Scenarios for HDVs

Summary Emission Limits and Test Conditions

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Contents

Tasks and Methods

Main aims for test and limit regimes:

I. Comprehensive coverage of driving conditions* of all HDVs from
- urban delivery and bus (ca. 55km ~ 3 x WHTC, shorter if re-starts included) up to
- long haul and coaches (ca. 230 km, ~ 11 x WHTC)

II. Consideration of demands from CO_2 certification (Reg. 2017/2400):
- Engine tests and VTP-on-road test with less than 120 minute duration (drift of torque meter wheel rims)

III. Comparable requirements with LDV proposal (comparability of requirements for N1-III and small HDVs)

IV. Limits to be attainable with defined technology packages in the defined test conditions

* **Relevant driving conditions** with significantly different [g/kWh] emission levels:

1. Cold start vs. hot conditions
2. Low load (< ca. 10% P_{rated}) vs. normal and high load
3. DPF regeneration vs. normal driving

→ **Options for limits**

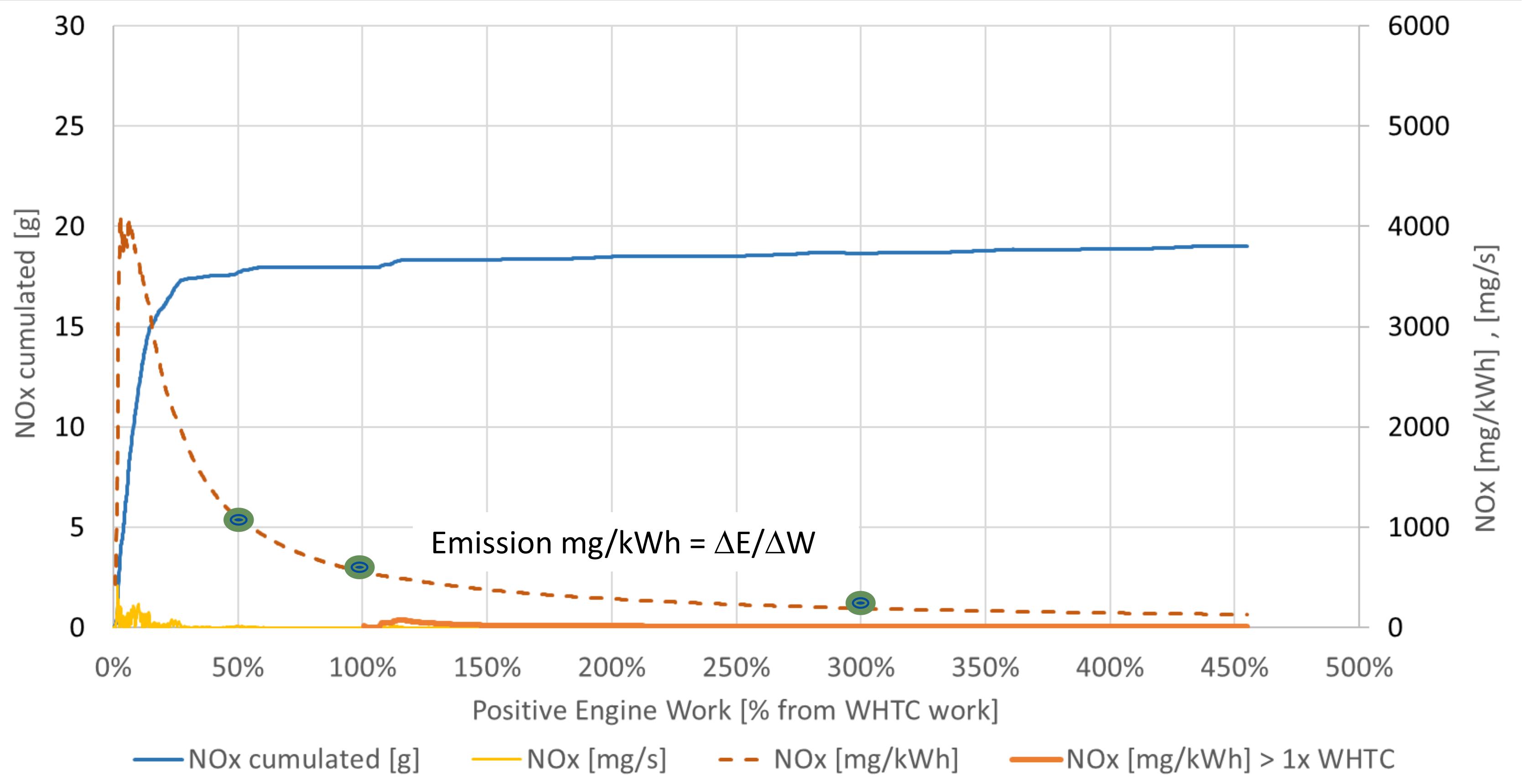
a) One limit for all
b) Different limits for hot and cold
c) Different for hot and cold and for low load
d) As above + separate handling in case of DPF regeneration

Best control of low emissions in all conditions.
Challenge: keep it simple!

Influence of the Test Length

Emissions well controlled by catalysts have pronounced cold start and almost zero hot emissions (NOx, CO and HCs)

→ Given vehicle technology needs higher limits for shorter minimum trip distances

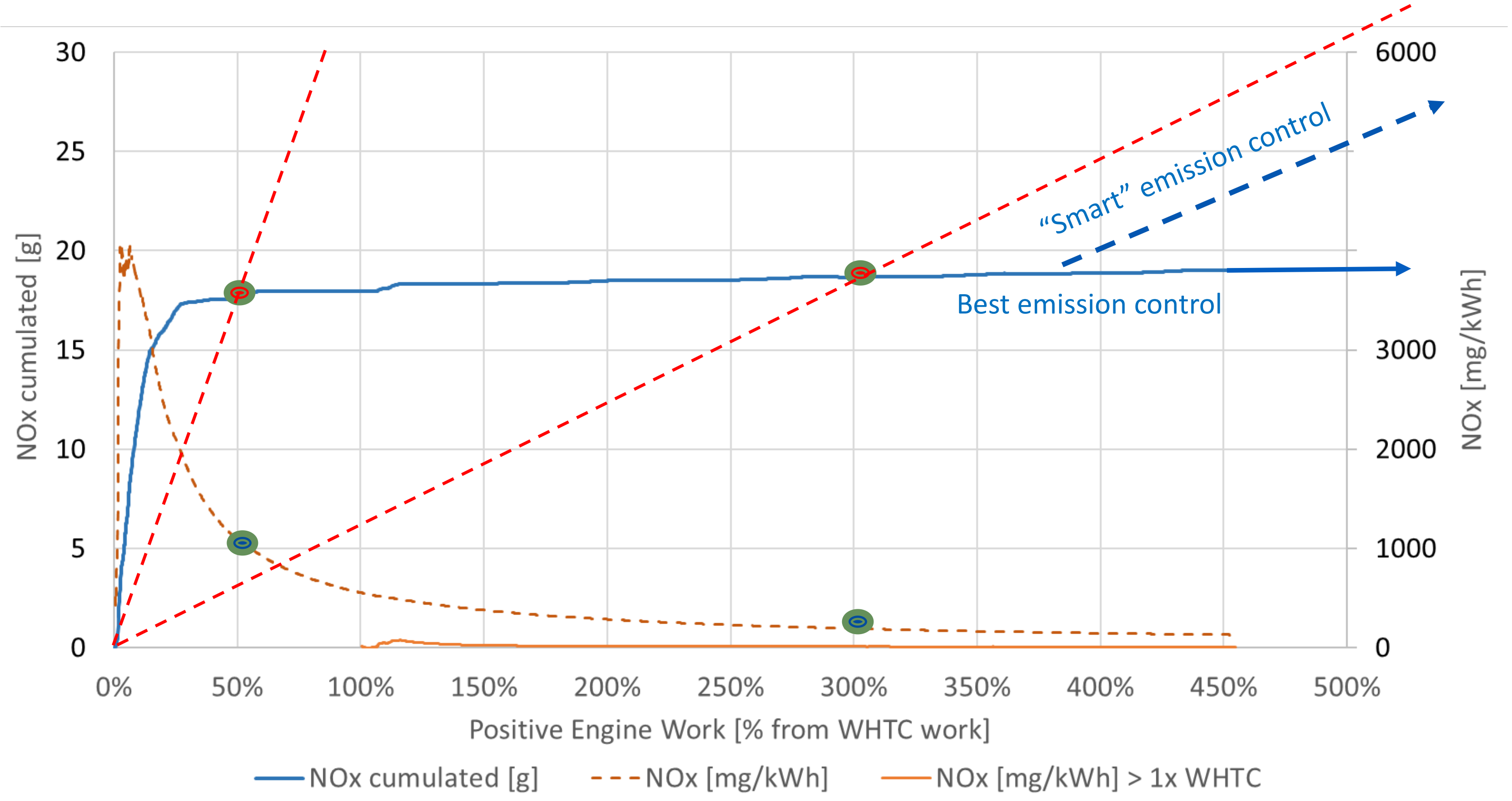


NOx of best performing EURO VI D truck (300kW diesel engine) in consecutive WHVC test after 20°C cold start

Influence of the Test Length

→ Limits for short distances are too high for long haul operation
Long haul operation has highest share in HDV km driven

→ Either minimum distance ≥ 3xWHTC or separate limits for cold and hot phases suggested

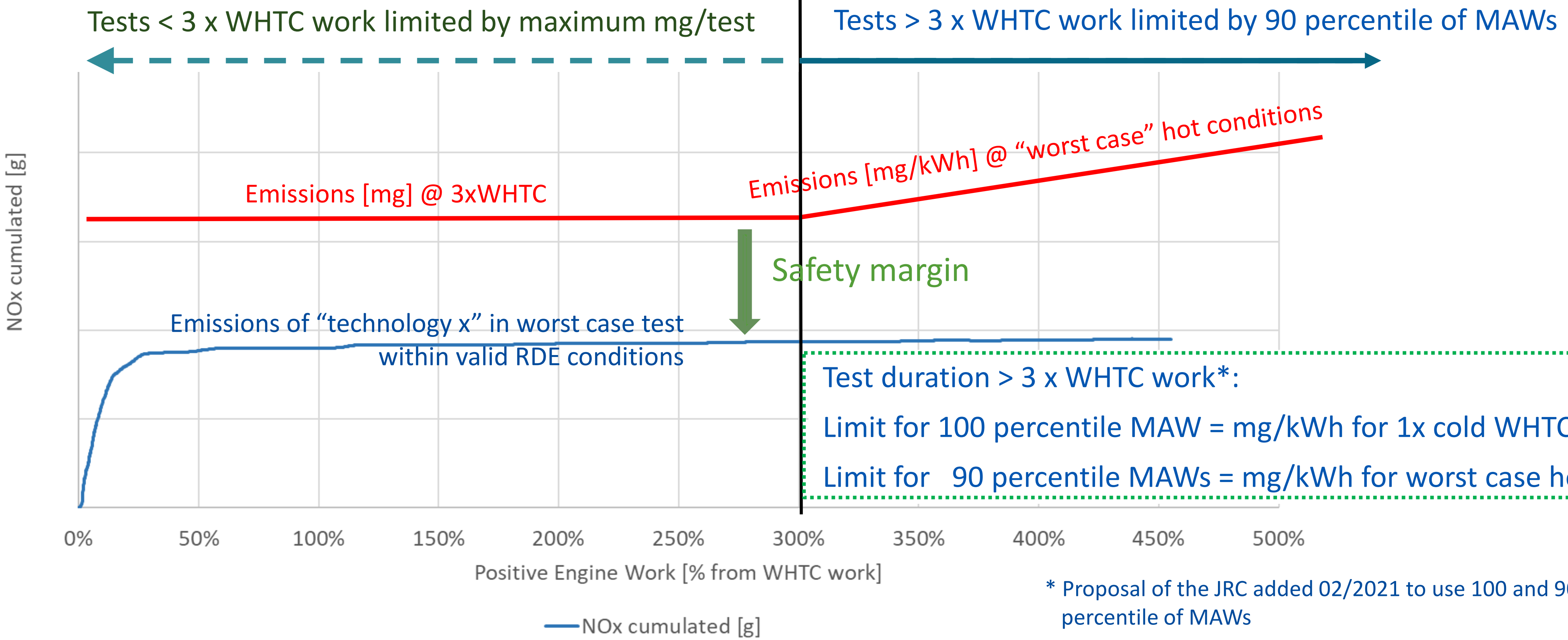


NOx of best performing EURO VI D truck (300kW diesel engine) in consecutive WHVC test after 20°C cold start

HDV Limit Design

Short tests covered by maximum value ("budget") in [g/Test]

Long tests limited by 90 percentile of hot MAWs and 100 percentile (highest (cold window)



Test duration > 3 x WHTC work*:

Limit for 100 percentile MAW = mg/kWh for 1x cold WHTC distance

Limit for 90 percentile MAWs = mg/kWh for worst case hot driving

* Proposal of the JRC added 02/2021 to use 100 and 90 percentile of MAWs

MAW = Moving Average Window. (like EU VI ISC)

Limit Values Needed: Summary

In total **3 limit values** define the entire range of the test regime.

Values are defined by emissions of each technology package in worst case test conditions at 1xWHTC-work, 3xWHTC-work and hot conditions.

Limit for trips ≤ 3 x WHTC work:

Budget [g/test] = $\left(\frac{g}{kWh}\right)_{3xWHTC\text{-}work} \; x \; [kWh]_{3xWHTC}$

For trips > 3 x WHTC work:

100 Percentile
Limit for MAWs = $\left(\frac{mg}{kWh}\right)_{1xWHTC\text{-}work\ cold\ start}$

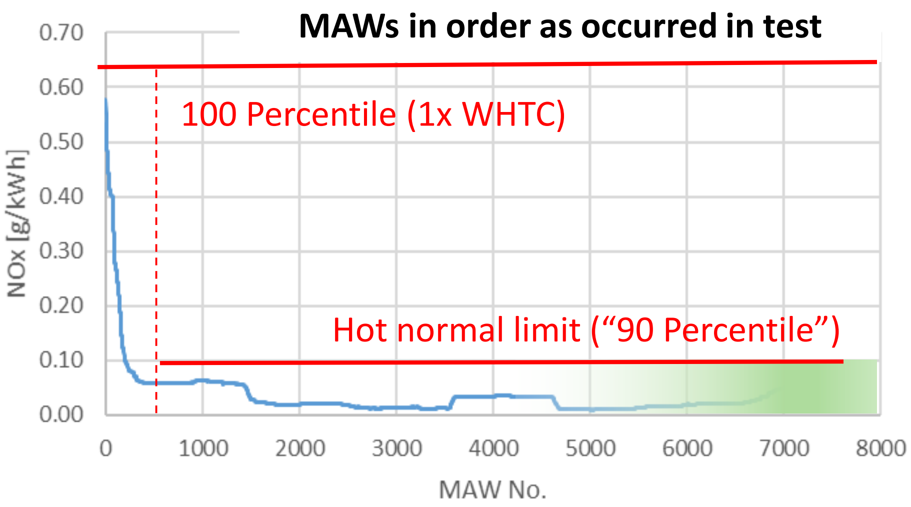
90 Percentile
Limit for MAWs = $\left(\frac{mg}{kWh}\right)_{Worst\ case\ hot}$

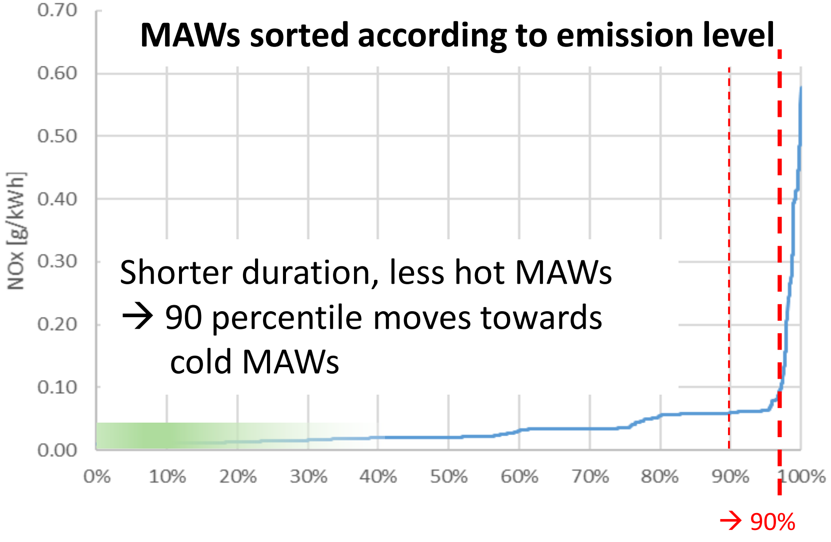
HDV MAWs and Percentiles

- Calculation of MAWs for **100 percentile** start from 1st second in test (includes cold start and covers the entire trip!)
- **90 percentile MAWs with lower limit shall include only hot conditions.**
  - It is assumed that EATS heat up is finished latest after 1 WHTC work
  - First MAW_{hot} is started after some time for EATS heat up, i.e. (0 to 1) (1) WHTC work is reached
  - First evaluation of the 90 percentile limit of $MAWs_{hot}$ after 3 WHTC work is reached
  - Below 3 WHTC work the 100 percentile limit and the cum. limit is in place to handle cold start

(1)…CLOVE is testing the 90% percentile, since it may not ensure only hot MAWs being included. Position of 90 percentile strongly depends on driving condition and trip duration. Evaluation is ongoing.

Example for ISC test from best performing EURO V D HDV (4.2 x WHTC work)





< ca. 3 x WHTC work can shift 90 percentile into cold start affected MAWs (depending on technology and test conditions (loading, route,…). With high load driving number of MAWs is also low and 10% are number of MAWs

HDV Limit Approach for Short and Low Load Tests

Only 1 line extension needed to current EURO VI evaluation method (1).

+ 1 more line to make trips and MAWs with average power < 10% of P_{rated} to be valid tests (2).

Mathematical expression of figures shown before:

$$\text{Emissions [g/kWh]} = \frac{\text{Emissions [g]}}{W_{pos}}$$

Same as in EURO VI

$$W_{pos} = \text{Pos. Work [kWh]} = \bar{P}_{pos} \times t_{test}$$

Same as in EURO VI

Introduce "Reference Work" $W_{pos\text{-}R}$:

(1) If $W_{pos} < 3 \times W_{WHTC} \rightarrow W_{pos} = W_{pos\text{-}R} = 3 \times W_{WHTC}$

→ "Short trip" = valid test

Introduce "Reference Power "$P_{pos\text{-}R}$":

(2) If $\bar{P}_{pos} < 10\%$ of $P_{rated} \rightarrow \bar{P}_{pos} = \bar{P}_{pos-R} = 0.1 \times P_{rated}$

→ "Low load testing" = valid test

Similar to $W_{pos\text{-}R}$: the absolute emissions per test are limited as for P_{pos} = 10% of P_{rated}

Method to be applied also for MAWs

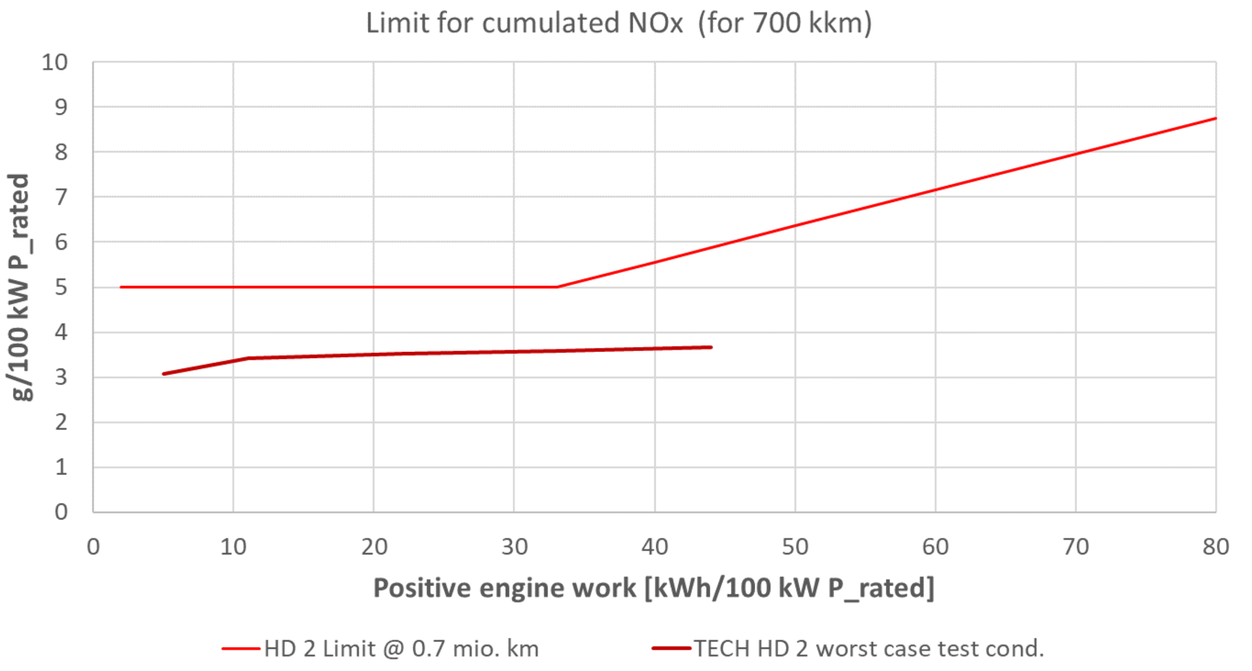
How The Limits are Shown in the Graphs

Cumulated emission limit [g/Test] for test work < 3xWHTC depends on WHTC work and thus on engine power

For general applicable graphs, the figures need to be normalised.

Simplification: 1 x WHTC-work [kWh] = 0.11 x P_{rated} = 22% x P_{rated} x 0.5h *with 0.11…..conversion factor [kWh/kW]*

→ x- and y- axis can be normalised **to P_{rated} (here per 100 kW rated power)**



How to read limit figure:

x-axis * (P_{rated}/100) = kWh,   11 = 1 x WHTC-work

y-axis * (P_{rated}/100) = limit [mg/test]

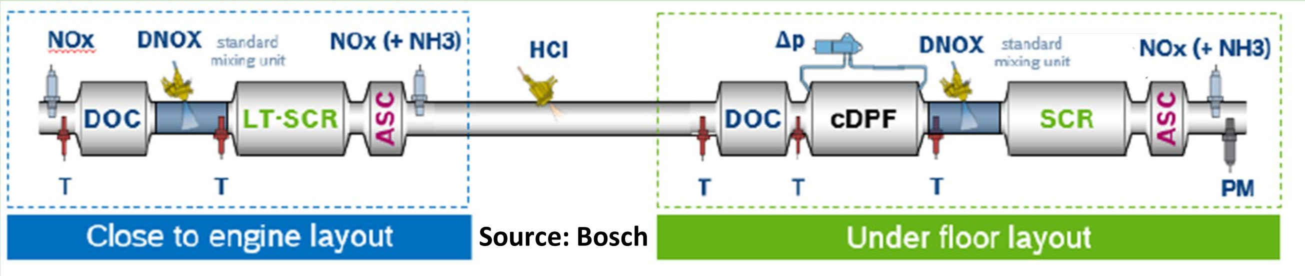
Testing Conditions for EU 7

Parameter	Current ISC	EURO 7 Normal conditions	EURO 7 Extended conditions
Amb. temperature [°C]	-7°C to 35°C	-7°C to 35°C	-10 to +45 C (1)
Cold start	Test evaluation from $t_{coolant}$ > 30°C on; cold start weighted with 14%	Test evaluation from engine start on; no weighting of cold start	Test evaluation from engine start on; no weighting of cold start
Auxiliaries use	None	Possible as per normal use	Possible as per normal use
Min Trip duration [kWh]	> 4 x WHTC work	All (> 30’ recommended for robust results)	All (> 30’ recommended for robust results)
Evaluation (MAW)	1 WHTC window	1 WHTC window + ref. work, ref power method	1 WHTC window + ref. work, ref power method
Engine load [kW/kW_{rated}]	Only work windows > 10% valid	All (2)	All (2)
Windows	90 % below the limit	90% (with lower limit) + 100% (with higher limit)	As normal but Limits x 2 to cover all conditions
Payload	10-100 %	0%-100%	0%-100%
Max. altitude [m]	1600 m	1600 m	2200m
Trip composition	Depending on class of vehicle	Normal trip as intended usage	Normal trip as intended usage
Minimum km before testing	15.000 km (>60 hours)	3.000 km	all
Durability [km]	N2, N3<16t, M3: 300k km N3 > 16t: 700k km	N2, N3<16t, M3: 700k km (3) N3 > 16t: 1,200k km	N2, N3<16t, M3: 700k km (3) N3 > 16t: 1,200k km

(1) extra provision for maximum AdBlue defrosting time (2) with reference power method (3) The durability of the emission control systems until the end of their lifetime will be dealt separately

Technology packages HD Diesel

Shown in presentation

Technology scenarios considered		Description
HD0	Average EU VI D	With and without EGR, DOC, DPF and SCR in EATS box
HD1	Best NOx performing EU VI D	Good thermal management, EGR, DOC, DPF and SCR in EATS box
HD2	Optimised diesel with cc SCR	Close couple DOC & deNOx + twin AdBlue dosing, ca. 6.5 : 1 = EATS : engine volumes:  Engines: hot and cold EGR, low raw NOx during cold starts (<2g/kWh), optimized thermal management, improved turbo-charging, fuel-injection,….
HD3	Optimised diesel with cc SCR and pre heating of EATS	= HD 2 + pre heating with diesel burner (5 minutes at 60kW for 330kW engine)
HL2	Optimised LNG HPDI engine	LNG CI engine with diesel ignition injection; emission control technology similar to HD2
HC2	Optimised SI CNG engine	Stoichiometric CNG engine with additional close couple 3WC and GPF, optimised Lambda control, low lube oil losses,…
HD4	Optimised diesel full hybrid with cc SCR and pre heating of EATS	= HD3 + full hybrid (optional electric pre heating instead of diesel burner)

Methods to Define Limit Values

Collection + analysis of EURO VI D HDV emission tests.
Selection of best performer for further processing.

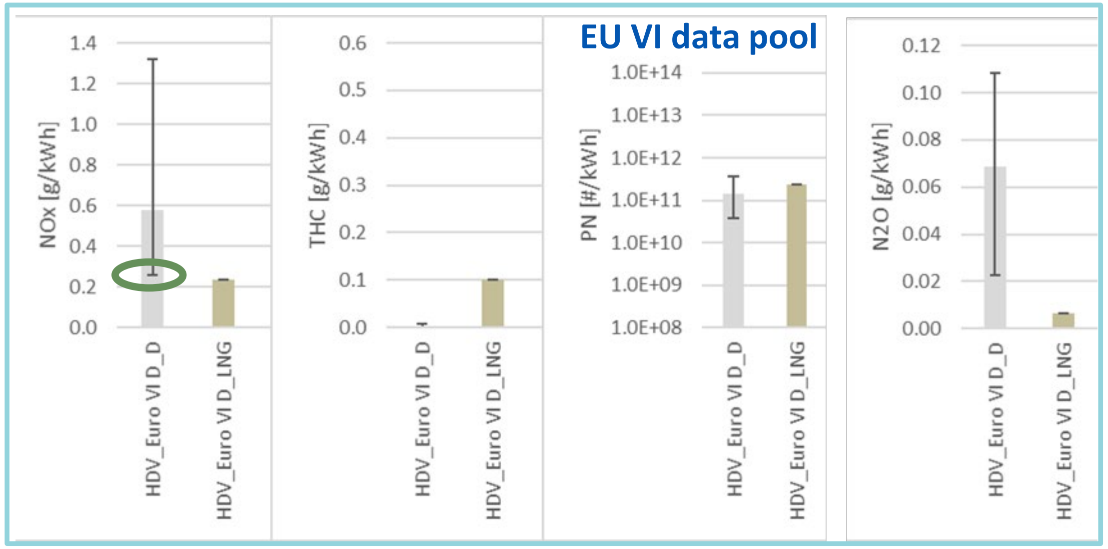
Collection and analysis of test data from literature and made available for EU 7 HD demonstrators

Definition of worst case test condition for cold and hot driving conditions within RDE boundaries

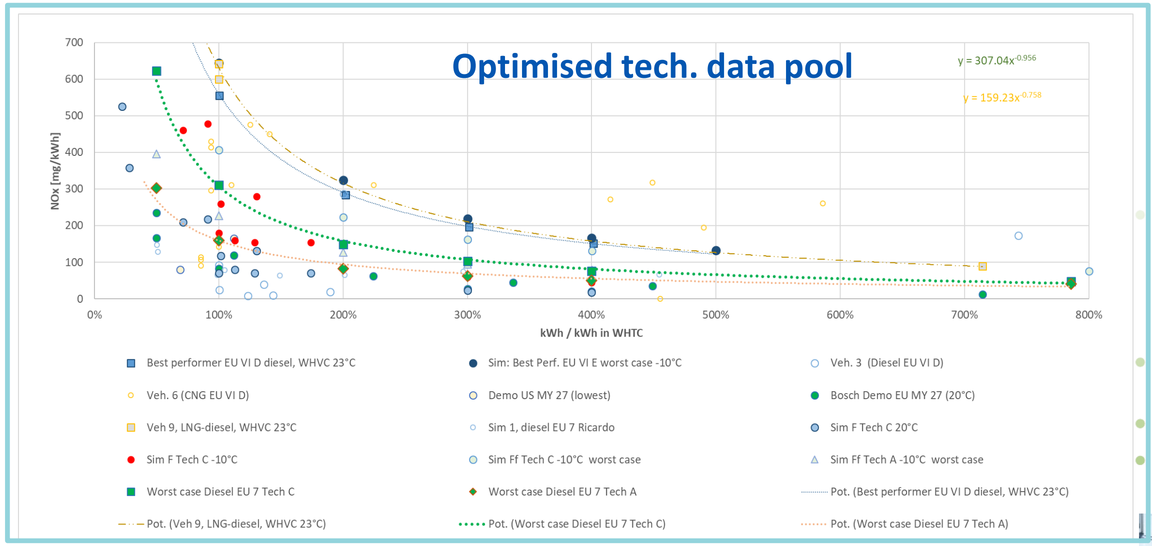
Simulation to close gaps in data:

- Convert tests at different temperatures to -7°C
- Convert tests at WHTC and other cycles to worst case conditions (uphill after cold start, followed by stop&go,..)
- Convert PN_{23} test data to PN_{10} values
- Assess cold start reduction by pre-heating
- Convert emission levels to extended useful life

Set up emission levels for the different technologies for the worst case driving conditions (cold start up to 1xWHTC, up to 3xWHTC and hot driving).
Add "safety margin" → limit scenarios per technology



Data from CLOVE, TUG, UBA Germany, (Weller, 2021), VTT and TNO

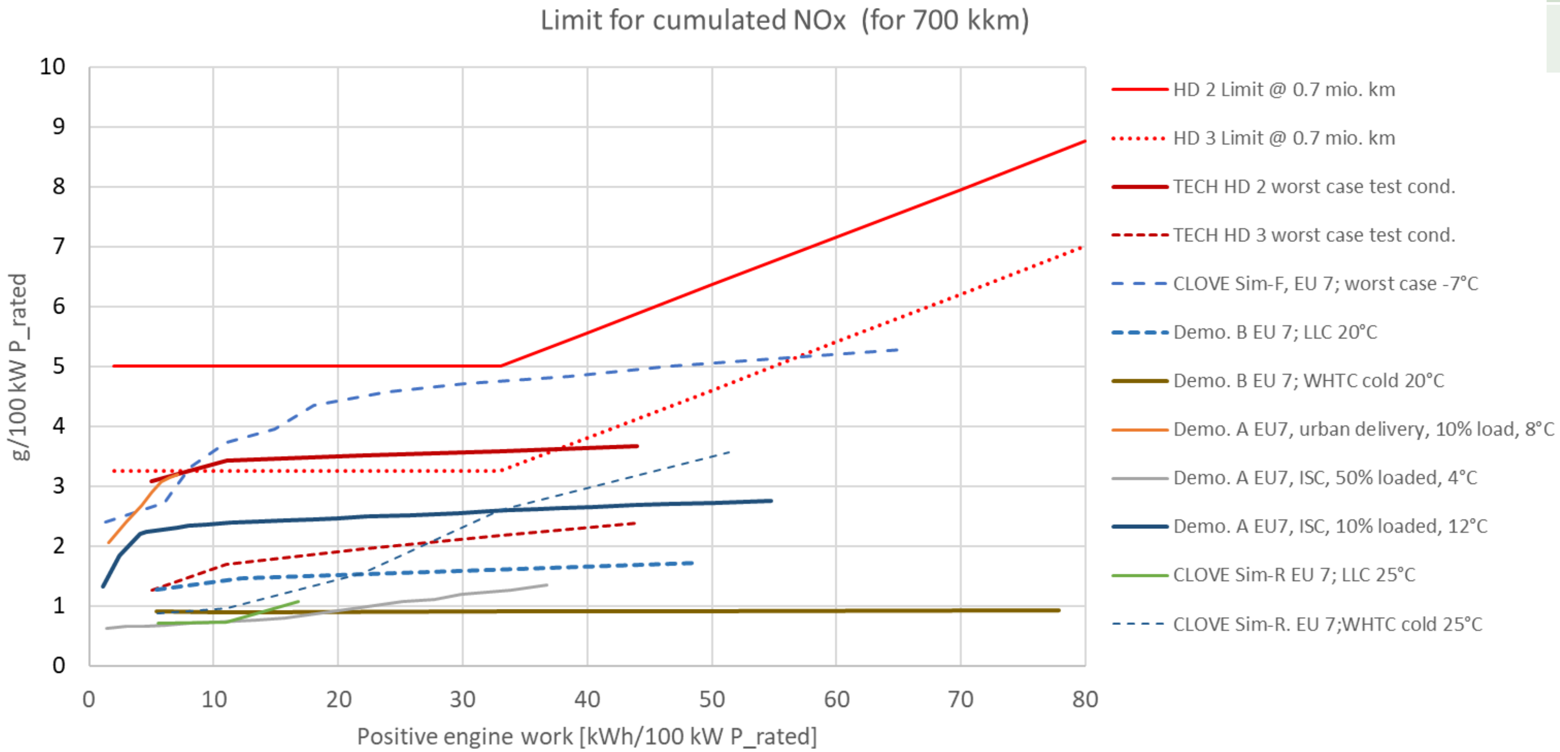


NOx Emission Levels

NOx:

HD 2 technology limits based on literature, test data from demonstrator truck and engine (note: no worst case tests!) and on simulation.

HD 3 technology limits based on simulated reduction of cold start emissions.



Limit Scenarios [mg/kWh]

kWh	HD2	HD 3	EU VI
100 Perc. (1xWHTC)	450	230	-
Budget (3xWHTC)	150	100	-
90 Percentile	80	80	-
4xWHTC*	*115*	*90*	460

* Only for comparison with EU VI.
Note EU VI E with cold start >30°C and 90 percentile

NOx Emission Levels EU 7 vs. EU VI

NOx:

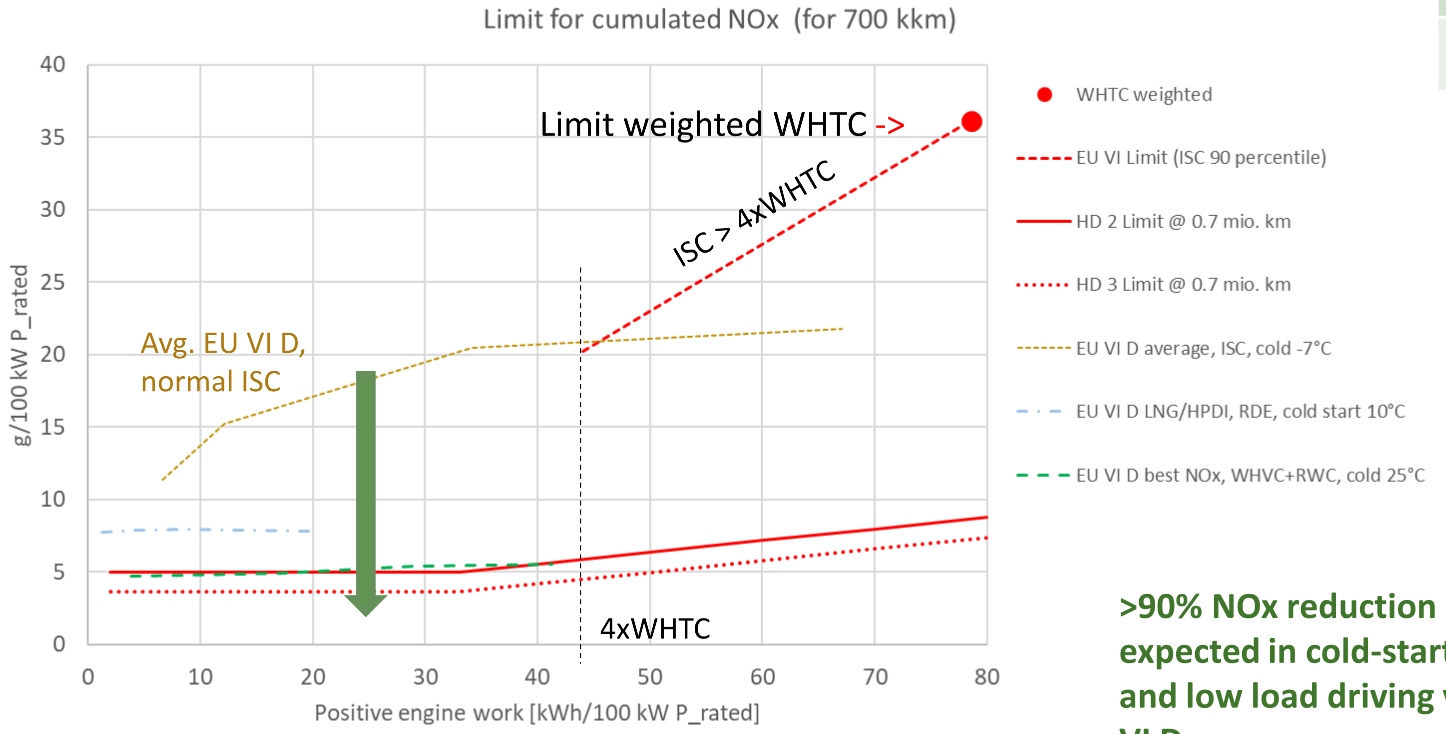
HD 2 technology leads to significant reduction in cold start and low load emissions and reductions in hot driving compared to avg. EU VI.

HD3 technology could improve cold start emissions vs. HD 2

Limit Scenarios [mg/kWh]

kWh	HD2	HD 3	EU VI
100 Perc. (1xWHTC)	450	230	
Budget (3xWHTC)	150	100	
90 Percentile	80	80	
4xWHTC*	*115*	*90*	460

* Only for comparison with EU VI. Note EU VI E with cold start >30°C and 90 percentile



>90% NOx reduction expected in cold-start, urban and low load driving vs. EU VI D average

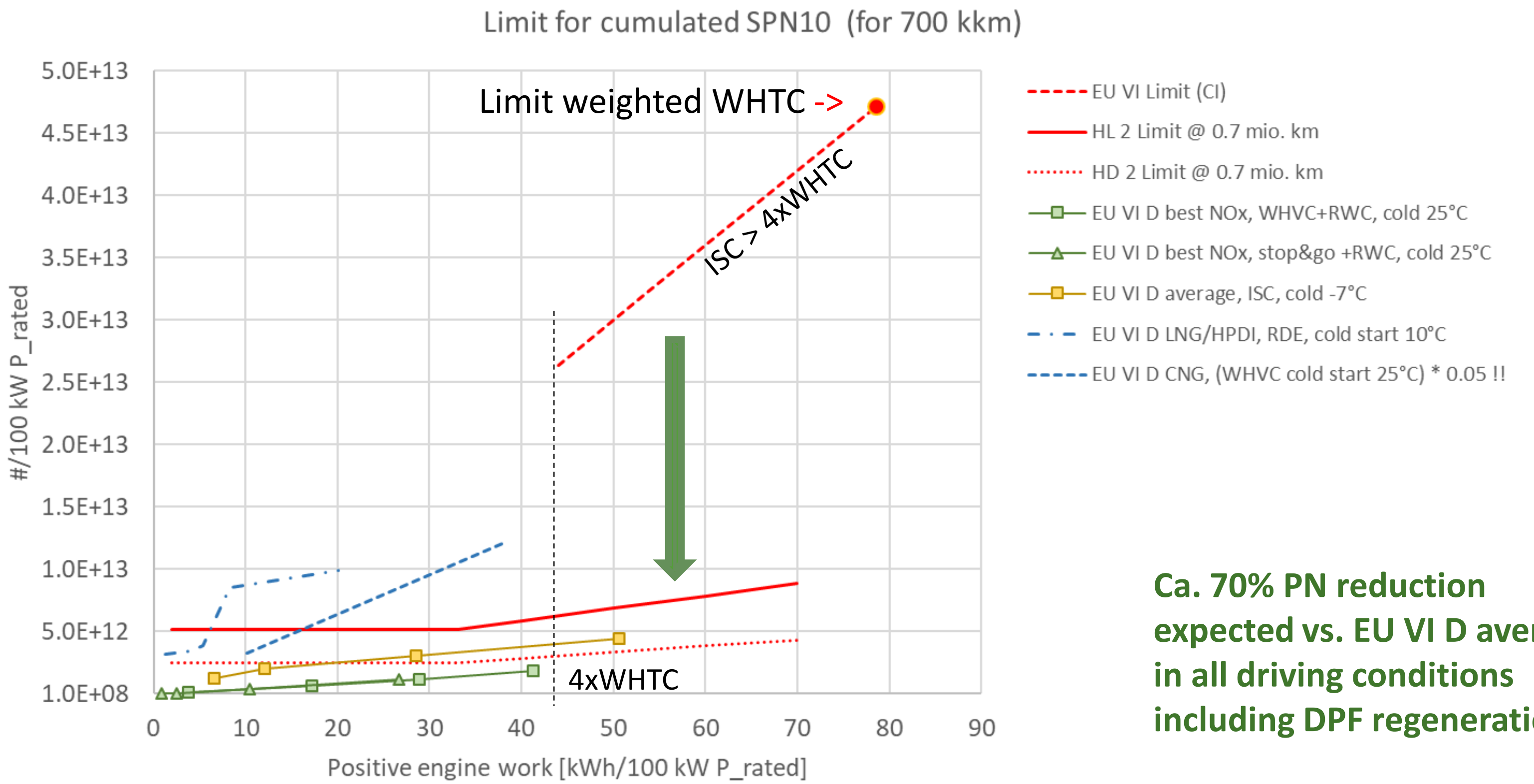
PN10 Emission Levels

PN10:

To include DPF regeneration (with extended test duration, see later), and to cover gas engines also, similar PN10 limits for all technologies are proposed (= “HL2”).

Gas SI engines need GPF with >95% removal efficiency (depending on raw emission level)

HD3 technology has no improvements vs. HD2 (DPF works also cold)



Limit Scenarios [#/km]

kWh	HD2&3 PN10	EU VI PN23
100 Perc. (1xWHTC)	6E+11	
Budget (3xWHTC)	2E+11	
90 Percentile	1E+11	
4xWHTC*	*1E+11*	6E+11

* Only for comparison with EU VI. Note EU VI E with cold start >30°C and 90 percentile

Ca. 70% PN reduction expected vs. EU VI D average in all driving conditions including DPF regeneration

PN10 Emission Levels

Integration of DPF Regeneration into valid RDE tests:

Option similar to LDVs presented before.

PN10 limit covers Gas SI engines as well as diesel with weighted inclusion of DPF regeneration.

Number of DPF regenerations to be integrated and stored in OBD memory
→ distance between regeneration accessible

Expected distance until next active regeneration shall be announced by vehicle (e.g. via TCI system)

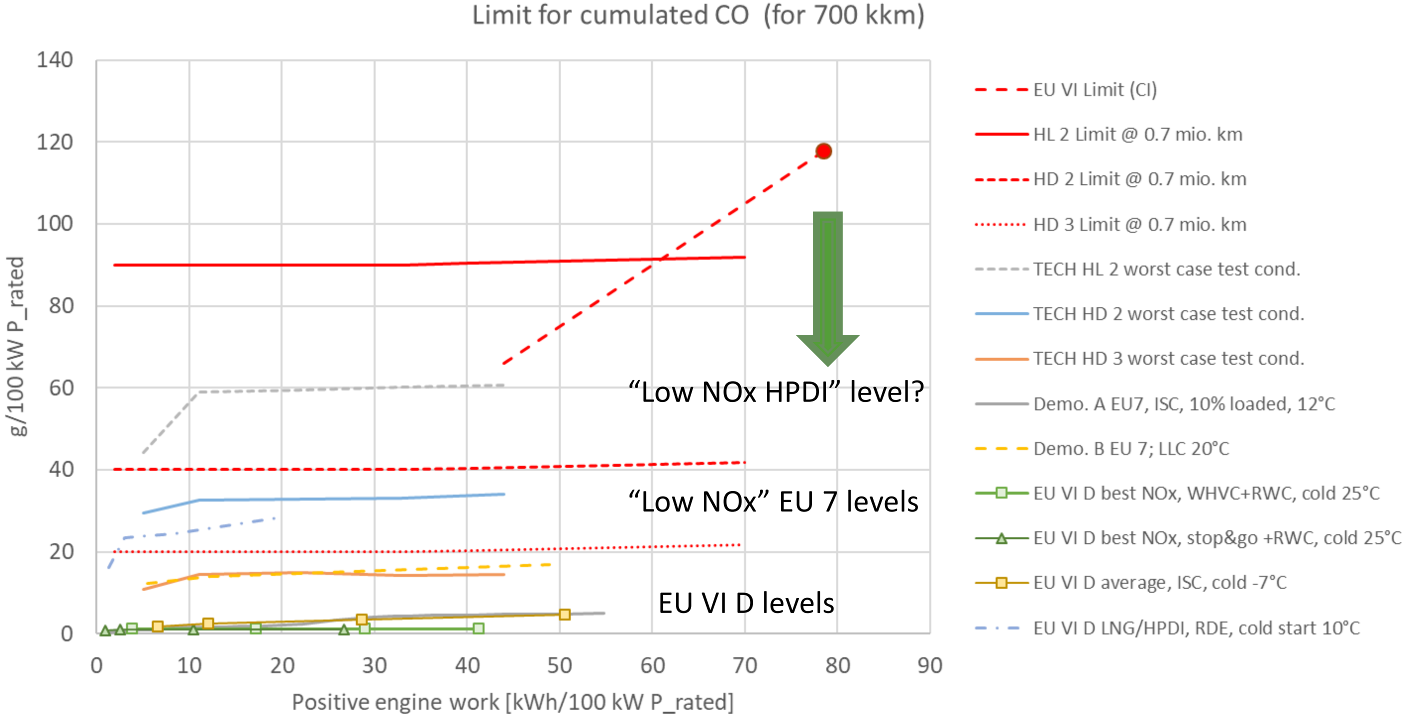
Evaluation, if regeneration occurs during a test:

- The DPF regeneration should be finished in one test and 10 km further driven after end of regeneration. Regeneration time to be limited, e.g. with max. 1xWHTC.
- Drive second test.
- Weight results according to avg. distance between regenerations.

CO Emission Levels

CO:

Technologies for thermal management of EATS and for low raw NOx tend to increase CO emission levels. For CI gas/diesel technology possibly even more demanding. → simultaneous massive reductions of NOx and CO limits is problematic. CO from HDV already very low → Moderate CO limit reductions vs. EU VI help to meet NOx targets.



Limit Scenarios [mg/kWh]

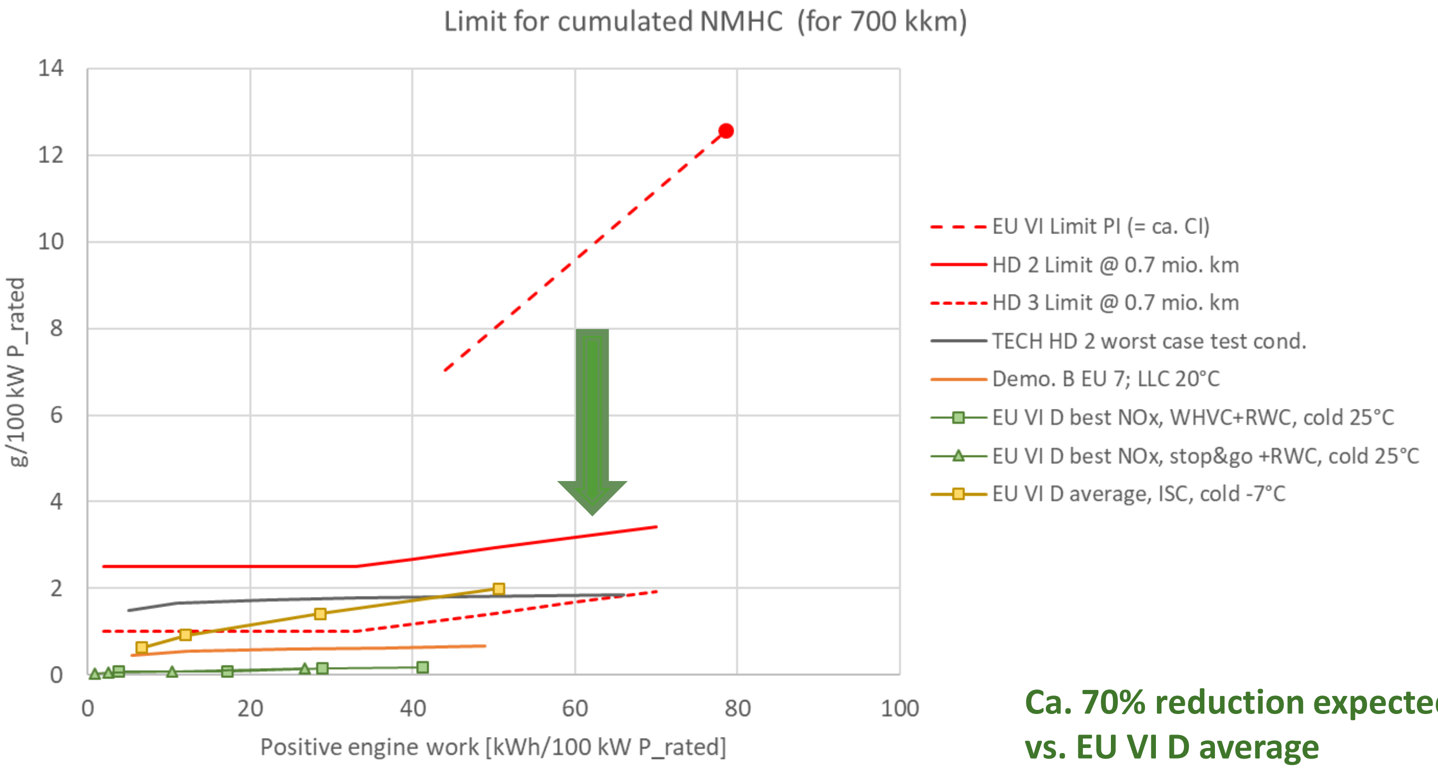
kWh	HD2	HL2	EU VI
100 Perc. (1xWHTC)	4000	8000	
Budget (3xWHTC)	1250	2700	
90 Percentile	50	50	
4xWHTC*	*1000*	*2000*	4000

* Only for comparison with EU VI.
Note EU VI E with cold start >30°C and 90 percentile

NMHC Emission Levels

NMHC (NMOG):

NMHC from diesel and gas engines already very low. Low NOx technologies tend to increase HC emissions. Due to health effects of NMHC components reduction of EU VI limits suggested to ca. HD2 level.
NMOG: data based on standard fuel where NMHC ~ NMOG;
regulating NMOG possibly relevant for oxygenated fuels.



Ca. 70% reduction expected vs. EU VI D average

Limit Scenarios [mg/kWh]

kWh	HD2	HD3	EU VI
100 Perc. (1xWHTC)	225	85	
Budget (3xWHTC)	75	30	
90 Percentile	25	25	
4xWHTC*	*57*	*26*	160

* Only for comparison with EU VI.
Note EU VI E with cold start >30°C and 90 percentile

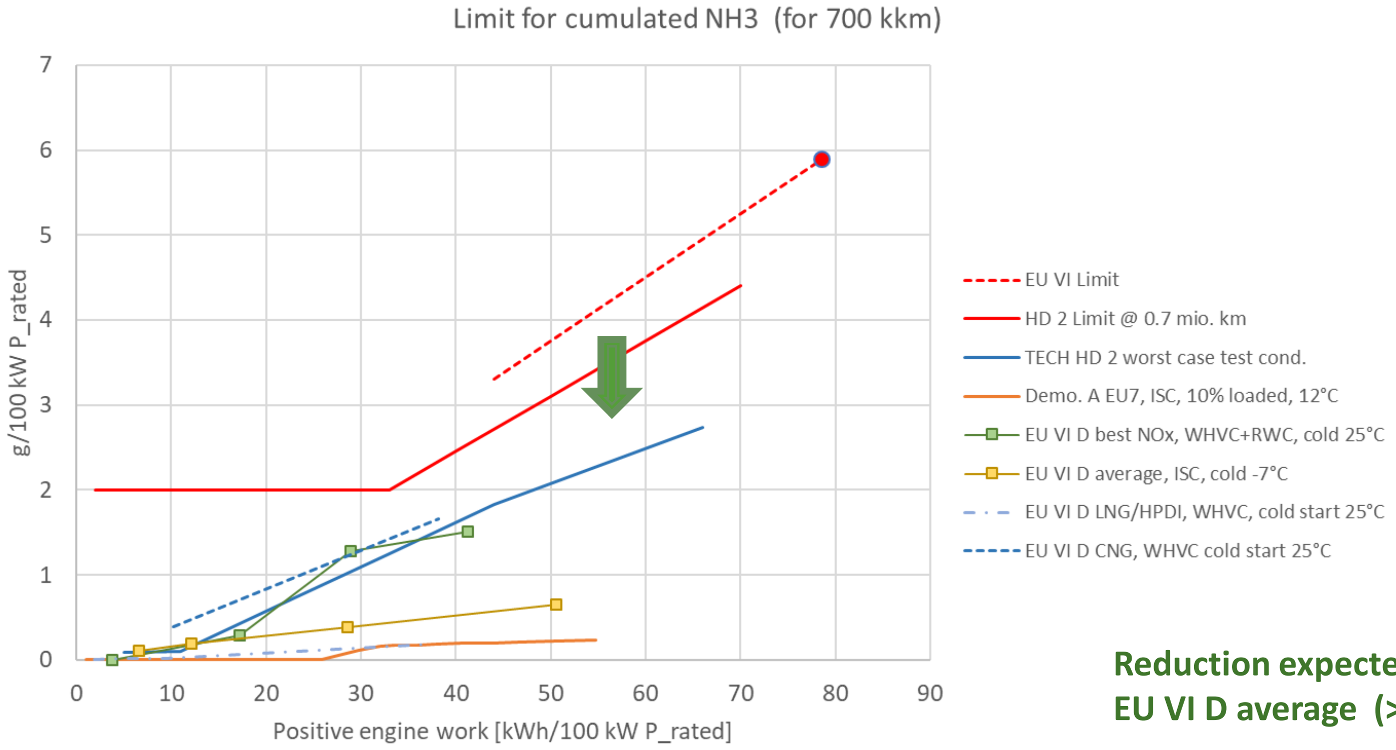
NH3 Emission Levels

NH3:

Main sources from NH3 slip at diesel and 3WC for Gas SI engines.

No reduction potential from AETS pre-heating HD3 technology (NH3 slip mainly during hot SCR conditions).

Reduction compared to EU VI possible, conversion to mg/kWh reasonable.



Reduction expected vs. EU VI D average (>50%)

Limit Scenarios [mg/kWh]

kWh	HD2&3	EU VI
100 Perc. (1xWHTC)	65	
Budget (3xWHTC)	65	
90 Percentile	65	
4xWHTC*	*65*	10 ppm ~75 mg/kWh

* Only for comparison with EU VI.
Note EU VI E with cold start >30°C and 90 percentile

CH4 and N2O Emission Levels LNG

CH4 and N2O can contribute significantly to total GHG emissions from modern vehicles (>10%).

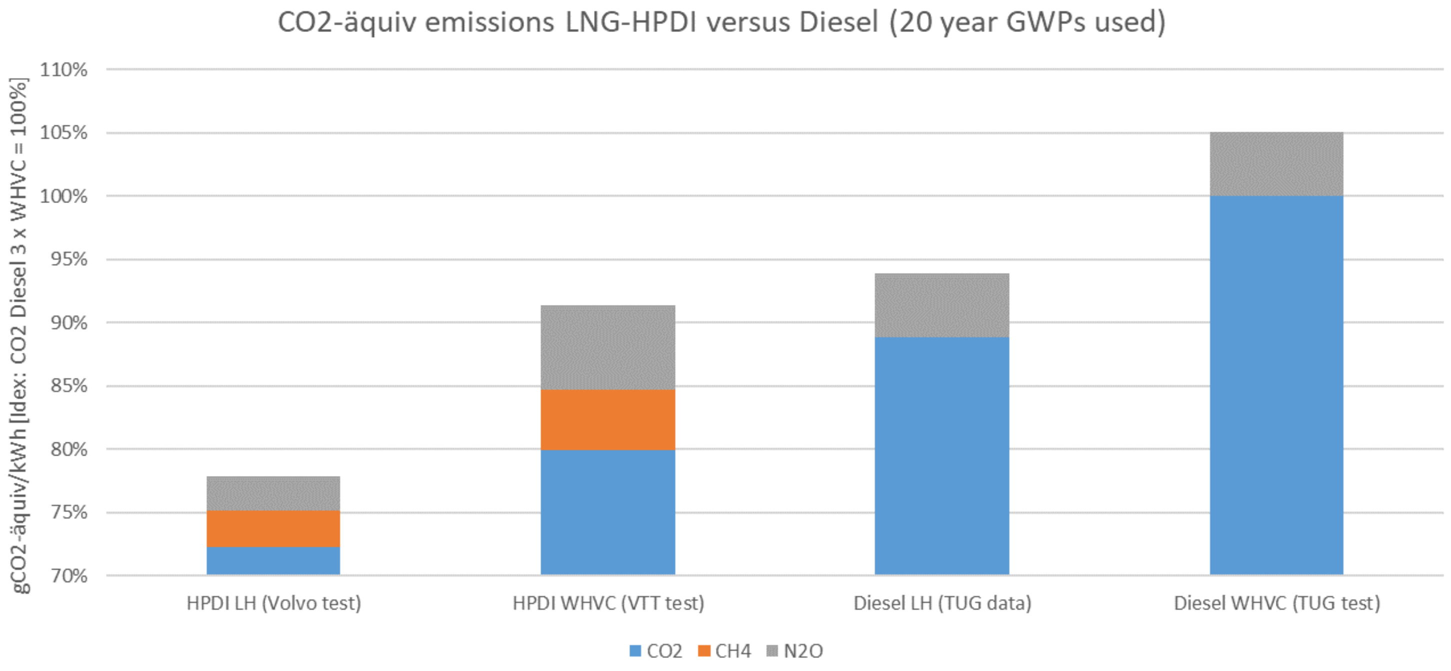
Regulation may use limits and/or allocation of CH4 and N2O to CO2 values of HDVs (via GWPs→ CO2-equiv. emissions)

<u>Current issues:</u>

Diesel HDV have significant N2O emissions as by-product from NH3 in EATS and almost zero CH4 emissions.

Gas SI engines have significant CH4 and almost zero N2O emissions.

Dual fuel with gas in CI engines (HPDI) have both, N2O and CH4 emissions.



→ Technology independent limits would be either too lax for GHG control of diesel and SI gas or hard to meet for HPDI.

	20 years	100 years
GWP CH4=	84	28
GWP N2O=	264	265

Limit Options for CH4 and N2O

oGHG-1: Set Limit for CO2-equivalents of CH4+N2O on diesel HD2 level, which could be met by CNG SI engines also (CNG have higher CH4, diesel higher N2O levels)

oGHG-2: As oGHG-1, but if limit is exceeded, the surplus (or total CO2e) is added as "other GHGs (oGHG)" to the CO2 values of the HD engine in CO2 declaration. Limits can be set lower than oGHG-1 and put less pressure on HPDI technology

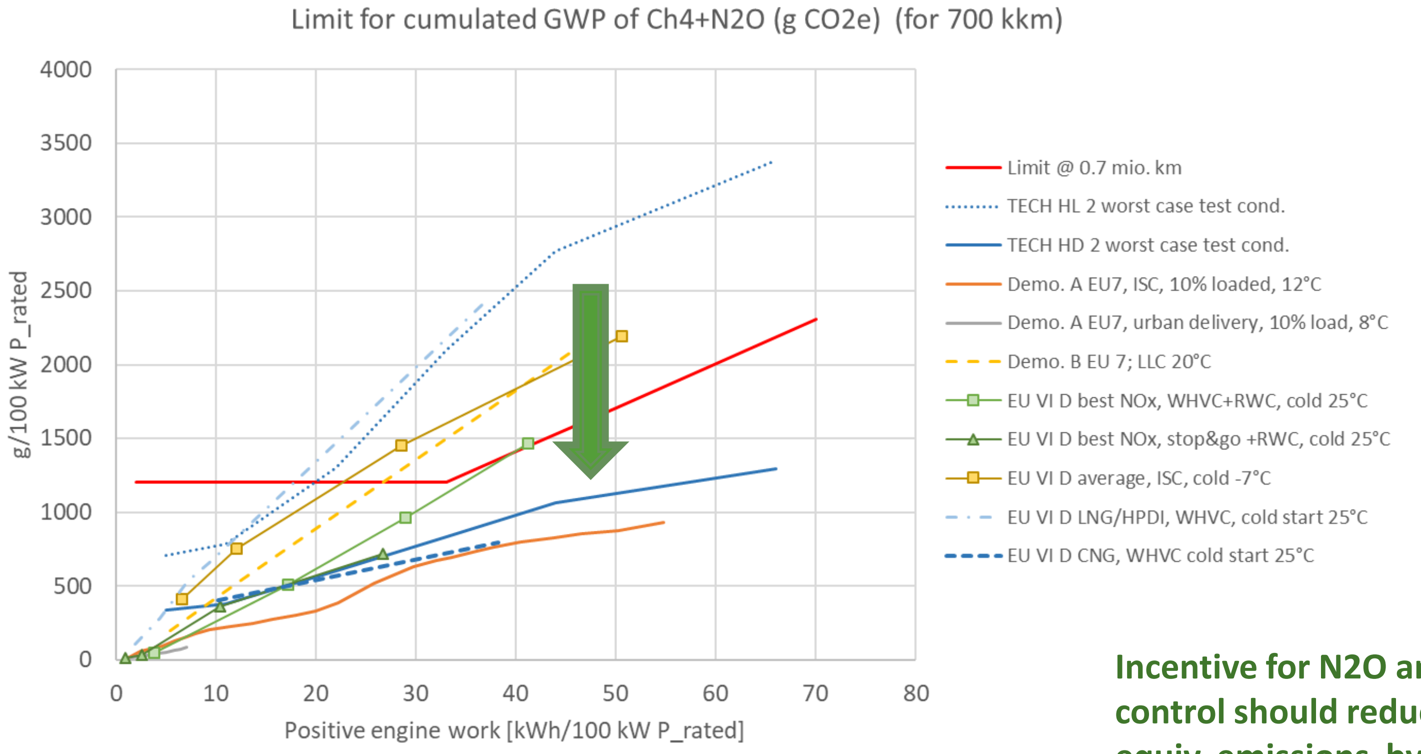
oGHG-3: separate limits for CH4 and N2O (not recommended, if same limits for diesel and CNG)

Limit Scenario oGHG-2 [g CO2e/kWh]

CO2e*	HD2&3 (oGHG-1)	oGHG-2 <5% level	EU VI
100 Perc. (1xWHTC)	50	40	
Budget (3xWHTC)	40	36	
90 Percentile	20	20	
4xWHTC	*36*	*33***	0.50g CH4 =42 *0.15g N2O=40*

* Based on 20 yr. GWPs

** Only CH4 for SI limited in EU VI.
N2O value refers to average measured in WHVC-like tests.



Incentive for N2O and CH4 control should reduce total CO2 equiv. emissions by some %

Elements for Discussion

- Emission levels of technologies
- Possible construction of emission limits

Overview on Limits

Proposals from AGVES October 2020 meeting are no longer under consideration.

Limits presented in October 2020:

Euro 7 scenarios	NOx	SPN_{10}	CO	CH_4 (1)	N_2O (1)	NMHC	NH_3
EURO VI	460	6×10^{11} (SPN_{23})	4000	500 (PI)	-	160 (CI, THC)	10ppm ~40 mg/kWh]
A	120	4×1011	1500	100	50	50	20
B	40	1×1011	400	50	25	25 (2)	10

Overview on Limits (1/2)

Limits shown for N3 > 16t: 700k km and N2, N3<16t, M3: 300k km for comparison with EU VI

Limit Scenarios for different technologies (2&3) and fuels (diesel, CNG SI, LNG/diesel CI) **[# or mg/kWh]**

100 Percentile Limit	NOx	SPN_{10}	PM	CO	NMOG	NH3	oGHGs*	*N2O***	*CH4***
HD 2 (opt. +cc SCR diesel)	450	6E+11	10	4000	225	65	50 000	160	100
HD 3 (as HD2+pre-heat)	230	6E+11	10	2000	85	65	50 000	160	85
HL 2 (LNG as HD2)	450	6E+11	10	8000	15	30	100 000	225	500
HC 2 (opt. CNG SI)	450	6E+11	10	4500	15	70	115 000	300	450

90 Percentile Limit	NOx	SPN10	PM	CO	NMOG	NH3	oGHGs*	*N2O***	*CH4***
HD 2 (opt. +cc SCR diesel)	80	1E+11	7	50	25	65	20 000	*60*	*50*
HD 3 (as HD2+pre-heat)	80	1E+11	7	50	25	65	20 000	*60*	*50*
HL 2 (LNG as HD2)	80	1E+11	7	50	10	25	45 000	*60*	*350*
HC 2 (opt. CNG SI)	80	1E+11	7	50	10	70	20 000	*10*	*90*

* For Scenario oGHG-1 ** for Scenario oGHG-3

Overview on Limits (2/2)

Limits shown for N3 > 16t: 700k km and N2, N3<16t, M3: 300k km for comparison with EU VI

Limit Scenarios for different technologies (2&3) and fuels (diesel, CNG SI, LNG/diesel CI) **[# or mg/kWh]**

„Budget" ≤ 3 x WHTC work	NOx	SPN_{10}	PM	CO	NMOG	NH3	oGHGs*	*N2O***	*CH4***
HD 2 (opt. +cc SCR diesel)	150	2.0E+11	10	1250	75	65	40 000	*140*	*30*
HD 3 (as HD2+pre-heat)	100	2.0E+11	10	600	30	65	40 000	*140*	*30*
HL 2 (LNG as HD2)	150	2.0E+11	10	2700	15	25	94 000	*200*	*500*
HC 2 (opt. CNG SI)	150	2.0E+11	10	2300	6	70	83 000	*260*	*180*

* For Scenario oGHG-1 ** for Scenario oGHG-3

* For Scenario oGHG-1 ** for Scenario oGHG-2

Thank you very much for your attention!