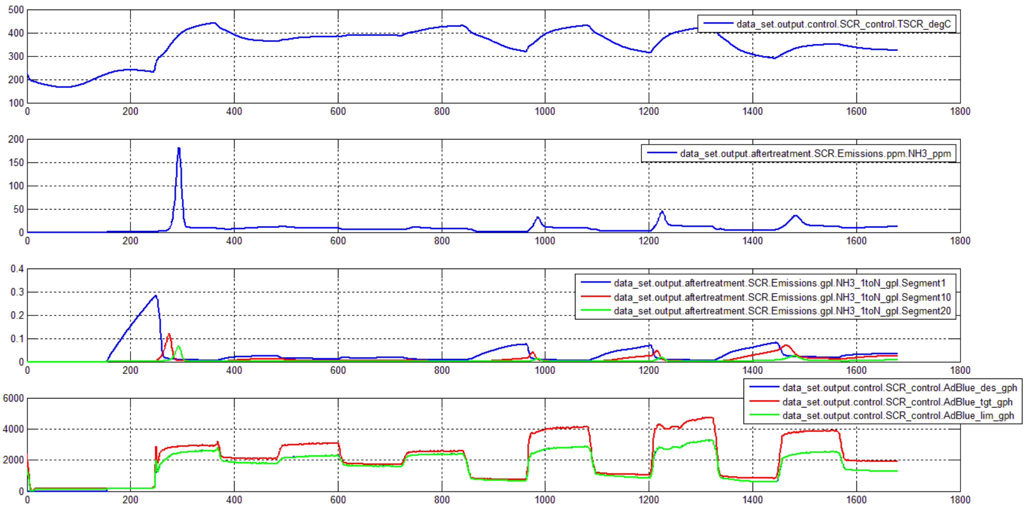


Figure 7: ESC results with initial NSR: ammonia storage results

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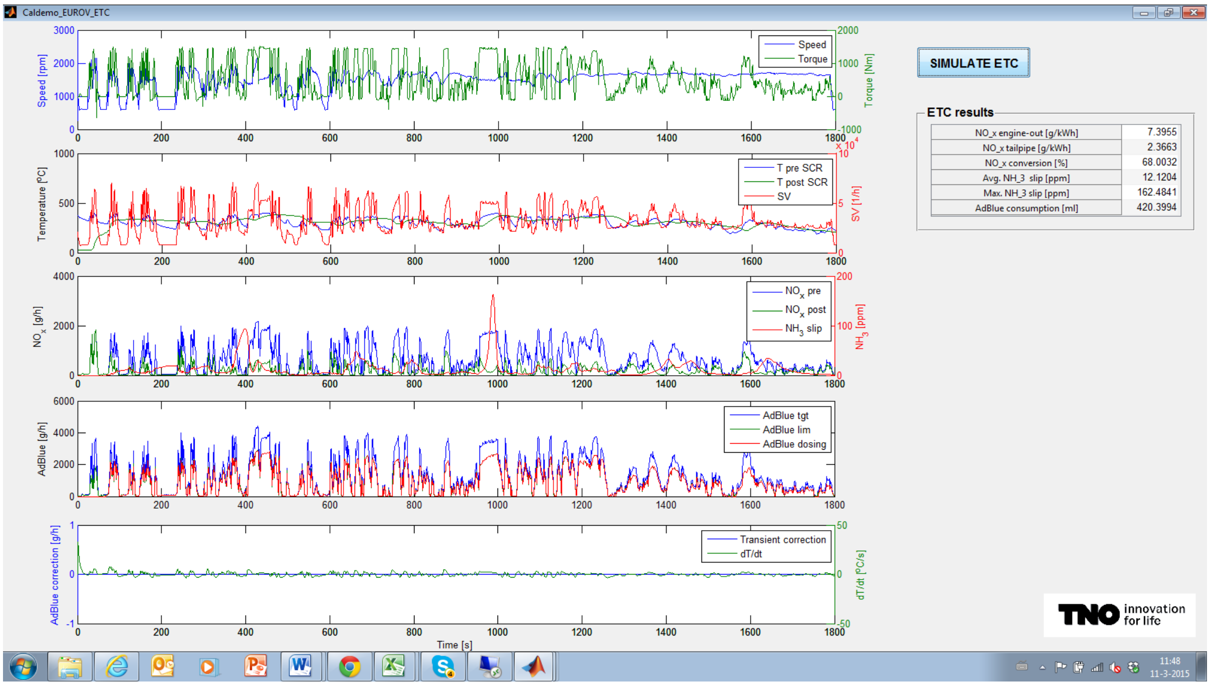

Figure 8: ETC results with initial NSR calibration (default catalyst dimensions)

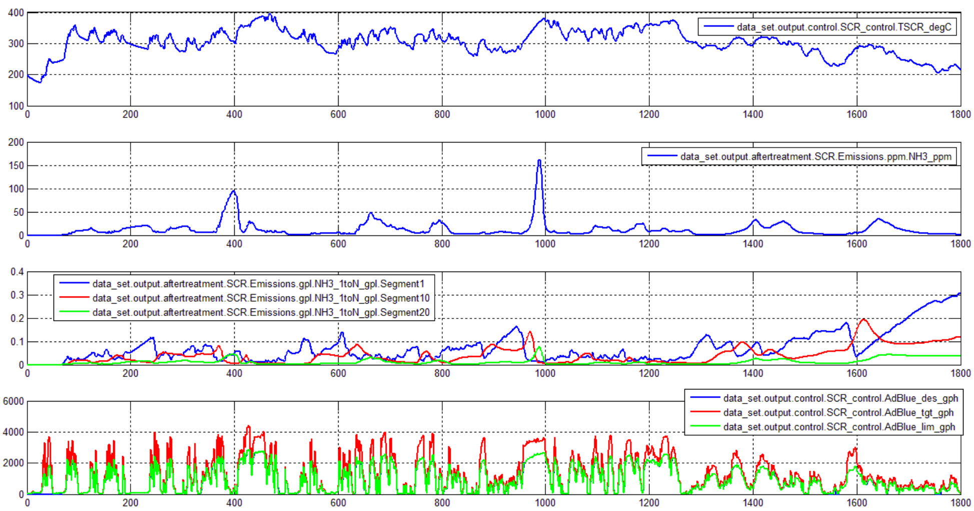

Figure 9: ETC results with initial NSR: ammonia storage results

A.1.4.3 Ways to improve performance

Now having base NSR map calibration, we have following options to further fine tune results:

1. NOX tailpipe map
2. Transient compensation

For option 2 the results are shown in the following figures.

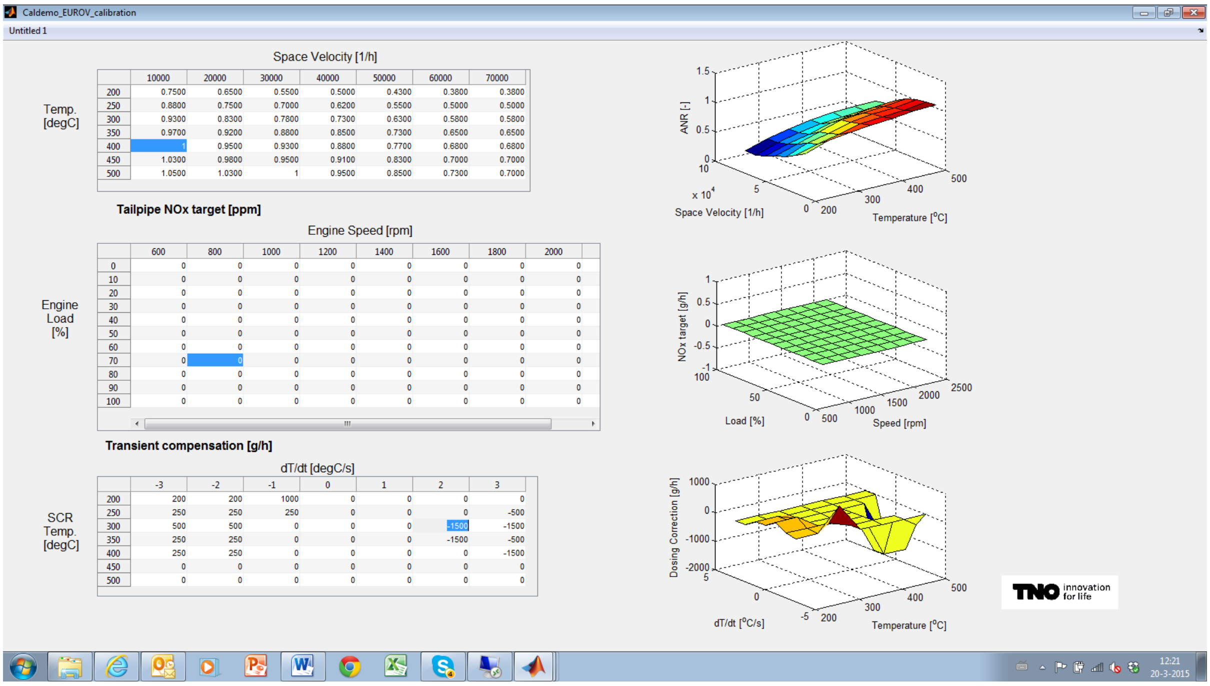

Figure 10: Calibration of NSR map and Transient compensation

As it is difficult to achieve Euro-V NOx and NH3 targets by NSR map-based control, the following additional options could be advised to the chief engineer:

- Change engine out calibration: go for lower engine out NOx
- Increase size of SCR aftertreatment system (by changing D or L)
- Install AMOX and recalibrate controller

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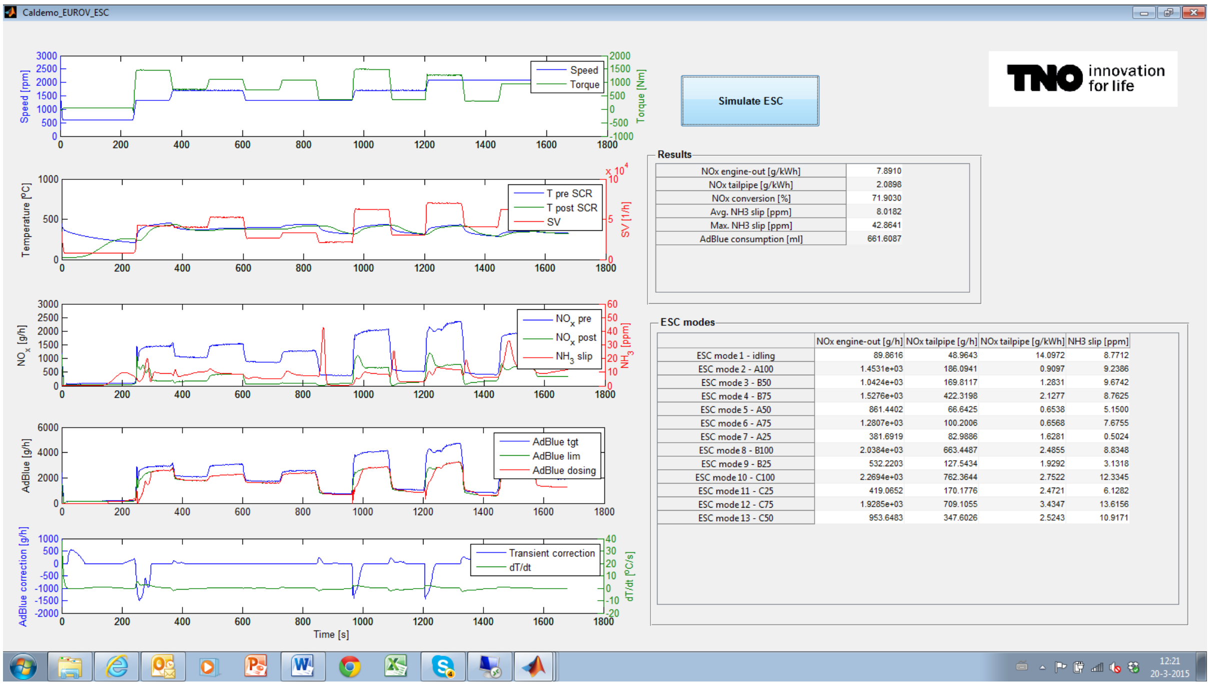

Figure 11: ESC result for NSR map and transient compensation

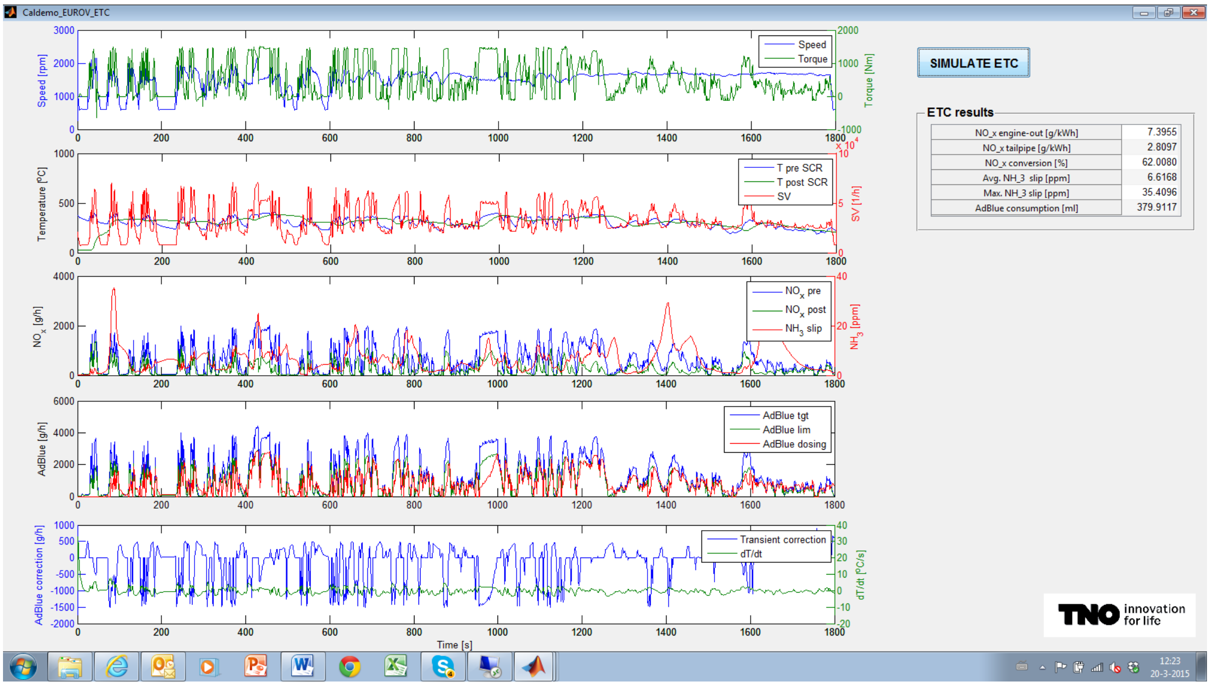

Figure 12: ETC result for NSR map and transient compensation