STUDY OF THE CAR FIFTH TDI-PCR-2L DIESEL ENGINE WITH SELECTIVE CATALYTIC REDUCTION MEDIAL LOAD

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Abstract

Author is pointing at the possibility of the utilisation of simulated computations for the research and development of the Car TDI diesel engines. Modern technical potential of them is discussed in the opening part of the paper with emphasis on the Latest Fuel Injection Technology. In this part of the paper one can find a short characteristics of the Engine, Exhaust Gas Recirculation, Selective Catalytic Reduction, MOPS Program and them before made Verification of the simulated results as real parameters.

The main part contains Computations with special point of view on the influence of modern TDI engine variable configuration and setting with Piezo Common Rail Injection System (PCR) on economic and ecological property in one-point test in medial load of the car TDI Diesel engine FIFTH PCR 2L, dedicated to era of the relevance Euro 5 (2008- 2020).

In the paper it is getting on methodological solution demonstration of Diesel Dilemma at standard apply of EGR Technology for NOx diminution with typical BSFC increase. New SCR Technology, known from large scale to Heavy Duty Tracks, is in this paper tested versus EGR. Computation and analysis results with SCRT show excellent low NOx and too BSFC and PM. For emissions amelioration with SCRT any compromises do not have to done in next time. The main simulation result is: NOx reduction efficiency of 96.5-97 %! SCRT by exploitation all the time diminish BSFC by 10-20 % and the best result is NOx, PM, CHx, CO and exhaust noise diminution in atmosphere. In principle, it can be regarded that actual Dilemma of modern Diesel engines as very well resolved.

Here presented results of Car Diesel engine TDI FIFTH 2L PCR are very comparable with real results operating with urea-SCR in large scale to Heavy Duty Tracks. It warrants us to apply practice know-how and practice realisation from HD tracks to Car diesel engines. At the end of the paper there is short substantiation of SCR profitability.

It is really to say from global point of view that diesel engines have such potential which guarantees their successful development during the next thirty-year of the 21st century. The utilization of the computer simulation is certainly a means for acceleration of the R&D work and for reduction of costs in permanent innovation of TDI-Diesel engines.

1. Introduction and principles of work hypothesis

Car TDI diesel engine is seen the best solution for reducing fuel consumption and thus reducing CO_2 emissions. The increasing of future needs on Diesel engine **fuel economy, comfort, exhaust- and noise- crude emission reductions** (Fig. 1) is possible with application of the Latest Fuel Injection Technology with integrated Electronic Diesel Control under assistance of electromagnetic or piezo-electrically valves only. The Multiple Injection Strategy in the flexible configuration with Pilot-, Pre-, Main-, After- and Post- Injection is a new phenomenon in fuel-injection systems.

In this time is most used EGR Technology with Cooling for diminution of the NOx, bath with her disadvantage of the BSFC-augmentation.

It is sure, that TDI 2 L Diesel engine and with more engine displacement for years 2010-2020 will not suffice with preventive arrangements before and inside engine only (special with EGR), but they have to be equipped also latest technology behind engine, i.e. in exhaust system (Catalysts, Sinox, Denox, Filters and other). The Technology SCR (Selective Catalytic Reduction) is nowadays the best solution for the Diesel TDI engine for Heavy Duty Tracks. SCR technology resolved the well-known DIESEL-DILEMMA between contrary dependences of the NOx and BSFC, PM and other parameters.

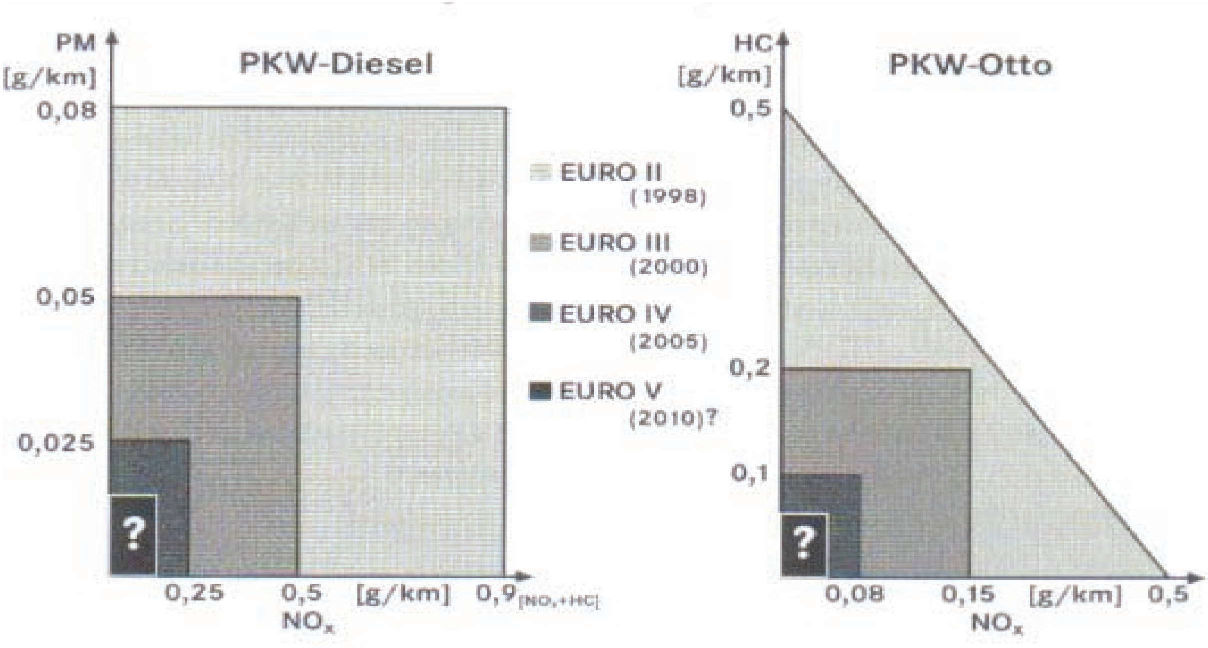


Fig. 1. EUROLIMITS for Passenger Cars

It is the fact that modern diesel engines with high pressure injection system **Common Rail (CRS)** is generally considered the most perspective concept of the further development of diesel combustion engines. For this reason I have a go at explanation and analysis **of SCR Technology (SCRT) Application for Car Diesel engine TDI-CR 2L** with means of Work Process Simulation (Virtual Experiment, Virtual Testing) at the moment **in on point test by medial load**. Show on strong points of the Paper Work Hypothesis can find and understand in Fig. 2**.**

2.2. PCR Injection System Characteristic

Piezo Common Rail System is accumulator injection system. Compared with conventional cam-driven systems PCRS provides for considerably superior flexibility in the adaptation of the injection system to the engine for passenger cars, as well as for heavy-duty vehicles, locomotives and ships. CRS has high Injection pressures of up to 1600 bar (Denso to 1800 bar), Variable begin and course - injection; Possibility of Variable Multiple Injection Strategy; Matching of injection pressure to the operating mode a. o. The injection pressure is lesser dependent of engine speed. It valid for all CRS (in vacuum circuit controlled or non-controlled).

Engine basic configuration and setting is dedicated from the best European car engines with: HD=550 ccm_{Bosch}, Holes Nr.=7, with Pilot injection=1 cmm/c, Main injection MI=38,3 cmm/c, MI-Begin = 0 deg CA BTDC, Swirl Nr.=3, Turbocharger TCH=KKK2470. By PCRS is applied to pCRmax=1300 bar, electronic Multiple Injection Strategy Duplejet with Distance A_{PI-MI}=25 deg CA and with New Profiling Injection Main Rate Type CRJU2 (Fig. 3) and with high pressure-piezo injector) [5].

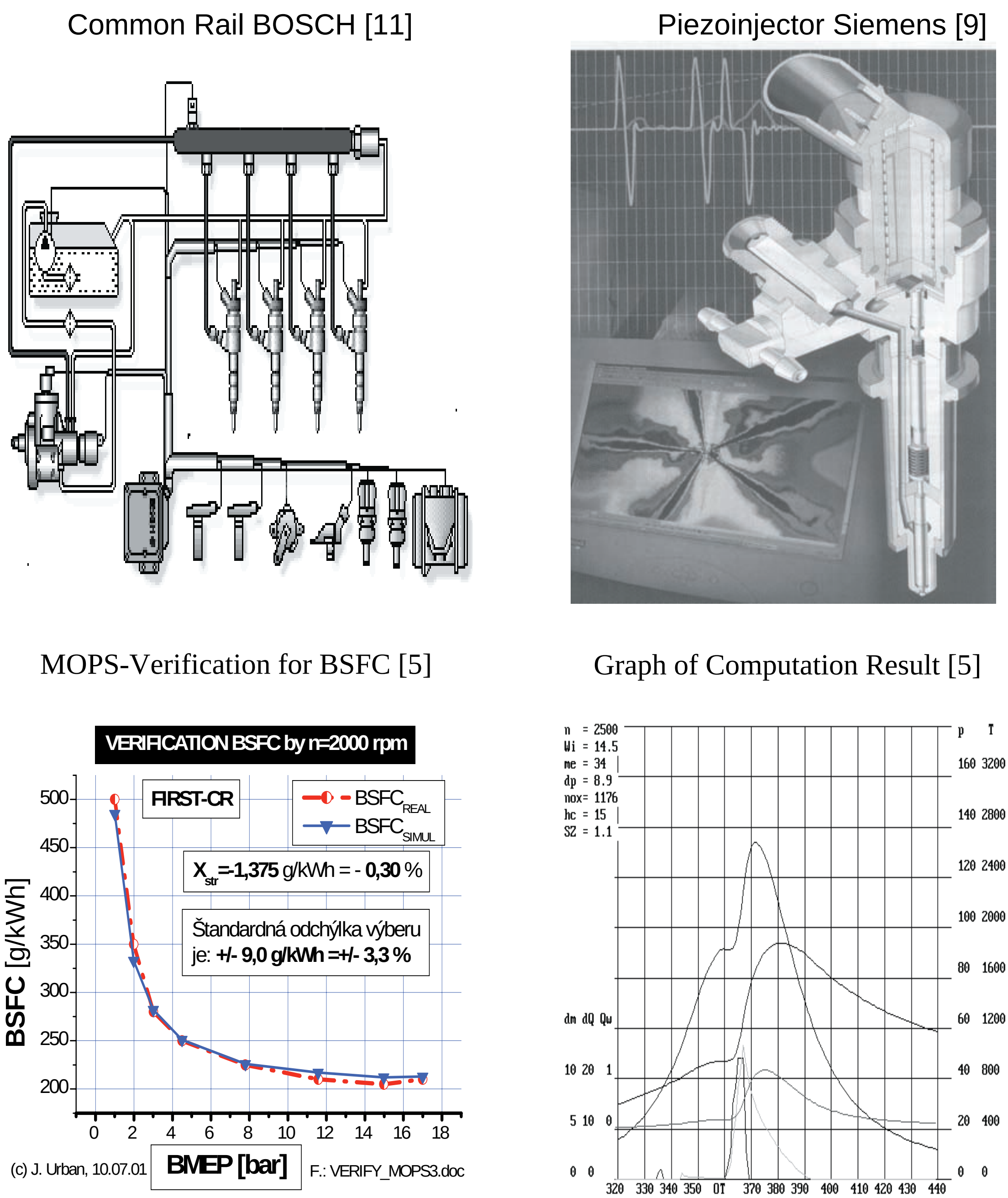


Fig. 2. Strong points of the paper work hypothesis

2.3. SCR Technology (NOx catalytic converter) characteristic

The measures taken at the engine and fuel injection system to reduce particulate emissions-PM and fuel consumption-BSFC, lead to a relatively high share of NOx in the exhaust gas. NOx catalytic converters convert the exhaust-gas nitrogen oxides (NO, NO_2) into the air component nitrogen - N_2 and CO_2. It utilises a reduction agent (Watery Urea Solution, or NH_3) which is electronically precisely sprayed for all operating states into the exhaust-gas stream.

Urea $(NH_2)_2$ CO is produced in high quantities, widely available through a dense distributor network and used for many different applications e.g. as fertilizer, animal feedstuff, additive in food and pharmaceutics. Urea dissolves easily in water. Optimal urea concentration in watery solution (WUS) for SCR Catalyst is 32.5 +/-0.5 %.

Table 1. Basic data of the configuration and basic setting of the car diesel engine TDI FIFTH 2L PCR in one point test

Torque/Speed = 183 Nm/2500 rpm

ENGINE	**TDI FIFTH 2L PCR**
Cylinders / Configuration	4 / Line
Combustion System	Diesel TDI Intercooler
Bore / Stroke [mm]	84/90
Engine Displacement [ccm]	1995
Compression Ratio [-]	19
Valve number / Cylinder	4
Rod [mm]	140
Relative d/Ḍ combustion space [-]	0,60
Turbocharger name	KKK2470
TCH Characteristic	$\eta_{CH\ max}$=0.7 by n_{TCH}=90 000 rpm, m_{air}=0.08 kg/s and p2/p1=1.7, $m_{CH\ air\ max}$=0.21 kg/s D_T=59 mm, η_{Tmax}=0.7
TCH Regulation	VTG
p2 Cool [bar]	1.7
EGR with cooling [%]	0 (For comparison 0 - 20)
Injection system	Bosch PCRS 3 generation
Number of inj. holes	7
Vertex injector angle [^{o}]	155
HD of Injector [Bosch- ccm/(10 MPa.30 s)]	550 PCRS
Injection course	PMCRS Duplex Jet
Pilot Injection dose [cmm/cycle]	1
Main Injection [cmm/cycle]	38,3
Distance PI-MI [deg CA]	25
Vol. fuel total [cmm/cycle]	39.3
p PCR in injector (2500 rpm) [bar]	1300
BSFC by 183 Nm/2500 rpm [g/kWh]	202
$Power_{max}$ [kW / rpm]	145/4000
$Torque_{max}$ [Nm / rpm]	356/2000
$BMEP_{max}$ [bar]	22.42
$BSFC_{Pe\ max}$ [g/kWh]	216
$BSFC_{Mt\ max}$ [g/kWh]	196
Vol. Power [kW/cdm]	72.5
Vol. Torque [Nm/cdm]	178

WUS is non-hazardous, non-odorous and safe to handle. Aqueous urea is stored on board a vehicle in plastic or steel tanks, not requiring any special safety equipment. All these advantages make urea solution the preferred reducing agent for nitrogen oxides [6,7,8, 9,10,11].

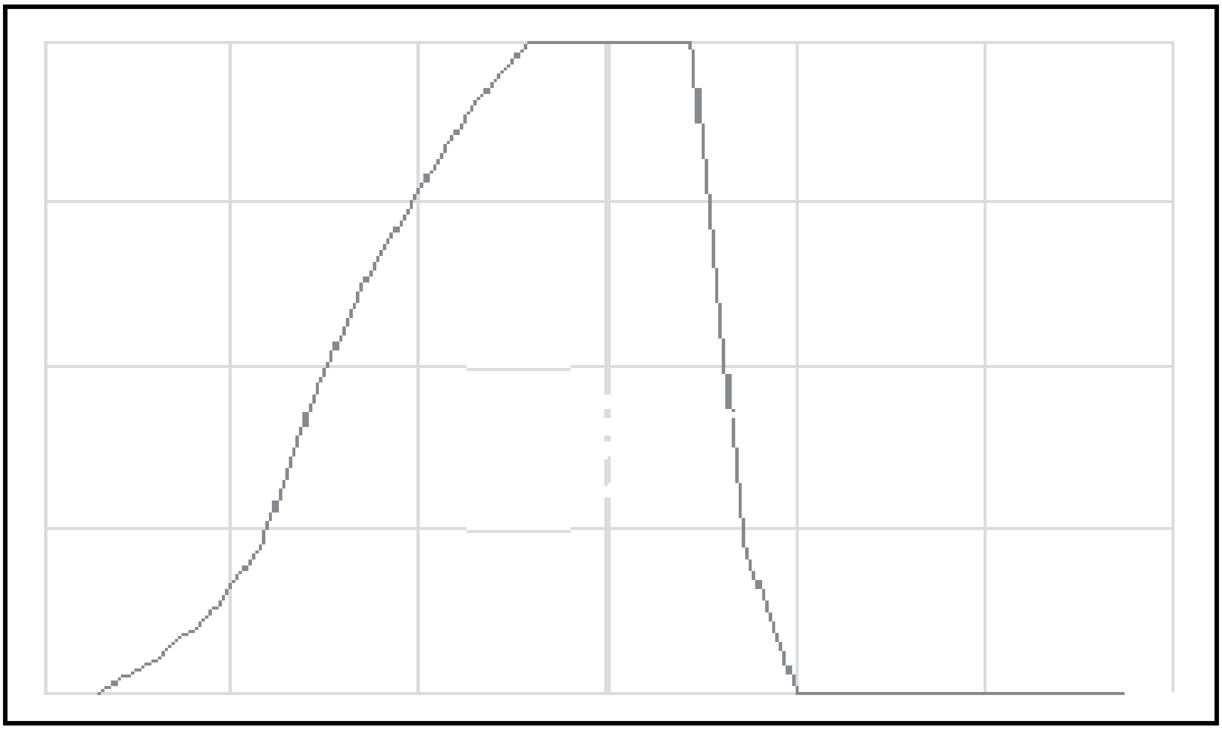
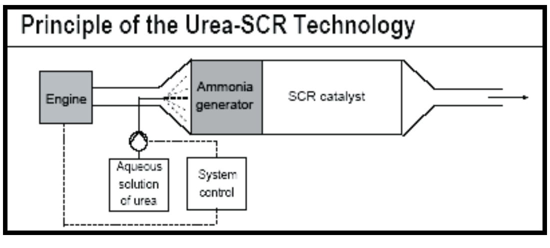


Fig. 3. New Derivative Course of Main Injection Rate: CRJU2 for FIFTH PCR 2L TDI DIESEL engine in parametric graphic formulation [5]

Principle of the Urea-SCR Technology and basic chemically process in SCR Converter can to see and understand in Fig. 4.



$$(NH_2)_2\,CO + H_2O \rightarrow CO_2 + 2\,NH_3 \quad (1)$$

NOx conversion:

$$4\,NO + 4\,NH_3 + O_2 \rightarrow 4\,N_2 + 6\,H_2O \quad (2)$$

$$6\,NO_2 + 8\,NH_3 \rightarrow 7\,N_2 + 12\,H_2O \quad (3)$$

Fig. 4. Principle of the Urea-SCR Technology and the basic chemical reactions of the urea SCR process (NH_3 generator-Urea hydrolysis-NOx conversion) [6, 9, 10]

Behind or before the SCR Catalyst can stay the Oxicatalyst. In our case by computation is not set the Oxicalyst. The SIEMENS SINOX Catalyst with cell density 200 cpsi by varied catalysers suffices safety to convert CHx and CO emissions [10].

SCR electronic control processes all the relevant engine-management data and the measured data from exhaust-gas passage with Exhaust-Gas-Sensor (EGS). The EG-Sensor, situate behind SCR-Catalyst, measures the exhaust gas oxygen content and the NOx content. The system then adapts the quantity of reduction agent metered into the exhaust gas to be in line with the specific characteristics of the engine and catalytic converter at every operating point [11,12].

The reduction catalytic converter can convert up to as much as 95-98 % of the NOx. At the same time, the SCRS in comparison with EGRS can be designed for a fuel-consumption reduction from 5 to 20 %. Definition of the NOx reduction efficiency (similarly for other components) is

$$\eta(NO_x) = [c_0(NO_x) - c(NO_x)] / c_0(NO_x) \quad \text{with}$$

$c_0(NO_x)$ - input concentration
$c(NO_x)$ - output concentration

2.4. MOPS Program Characteristic

The program of mathematical model used here **MOPS v. 16.5** (MOtor Process Simulation) is specifically determined for complex solution of work cycle of direct injection diesel engines with turbocharger, intercooler, EGR and catalyst [3]. In output of calculation (Fig. 5) are cca 50 parameters, which could be then processed by standard method of tables and graphs. In Fig. 2 left down is documented before made MOPS-Verification of the simulated and real parameter BSFC. This result is strong argument for MOPS-Program using in next computation and analyse.

2.5. Short Methodology of the Solution

Methodological is in paper Inverse Application of the Methodology Downsizing used. Computation is oriented on the finding of the influence of the potential technical means (SCRT versus EGRT) by equal conditions on **economic (BSFC) and main ecological engine parameters (NOx, PM, CHx, Soot (Smoke))**.

Basic condition in one-point test of medial load is: **Torque/Speed = 183 Nm / 2500 rpm.**

3. Graphic presentation of Computation results

3.1. Direct graphic outputs from computing

The computation is analogous with experimental research in test cell from methodology point of view. Direct graphic outputs from PC (MOPS Program v.16.5) for all point tests presents Fig. 5**.** Every one regular characteristic has 5-6 quantity of the main regular parameter NOx (with before determined constant optimal Injection Begin of main injection rate = 0 deg $_{\text{CA BTDC}}$) as per independent dimension. From direct tabular outputs of computation in MOPS program, chosen parameters they were configured in program ORIGIN v. 6 to the tables and graphs. This paper contains mainly the graphs only.

3.2. Engine parameters - EGR and various SCR Relationship

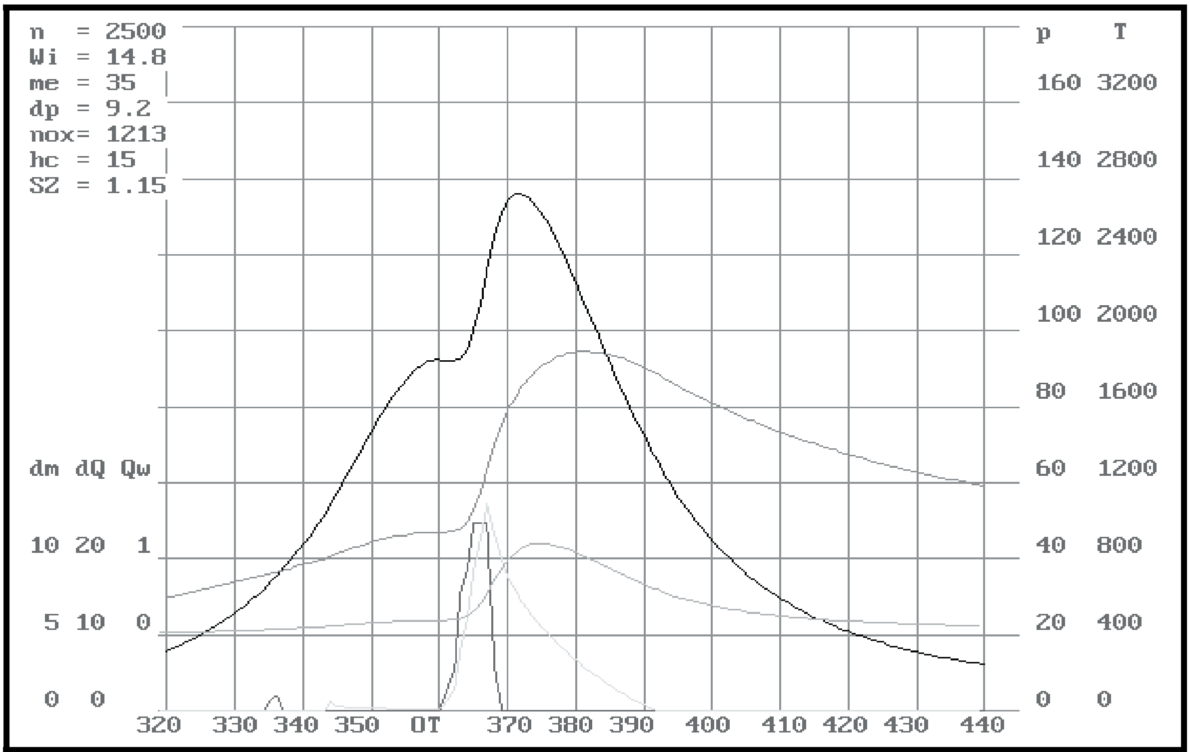
Fig. 5 shows computing output for engine-out sans EGR, sans SCR and sans OXICAT so-called the point of departure (baseline).

Fig. 6 as "pipe" diagram presents the graphic dependence of complex economic and ecological parameter in first variant on EGR-dose (from 0 % to 20 %) and in second variant of urea SCR converter-dose (WUS from 0 % to 100 % to Stoichiometry) in one point test:

Torque/Speed=183 Nm/2500 rpm. Independent parameter is NOx in g/kWh. This graph has to respond   the question nip and tuck by resolution of the well-known Diesel Dilemma.

CAR TDI DIESEL ENGINE-OUT FIFTH-2 L PCR-DUPLEJET

The point of departure (baseline)



DATEN:

n	=	2500	Qe	=	39.3						
FB	=	0	SB	=	0	SD	=	14			
lam	=	1.87	etal	=	.91	m	=	.073			
p2	=	1.711	p2s	=	1.696	p3	=	1.426 (1.925)	p4	=	1.426
T2	=	101	T2s	=	34						
T3	=	579	T4	=	518	T4a	=	472			
T5	=	518	T5a	=	472						
nl	=	95400	ma	=	2						
etav	=	.7	etat	=	.57						
Pv	=	-4.1	Pt	=	4						
etatn	=	.43	Pn	=	0						
pr	=	2.37	pl	=	.63	pvges	=	3			
pe	=	11.53	Pe	=	47.9	Md	=	183	be	=	202
NOxp	=	8.63	HCp	=	.13	Part	=	.179	Lp	=	128.6
NOx	=	1176	HC	=	16	SZ	=	1.11			
Tkomp	=	748	Tzmax	=	1878	Pzmax	=	134	plmax	=	1300
AGR	=	0	Xwas	=	0	F-Mi	=	1			
Wi	=	14.53	Qw	=	.24						

Fig. 5. Computing outputs sans EGRT, sans SCRT and sans OXICAT

Engine FIFTH-EGR Cooled versus FIFTH-SCR
Torque/Speed = 183 Nm / 2500 rpm

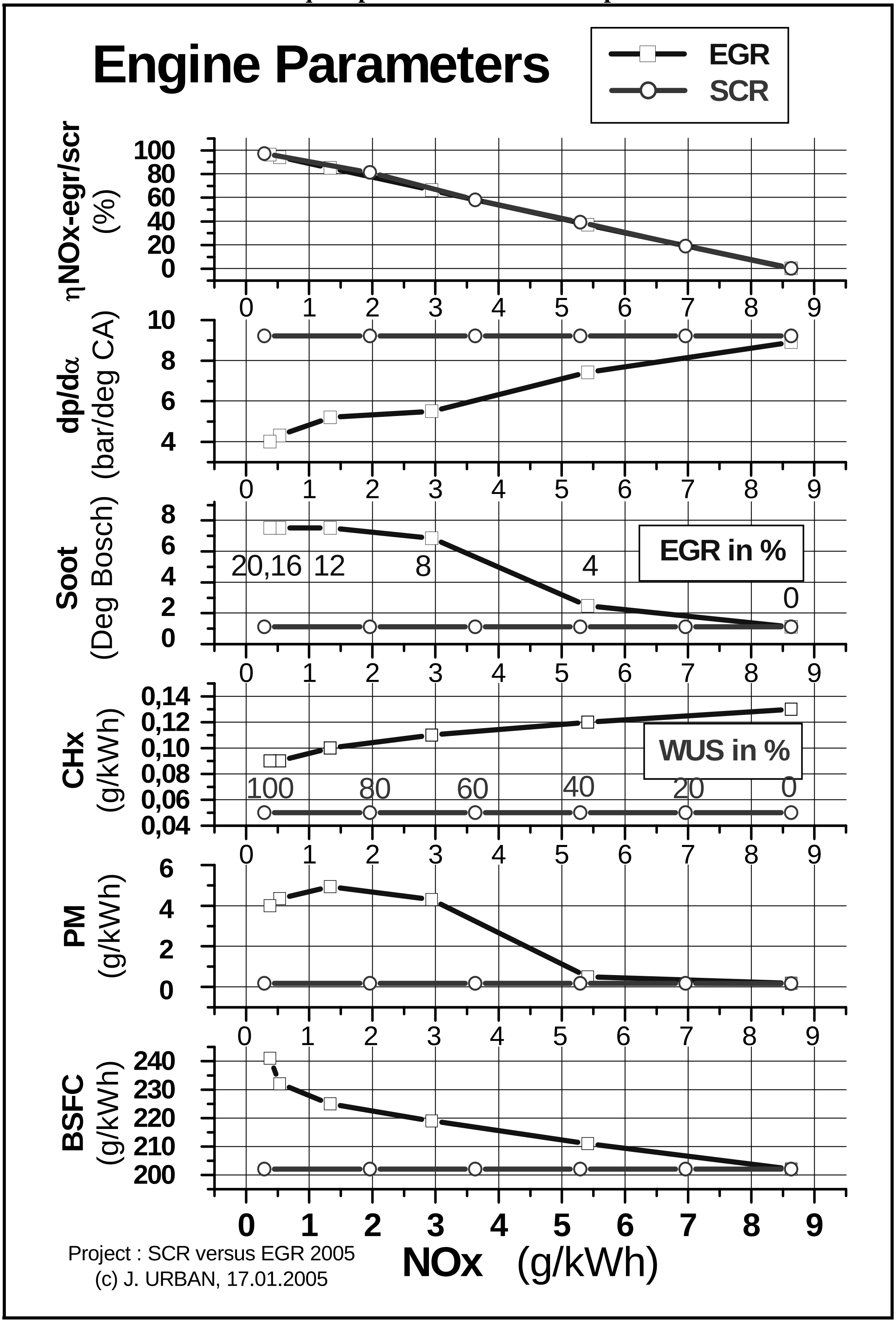


Fig. 6. Show to graphic course of economic and ecological parameters versus NOx. Catalyser by SCR 2L is Zeolite. Resolution of the Diesel Dilemma?

Torque/Speed = 183 Nm / 2500 rpm EGR = 20 %, WUS = 100 %
B-Engine-out, C- EGR, D-SCR 2L Zeolite, E-SCR 2L VTi, F-SCR 0,8L VTi, G-SCR 4,5L Pt

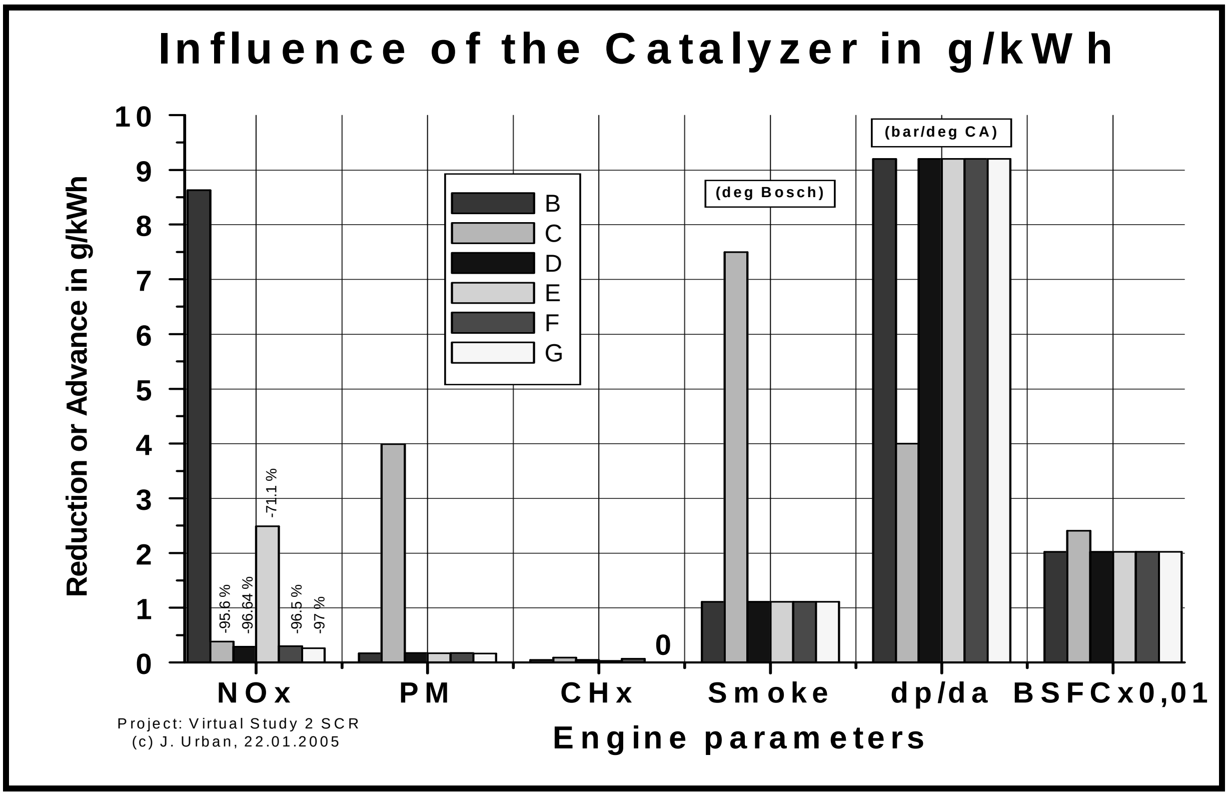


Fig. 7. Show to graphic course of six technical configurations and setting influence on car FIFTH - PCR 2L DIESEL engine parameters in g/kWh

Fig. 7 shows in column graph important dependences of engine economic and ecological parameters in percentage and in physical dimension from six technical configurations and setting influence of the car FIFTH - PCR 2L DIESEL engine.

4. Results Analysis, Evaluation and Discussion

The next partial conclusions result from presented diagrams.

4.1. Dynamic parameters (Fig. 5)

Dynamic parameters are from methodology point of view (one point test by Torque/Speed = 183 Nm/2500 rpm) equal magnitude. It's applied too for Power = 47.9 kW and for BMEP = 11.53 bar. Engine maximal torque is 356 Nm by 2000 rpm, maximal power is 145 kW by 4000 rpm. These parameters manifest that engine configuration and setting is more extreme per regard: The research must be forwards.

The best **economic parameter is BSFC=202 g/kWh**. It's valid for engine baseline and for all SCR configurations of exhaust aftertreetment (catalysts). Not counting by EGR > 0 %. With EGR = 8 % BSFC = 219 and with EGR = 20 % BSFC = 241 g/kWh. In last case the augmentation is 19.3 %! Similarly it's by PM emission. **The EGR Technology brings the Diesel Dilemma in contradictory course of main parameter NOx versus BSFC and PM.**

The best NOx and the best BSFC contemporary give in this study alone SCR Technology particularly SCRT with catalyser/volume: Zeolite/2L, V_2O_5+TiO_2/0.8L and Pt/4.5L. **Their NOx reduction efficiency is 96.5-97 %!** This is excellent result. Next notable is at the same time the very low value of CHx rate behind SCR catalyst (0-0.07 g/kWh), id est. in SCR Cat realizes parallel oxidation process. Value PM (0.166-0.176 g/kWh) and soot (1.11 deg Bosch) is acceptable (or using of the filters new generation).

Tab. 2. Results of influence of varied means on engine FIFTH 2L PCR economic and ecological parameters

Parameter and dimension	**Baseline (Engine-out)**	EGR 20%	SCR2L 100% Zeolite	SCR2L 100% V+Ti	SCR0.8L 100% V+Ti	SCR4.5L 100% Pt
NOx (g/kWh)	**8.63**	**0.38**	**0.29**	**2.49**	**0.3**	**0.26**
NOx reduction (%)	**0**	**95.6**	**96.64**	**71.1**	**96.5**	**97**
PM (g/kWh)	**0.185**	**3.993**	**0.173**	**0.170**	**0.176**	**0.166**
CHx (g/kWh)	**0.13**	**0.09**	**0.05**	**0.03**	**0.07**	**0**
Soot (deg Bosch)	**1.11**	**7.5**	**1.11**	**1.11**	**1.11**	**1.11**
dp/dα (bar/deg CA)	**9.2**	**4**	**9.2**	**9.2**	**9.2**	**9.2**
BSFC (g/kWh)	**202**	**241**	**202**	**202**	**202**	**202**
BSFC (%)	**100**	**119.3**	**100**	**100**	**100**	**100**

4.2. Economic and ecological parameters (Fig. 5, 6, 7 and Tab. 2)

From ecological parameters rests untouched **dp/dα**. Its potential for diminution is in engine setting (Injection Begin, Injection Course, Variable Multijet) and in engine noise elimination (Isolation).

Here present results of Car Diesel engine TDI FIFTH 2L PCR are very comparable with really results operating with urea-SCR in large scale to Heavy Duty Tracks [6,7,8]. It is warrants **to apply practice know-how and practice from HD tracks in car diesel engines.**

By using of SCR Technology is needed to calculate with capital budget 40-70 euro/kW (SCR converter lifetime is 10 000-40 000 h), with operating costs 3-4 euro/MWh (watery urea solution consumption is 15-20 cdm / MWh), resp. NOx costs 0.35 euro/kg NOx [9,10]. **Opposite SCRT by exploitation all the time diminish BSFC of 10-20 % and the best result is NOx, PM, CHx, CO and exhaust noise diminution in atmosphere. In principle can regard to actual Dilemma of modern Diesel engines as very good resolved.**

5. Conclusion

On basis achieved results from the above-mentioned calculations and analysis is possible to observe, that designed source innovation is in harmony with worldwide evolutional trend in all diesel engine volume class [1,3,5,6]. Computation was oriented on the finding of the influence of the variable engine configuration on economic and ecological parameters in one-point test. Discussion shows on important specific very good alias negative properties of applied **EGR- or SCR-Technology** on economic and ecological engine parameters.

The paper result shows, that in medial load (Torque/Speed=183 bar/2500 rpm) can be modern Car Diesel Engine TDI FIFTH 2L PCR with SCRT better as with EGRT.

The best **economic parameter is BSFC=202 g/kWh**. It's valid for engine baseline and for all SCR configurations of exhaust aftertreatment (catalysts). Not counting by EGR > 0 %. With EGR = 8 % BSFC = 219 and with EGR = 20 % BSFC = 241 g/kWh. In last case the BSFC augmentation is 19.3 %! **The EGR Technology brings the Diesel Dilemma in contradictory course of main parameter NOx versus BSFC and PM.**

The best NOx and the best BSFC and PM contemporary give in this study alone **SCR Technology** particularly SCRT with catalyser / optimal volume: Zeolite/2L, V_2O_5+TiO_2/0.8L and Pt/4.5L. **Their NOx reduction efficiency is 96.5-97 %!** This is excellent result. Next notable is at the same time the very low value of CHx rate behind SCR catalyst (0-0.07 g/kWh), id est. in SCR Cat realizes parallel oxidation process. Value PM (0.166-0.176 g/kWh) and soot (1.11 deg Bosch) is acceptable (or using of the new generation filters).

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It is sure, that TDI 2 L diesel engine type for years 2008-2015 will not suffice with preventive arrangements before and inside engine only, but they have to be equipped also latest technology behind engine, i.e. in exhaust system. At complex engine innovation will grow on R@D works in addition connect with solution of engine noise and vibrations, its lifetime, reliability, decreasing production costs and others.

It is really to say from global point of view that diesel engines have such potential, which guarantees the successful development in coming thirty years of the 21st century. The utilization of the computer simulation is certainly a means for acceleration of the R&D work and for reduction of costs in permanent innovation of TDI - Diesel engines.

References

[1] Trnka J., Urban J., Spaľovacie motory, učebnica pre TU, Vydavateľsvo ALFA, 1992, ČSFR.

[2] Kollektivarbeit, Handbuch - Verbrennungsmotor, Siemens VDO Automotive, Vieweg 2002, s. 438, BRD.

[3] Huber G., Výpočtový program MOPS-Motor Prozess Simulation, v. 16.5, Privat, 2002, BRD.

[4] Steinpanzer F., Kratochwil H., Mattes W., Steinmayr T., Neuer Vierzylinder - Dieselmotor von BMW mit Common-Rail-Einspritzung, MTZ 11/2001/62, S. 888-897, BRD.

[5] Urban J., Termodynamický a technický potenciál naftových motorov typu TDI Common - Rail, Archív zverejnených 27 publikácií z rokov 1995-2004 ku pripravovanej monografii, s. 340, Bratislava, SR.

[6] Miller W. R., Klein J. T., Müller R., Dölling W., Zürbig J., The Development of Urea-SCR Techno-logy for US Heavy Duty Trucks, FL-164 SAE 2000-01-0190, 2000, USA.

[7] Rigby K., Klatt A., Libuda T., Zürbig J., SCR, The most effective technology for NOx reduction in large combustion plants, NOXCONF: International Conference on Industrial Atmosferic Pollution, Paris, 21-22.3. 2001, F.

[8] Cartillieri W. und Kollektiv, Entwicklung es verbrauchsoptimirten EU 5 NFZ-Dieselmotors mit Harnstoff-SCR-Abgasnachbehandlungssystem, VDA Technischer Kongress 2000, BRD.

[9] Siemens Automotive CD, POWER VISION, Experience the Power of Siemens Automotive, BRD.

[10] Argillon GmbH CD, SINOX Emissions Control, Redwitz, BRD.

[11] Robert Bosch GmbH CD, Diesel Systems, Stuttgart, BRD.

[12] Gstrein W. und Kollektiv IVECO AG, CH, Chancen des Dieselmotors bei verschärften Emissionsvorschriften, 9. Tagung "Der Arbeitsprozess des Verbrennunungsmotors", Technische Universität Graz, 25.-26.September 2003, VKM-THD Mitteilungen, Heft 83-2003, Graz, A.