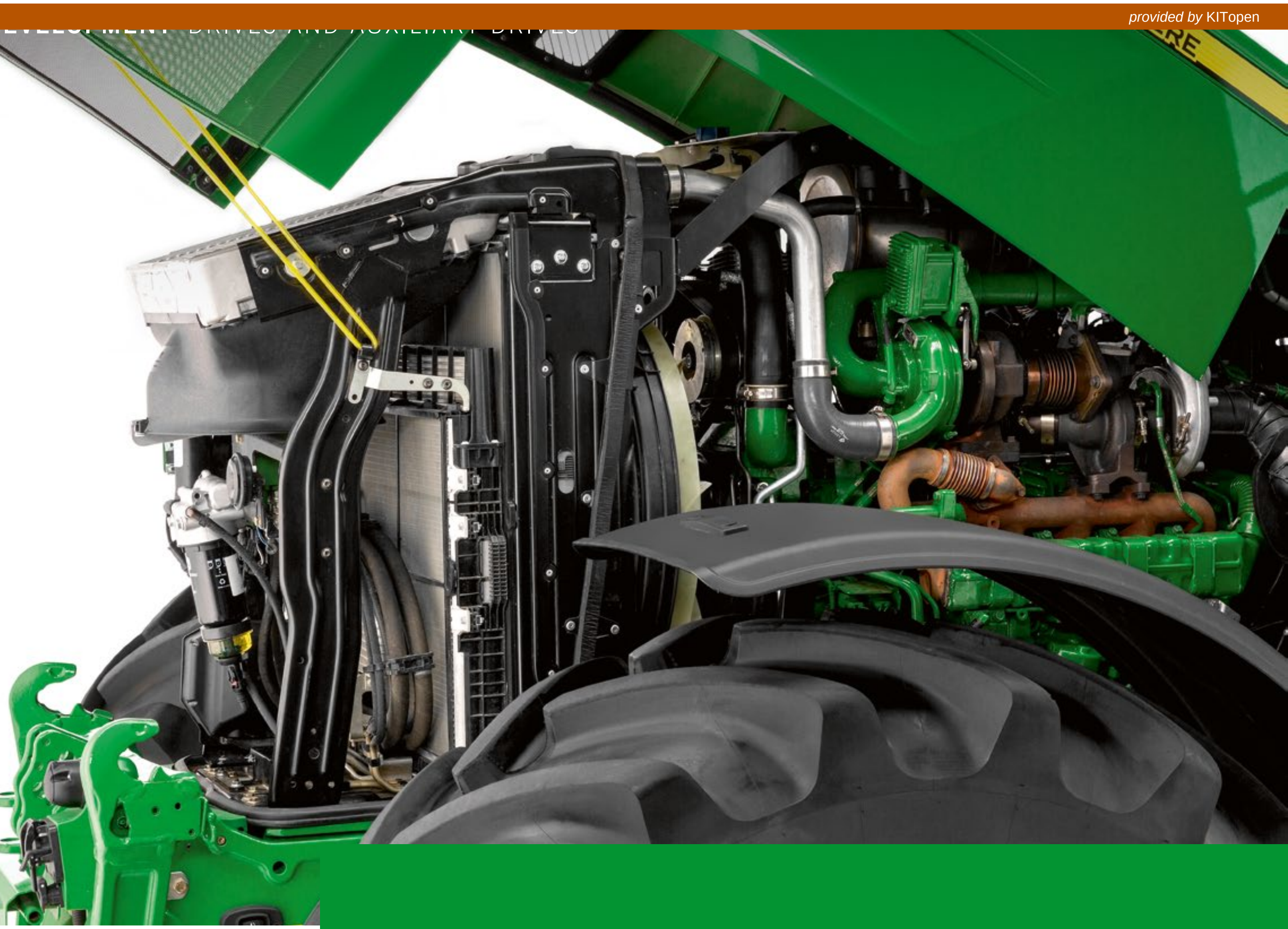


© John Deere

Development of Tractor Engines in the Past Twenty Years

AUTHORS

Dipl.-Ing. Agr. Dipl.-Ing. Wirtsch. Roger Stirnimann, Executive MBA is a Lecturer in Agricultural Engineering at Bern University of Applied Sciences/School of Agricultural, Forest and Food Sciences (HAFL) in Zollikofen (Switzerland).

Dipl.-Ing. Danilo Engelmann is Research Assistant and Head of the Acoustic Chassis Dynamometer at the Chair of Mobile Machines of the Karlsruhe Institute of Technology (KIT) in Karlsruhe (Germany).

Since 1990 years, EU legislation has also been applicable to non-road vehicles, including tractors used in the agricultural sector. As a result of the stepwise introduction of exhaust gas EU emission Stages I to IV, emissions of particle mass and nitrogen oxides, the main pollutants of diesel engines, in the middle and upper power classes have been reduced by about 95 %. This could only be achieved by the intensive further development of both engine and exhaust gas technologies. HAFL and KIT explain the development and some underlying technical relationships in this sector, with a classical tractor diesel engine being used as an example.

MOTIVATION

As regards cars, a rather persistent trend is downsizing of combustion engines. Compared to predecessor engines, displacement is decreased, which is compensated by charging. Development of tractor engines, however, has been characterised by the trend of higher mean effective pressure at constant displacement. By increasing the torques, outputs were enhanced. In the range from 100 to 140 kW, smaller six-cylinder engines (1 to 1.15 l displacement per cylinder) were increasingly replaced by four-cylinder systems. In principle, this may also be referred to as downsizing. Still, the size of existing engines remains the same, while use focuses on the next smaller engine series.

This article deals with output increase at constant displacement. Taking the 6-cylinder diesel engine of 6.8 l displacement by John Deere as an example, development of tractor engines in the past twenty years is outlined. In addition, the engine and exhaust gas technologies chosen by the manufacturer to comply with the increase stricter emission limits are highlighted. In 1993, the above engine was first installed in the tractor model 6800. It increase replaced the six-cylinder machine of 5.9 l displacement that had been used until then in the range from 70 to 90 kW. **TABLE 1** illustrates the development of tractor models manufactured in Mannheim. The data were taken mainly from sales documents. Some were obtained directly from John Deere or sales partners.

CHARGING POTENTIAL RECOGNISED EARLY

As early as in the mid-1990s, the potential of modern technologies tractor engines, for example turbocharging and common-rail injection, was reported in several publications [1, 2]. Engine outputs per unit of displacement of the 4 to 8 l classes relevant at that time were prognosticated to reach an average of 30 kW/l by 2012. Today, engine outputs per unit of displacement indeed are in the range of 30 to 45 kW/l. Current displacements and numbers of cylinders, however, differ strongly from the prognosis. Three-cylinder engines are barely used anymore. In the transition range from 100 to 140 kW, smaller aggregates of six cylinders (1 to 1.15 l displacement per cylinder) are increasingly replaced by four-cylinder engines, **FIGURE 1**. Larger six-cylinder engines have an increased output at constant displacement. This development is closely linked with turbocharging that is currently applied in nearly all tractor engines to comply with exhaust emission limits. The continuously variable power-split transmissions frequently applied in tractors are characterised by high conversion ranges and, hence, offer ideal conditions for the conversion of high torques as well [3].

NO CLASSICAL DOWNSIZING

When looking at the 6.8 l reference engine, it can be seen that maximum torques in top tractor models have increased from 536 to 1167 Nm since 1993. This corresponds to a factor of more than two, even when considering the different measurement standards applied (ECE-R24, 97/68EG). When taking into account the additional torque resulting from the boost feature applied today, the increase is even more pronounced. Specific work of the engine, the mean effective pressure, increased accordingly. In the current top model, mean pressure reaches about 23 bar at maximum torque with boost (97/68EC). The constant torque rise of 38 to 40 % and the higher output at constant nominal speed of 2100 rpm allow the conclusion to be drawn that the torque at nominal power also increased considerably. This caused the output per unit displacement to rise as well, **FIGURE 2**. This is no downsizing, as displacement was not

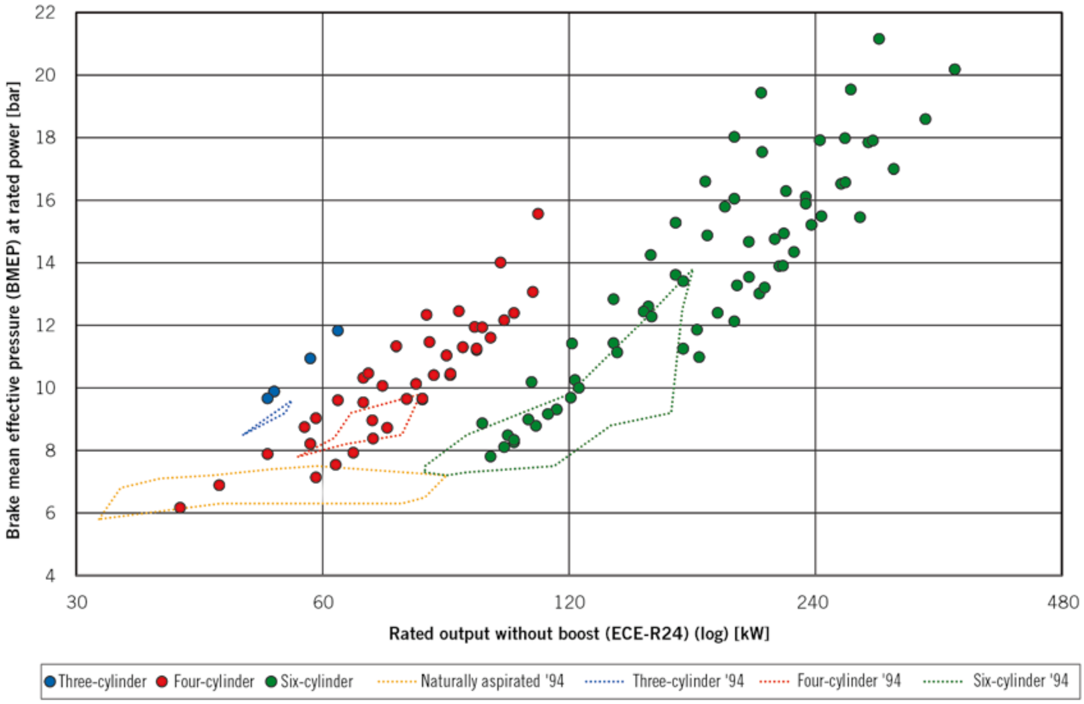


FIGURE 1 Comparison of BMEP to the rated power for on the market available tractors 1994 to 2017 (colour-filled points as of 2017; coloured areas indicate point clouds from 1994) (© HAFL)

General information on the tractor-/engine model										
Tractor model	6800	6900	6910	6910S	6920S	6930	7530	6210R	6215R	6250R
Introduction year	1993	1995	1997	1999	2002	2007	2008	2012	2016	2017
Emission stage	-	-	I	I	II	III A	III A	III B	IV	IV
Engine designation			PowerTech	PowerTech	PowerTech	PowerTech Plus	PowerTech Plus	PowerTech Plus PVX	PowerTech PVS 1)	PowerTech PSS
Displacement [l]	6.788	6.788	6.788	6.788	6.788	6.788	6.788	6.788	6.788	6.788
Number of cylinders	6	6	6	6	6	6	6	6	6	6
Rated speed [rpm]	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100
Compression ratio	17:1	17:1	17:1	17:1	17:1	17:1	17:1	17:1	17:1	17:1
Power characteristics	Constant power	Constant power	Extra power	Extra power	Extra power	Extra power	Extra power	Extra power	Extra power	Extra power
Boost performance	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Engine technologies/parameters										
Injection	Distributor pump	Distributor pump	Distributor pump	VP44 2)	Common Rail 3)	Common Rail	Common Rail	Common Rail	Common Rail	Common Rail
Motor control	Mechanical	Mechanical	Mechanical	Electronic	Electronic	Electronic	Electronic	Electronic	Electronic	Electronic
Maximum injection pressure [bar]	N/A	650 4)	1100	1100	1350	1600	1600	2000	2500	2500
Number of nozzle holes	4	4	4	4	N/A	N/A	N/A	6	6	6
Number of inlet / outlet valves	2	2	2	2	4 3)	4	4	4	4	4
Turbocharger technology	Standard	Standard	Standard	Standard	Standard	VGT	VGT	VGT	VGT	2-st./VGT
Charge air cooling (air / air)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Loading pressure at rated power [bar]	0.7–0.9	0.7–0.9	0.7–0.9	0.7–0.9	0.7–0.9	N/A	N/A	1.75–1.95	N/A	2.25–2.45
Maximum full load loading pressure [bar]	N/A	N/A	N/A	N/A	N/A	1.62	1.95	2.47	2.23	2.81
Fan blades	Visco	Visco	Visco	Visco	Visco	Visco	Visco	Visco	Visco	E-Visco
Emission technologies										
Refrigerated exhaust gas recirculation	-	-	-	-	-	Yes	Yes	Yes	Yes	Yes
Diesel oxidation catalyst	-	-	-	-	-	-	-	Yes	Yes	Yes
Diesel particle filter	-	-	-	-	-	-	-	Yes	Yes	Yes
Selective catalytic reduction	-	-	-	-	-	-	-	-	Yes	Yes
Performance specifications										
Rated power according to ECE-R24 [kW]	88	96	99	103	N/A	110	N/A	N/A	150	176
Maximum power according to ECE-R24 [kW]	90	98	102	N/A	N/A	N/A	138	163	167	195
Rated output with boost according to ECE-R24 [kW]	N/A	N/A	N/A	110	116	129	143	N/A	178	205
Maximum oower with boost according to ECE-R24 [kW]	N/A	N/A	N/A	N/A	124	132	148	175	182	213
Speed at maximum power [rpm]	N/A	N/A	N/A	1900	1900	1900	1900	1900	N/A	N/A

Torque specifications										
Torque increase [%]	34	38	34.5	38	38	38	38	40	40	40
Maximum torque according to ECE-R24 [kW]	536	603	606	630	N/A	N/A	N/A	N/A	N/A	N/A
Maximum torque according to 97 / 68EC [kW]	N/A	N/A	N/A	N/A	700	715	828	983	1004	1167
Torque increase with boost [%] 4)	N/A	N/A	N/A	N/A	28	28	28	28	28	28
Maximum torque with boost according to 97 / 68EC [kW] 4)	N/A	N/A	N/A	N/A	710	768	867	1030	1094	1240
Speed at maximum torque [rpm]	1300	1300	1365	1400	1500	N/A	N/A	1600	1600	1600
Calculated effective medium pressure										
... at rated power according to ECE-R24 [bar]	7.41	8.08	8.33	8.67	-	9.26	-	-	12.63	14.82
... at maximum power according to ECE-R24 [bar]	-	-	-	-	-	-	12.84	15.17	-	-
... at rated power with boost to ECE-R24 [bar]	-	-	-	-	9.77	10.86	12.04	-	14.98	17.26
... at maximum torque according to ECE-R24 [bar]	9.93	11.17	11.22	11.67	-	-	-	-	-	-
... at maximum torque according to 97/68 EC [bar]	-	-	-	-	12.96	13.24	15.33	-	18.59	21.61
... at maximum torque with boost to 97/68 EC [bar]	-	-	-	-	13.15	14.22	16.06	19.07	20.26	22.96

1) first models PSS, from 2017 PVS 2) with AutoQuad (automatic transmission) 3) from model year 2003 4) Estimates of the authors

TABLE 1 Development of the 6.8-l diesel engine from John Deere using the example of the top models of the tractor series 6000/6010/6020/6030/7030/6R (© HAFL)

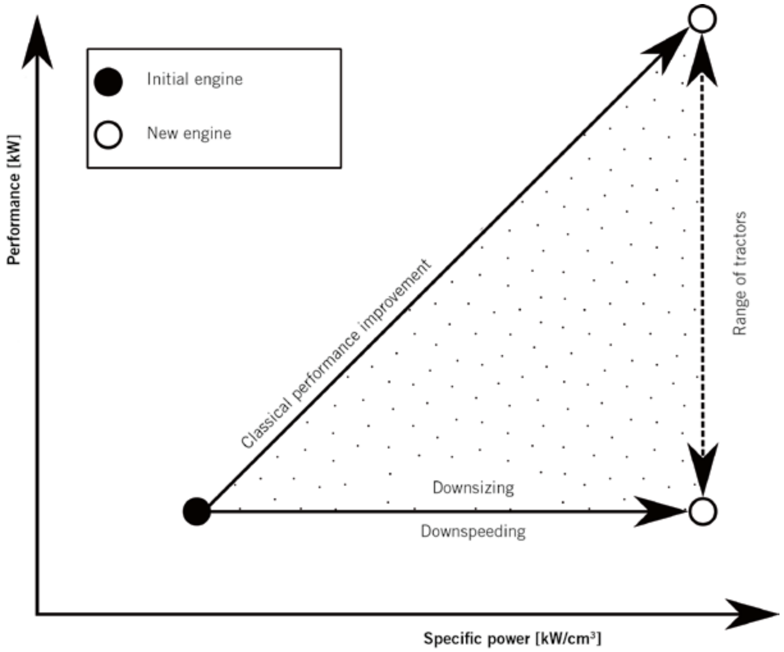


FIGURE 2 Comparison of downspeeding/downsizing with performance enhancement (© KIT)

decreased, **FIGURE 2** and **FIGURE 3**. It may rather be compared to downspeeding, **FIGURE 3**. Downsizing means that displacement is decreased at constant load. The engine is subjected to a higher specific load, as a result of which emissions and consumption are reduced. The key technology used for this purpose is turbocharging. It has been applied in car combustion engines for several years now. Another option is downspeeding. In this case, displacements are about the same, while speeds are reduced. With the help of accordingly adapted gear ratios, consumption can be reduced to a similar extent [4].

CHARGING AS A KEY TECHNOLOGY

In the top models manufactured in Mannheim, the reference engine always was equipped with turbocharging. Before stricter exhaust gas emission limits were

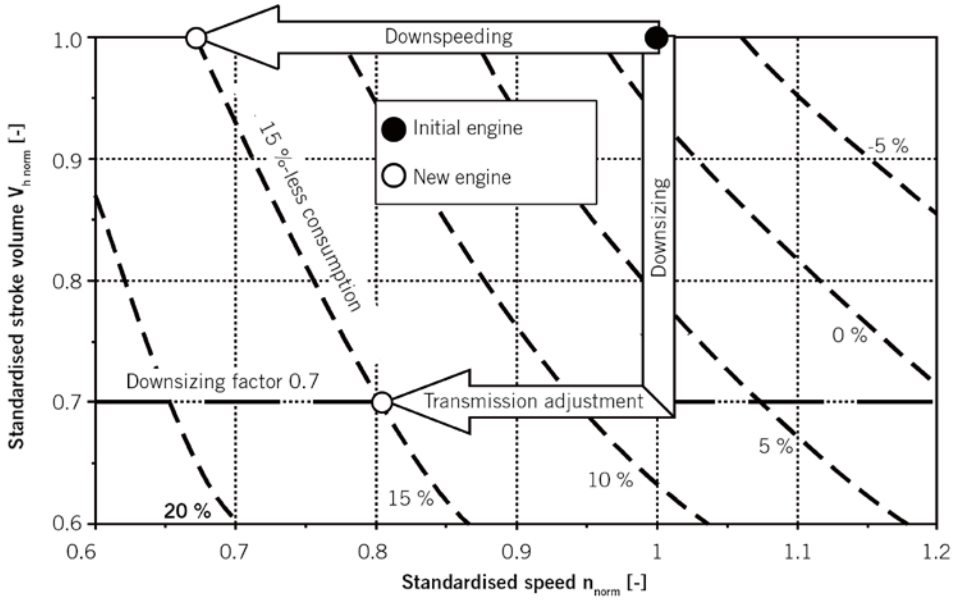


FIGURE 3 Definition of downspeeding/downsizing according to [4] (© [4])

adopted, manifold pressure at nominal speed ranged from 0.7 to 0.9 bar. Charging means that air of a density higher than that of ambient air is supplied to the cylinders of the combustion engine. With the increased air mass flow, an increased fuel mass can be injected and the engine output rises. Density is increased by means of a charger that increases pressure. As this also causes the temperature to rise, density does not increase to the same extent as pressure. By cooling the charged air in a downstream cooler, air density at a certain pressure can be increased considerably [4]. In the reference engine, charge air cooling was first applied in the late 1990s and since then has been one of the basic features. Thanks to the positive impacts of smaller peak temperatures on NO_x emissions, there are hardly any tractor engines that are not equipped with this system today.

In 2002, John Deere completely revised the engines and switched to four-valve technology and common-rail injection. Thanks to four-valve technology, cross-sections of the inlet and outlet valves were increased and cylinder filling was optimised [4]. Another advantage of this technology is the possibility to arrange the injectors in the centre and vertically above the combustion chamber. Together with accordingly shaped piston recesses and adapted injection geometry, this leads to a better fuel distribution. Another important step with respect to charging was the introduction of turbochargers of variable geometry (VGT) in 2007. Using adjustable turbine vanes, maximum air quantity can be combined with a good response behaviour at low exhaust gas enthalpy. This helps improve transient response in case of acceleration and load skips as well as mixture formation under varying operation conditions. Apart from the turbocharger of variable geometry, the current top model is equipped with another big-

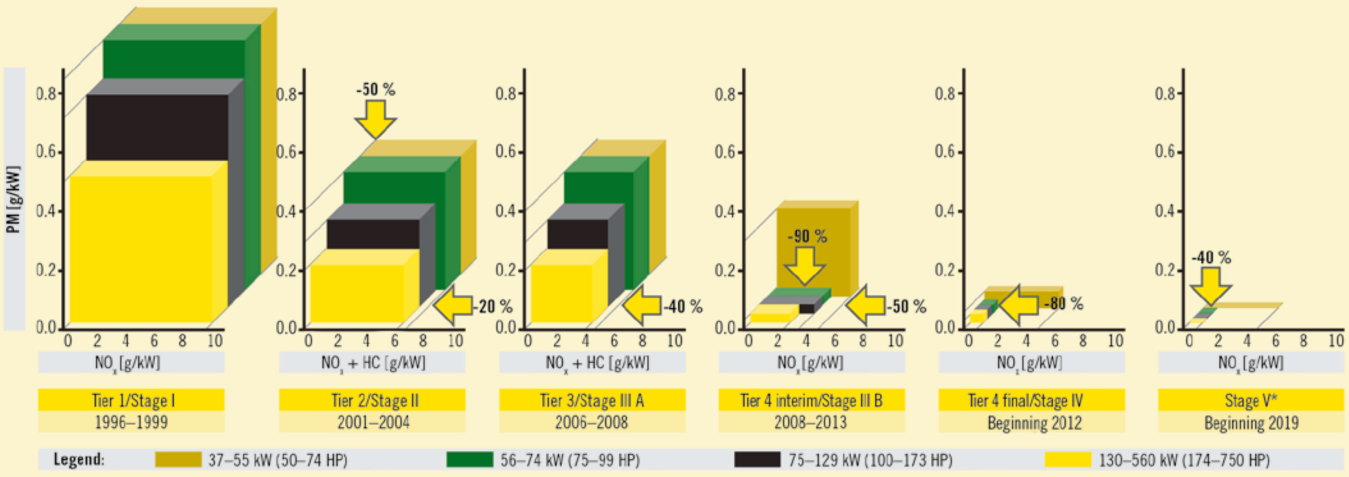
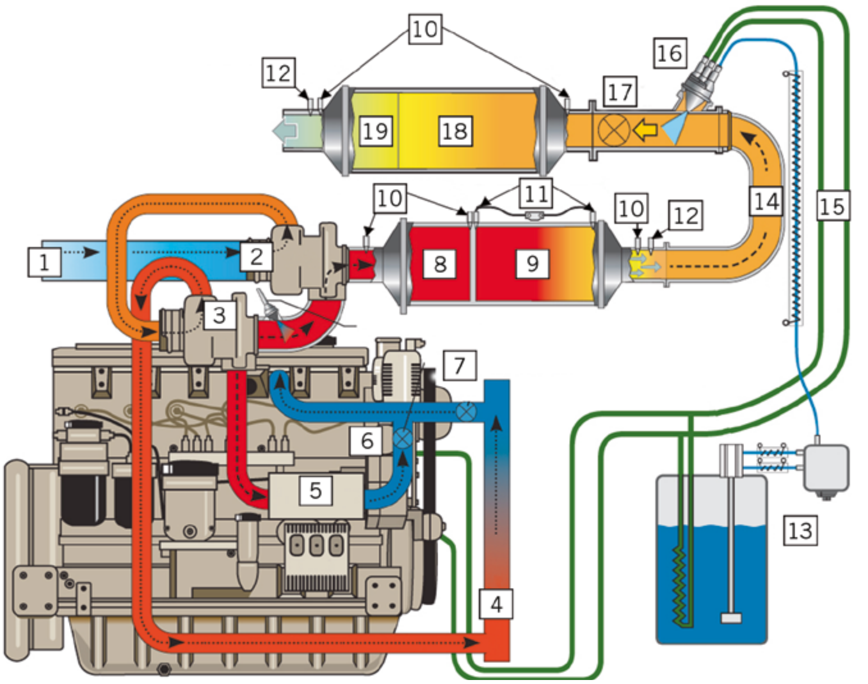


FIGURE 4 EU Stages I to V: presentation of limit values for NO_X and PM depending on power categories (© John Deere)



1	Fresh air
2	Turbocharger with fixed geometry
3	Turbocharger with variable turbine geometry
4	Intercooler
5	AGR cooler
6	AGR valve
7	Intake throttle valve
8	Diesel oxidation catalyst
9	Diesel particulate filter
10	Temperature sensors
11	Differential pressure sensors
12	NO_x sensors
13	AdBlue tank with supply unit
14	Exhaust gas
15	Engine coolant lines
16	AdBlue injector
17	Mixing section
18	SCR catalyst
19	AOC catalyst

FIGURE 5 Current 6.8-l engine from John Deere with supercharging and exhaust aftertreatment (EU Stage IV) (© John Deere)

ger charger. At low to medium loads, a variable turbine is applied. In the high-torque range, it is supported by the bigger turbocharger of fixed geometry. Optimisation of both turbochargers in their map ranges further improves their transient responses and reduces emissions [5]. Manifold pressure at nominal speed is in the range of 2.25 to 2.45 bar. Compared to pressures of previously applied standard chargers, this corresponds to an increase by a factor of about three. Much higher pressures are reached at the operation point of the maximum torque.

In the latest version of the reference engine, two-stage charging is not used to reach high peak pressures (3 to 3.5 would be possible), but to maintain a high-pressure level over a wide range of speeds down to the start-up speed of 1000 rpm. This also explains why the compression ratio has been kept at 17:1 in spite of two-stage charging. Normally, use of this charging technology leads to a slight decrease of compression ratios [6].

EARLY USE OF COMMON-RAIL TECHNOLOGY

Another important element in complying with emission limits is the injection system. Initially, mechanically controlled radial piston distributor pumps were used in the reference engine, followed for a short term by electronically controlled VP44 pumps of the same design by Bosch. Since 2002, the common-rail storage injection system has been applied. The reference engine was one of the first tractor engines with this new injection technology (in standard road vehicles, this technology was applied widely after 1997). Constant further development has resulted in maximum pressures of 2500 bar being reached by the youngest generation nowadays. Considering the last twenty years, this means an increase by about a factor of four. Separation of pressure generation and injection yields additional degrees of freedom, thus enabling multiple injections (pre-injection, main injection, post-injection), for instance. It also is an advantage that injection pressures are no longer dependent on the engine speed and, hence, can be adjusted over wide ranges. Consequently, mixture formation can be adapted to various states of operation and emissions can be reduced. Pre-injection, moreover, reduces engine noise. Increase in injection pressures, however, is associated with a high technical expenditure and, hence, high costs. Pressures in the reference engine increased in line with new stricter EU emission standards, which allows the conclusion to be drawn that emission legislation was an important technology driver, **FIGURE 4**.

COMBINATION OF EXHAUST GAS TECHNOLOGIES

Upon introduction of EU exhaust Stage III A, the reference engine for the first time was equipped with external cooled exhaust gas recirculation (EGR). By recirculating certain exhaust gas quantities in the partial-load range, combustion temperature can be lowered and formation of NO_x in the combustion chamber can be reduced significantly. For compliance with EU stage IIIB limit values, EGR had to be complemented by exhaust gas aftertreatment systems, such as a diesel oxidation catalyst (DOC) and diesel particulate filter (DPF). With this, John Deere decided in favour of cold combustion, the focus lying on engine-out emissions of particles and their reduction by EGR, adapted motor settings, and a DPF. The alternative of warm combustion would focus on engine-out emissions of nitrogen oxides (NO_x) and aftertreatment by SCR catalysis. In principle, one exhaust species inside the engine can be reduced, while the other species is subjected to aftertreatment [4]. For EU Stage IV, the EGR/DOC/DPF combination of the reference engine was complemented by an SCR catalyst, **FIGURE 5**. Compared to engines of other tractor manufacturers, the resulting setup is relatively complex. In view of the next EU exhaust Stage V that will become effective in 2019 and be associated with even lower PM limits and an additional limitation of the particle number (PN), however, this approach appears to be logical. Output and emission measurements in a PTO dynamometer suggest that the setup currently used by John Deere might already be EU Stage V-ready [7].

SUMMARY

With the 6.8-l engine by John Deere being used as an example, the high development expenditure driven by exhaust gas legislation for tractor engines in the past twenty years can be illustrated well. Classical downsizing is hardly implemented. Instead, the approach of higher mean effective pressure at constant displacement is applied. Considerable increases in torque and output are achieved. Electronic engine control, four-valve technology, turbocharging, charge air cooling, and common-rail injection are standard systems of modern tractor engines as are DOC and SCR exhaust aftertreatment systems. When EU Stage V will become effective in 2019, all manufacturers will presumably use DPF systems as well. Then, NO_x, PM, and PN emissions and the required engine and exhaust gas technologies will about correspond to those of Euro-VI trucks.

REFERENCES

[1] Renius, K. T.: Traktoren 1993/94. In: ATZ 96 (1994), no. 7/8, pp. 460–470

[2] Renius, K. T.: Traktoren und Erdbaumaschinen – Dieselmotoren: Motorisierungskonzepte, Daten, Tankgröße. München: TU München, 1996

[3] Förster, H. J.: Stufenlose Fahrzeuggetriebe in mechanischer, hydrostatischer, hydrodynamischer, elektrischer Bauart und in Leistungsverzweigung. Köln: TÜV Rheinland, 1996

[4] Eifler, W.; et al.: Küttner Kolbenmaschinen. Wiesbaden: Vieweg + Teubner, 2009

[5] Rakopoulos, C.; Giakoumis, D.; Evangelos G.: Diesel Engine Transient Operation. London: Springer London, 2009

[6] Schreiner, K.: Basiswissen Verbrennungsmotor. Wiesbaden: Springer Fachmedien, 2015, pp. 100–103

[7] N. N.: Agroscope Traktortest-Nr. 2003/15 John Deere 6215R. Online: www.services.art.admin.ch/traktor/d/2015/Testbericht_JohnDeere-6215R_d.pdf, access: 03.07.2017

ATZ elektronik
WORLDWIDE

International, Digital, Interactive: The new eMagazine from ATZelektronik

ATZelektronik worldwide reports on the very latest trends and developments in automotive electronics

Test now for 30 days free of charge:
www.ATZelektronik-worldwide.com

ATZelektronik eMagazine has 80 pages packed with information:

- company news and the latest products
- specialist articles from industry and research
- guest comment
- interview on the cover story

Keyword search: The search function enables you search for a keyword in the complete issue in a matter of seconds

PDF downloads: The classic function for saving and downloading articles

Didactically prepared: Animations and editorial videos offer genuine added value and complement the specialist articles from the automotive industry

Interactive contents: Jump immediately to your selected article with one click

Responsive HTML5 implementation: This ensures that you have access to your eMagazine not only from desktops and laptops but also from smartphones and tablets

User-friendly and direct without an app: HTML5 technology provides a direct link to the website, ensuring access without an app store