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Testing of an electronically controlled engine with a gasoline direct injection system

***Abstract**. The article presents a detailed analysis of the TSI (Turbo Straight Injection) gasoline direct injection system used in the vehicles manufactured by Volkswagen Group. The work presents the characteristic construction elements of this type of engine together with the descriptions of their influence on its operation. Next, it presents the results of engine power, torque, pollution emission levels, and fuel consumption tests conducted for the Skoda Superb 1.8 TSI and a comparison of the results with the results obtained for an equivalent engine with indirect fuel injection – Skoda Superb 1.8 T.*

Streszczenie.** W artykule zaprezentowano szczegółową analizę systemu bezpośredniego wtrysku benzyny TSI (Turbo Straight Injection) stosowanego w samochodach koncernu Volkswagen Group. W pracy przedstawiono charakterystyczne elementy budowy z opisem ich wpływu na działanie tego typu silnika. Następnie przedstawiono wyniki badań mocy silnika, momentu obrotowego, emisji zanieczyszczeń oraz zużycia paliwa, przeprowadzonych na modelu Skoda Superb 1.8 TSI oraz porównano z wynikami badań odpowiednika o wtrysku pośrednim – Skoda Superb 1.8 T.* ***Badania sterowanego elektronicznie silnika z bezpośrednim wtryskiem benzyny

Keywords: direct fuel injection, electronic engine control, TSI, uniform mixture, petrol engine.
Słowa kluczowe: bezpośredni wtrysk paliwa, elektroniczne sterowanie silnikiem, TSI, mieszanka jednorodna, silnik benzynowy.

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Introduction

The TSI engine is the next generation of engines with direct fuel injection developed in the Volkswagen Group concern. The first representative of this type of engines is the engine with the capacity of 1.8 dm^3 with turbo injection used successfully in Skoda Superb manufactured in the Czech Republic. The constructors placed the main focus on achieving the highest performance possible with optimal fuel consumption. During the engine design phase, the following assumptions were followed:

a) achieving high mechanical and thermodynamic performance in combination with compact structure,
b) meeting the requirements with respect to environmental protection, noise level, and fume content,
c) meeting the requirements of safety regulations regarding, for example, pedestrian safety or passenger compartment deformation resulting from a head-on crash,
d) reasonable price thanks to the reduction of manufacturing costs,
e) ease of performing repairs and technical servicing,
f) the possibility of longitudinal and transverse positioning in different car model.

The concept of the operation of a TSI engine was inherited from its predecessor (TFSI engine). However, a few minor changes that improve its performance were introduced. The new drive unit is fueled with a uniform mixture at the whole range of rotational speed values. Only the start is performed with the use of lean mixture. Thanks to the construction changes introduced in TSI engines, it was possible to reduce fume emission and meet the requirements of EURO 5 standard even [1].

Fuel supply system in the TSI system

The fuel supply system was slightly changed in comparison to the TFSI version. It consists of a fuel tank, a low-pressure line, a high-pressure pipe, fuel collector and four injectors. The pressure sensor as well as the safety valve and the check valve were removed from the low pressure circuit. The necessary pressure is calculated by the engine controller which controls the pump in the fuel tank. The pump can generate pressure in the range of 0,4÷0,8 MPa. There is no overpressure valve in the high pressure circuit as it was replaced with a fuel pressure regulating valve integrated with the high-pressure pump. It maintains the pressure within the range of 5÷15 MPa (depending on the load), and directs the excess of fuel to the low pressure circuit. Maximum regulator pressure is 20 MPa. The fuel supply system is presented in the *fig. 1* [5].

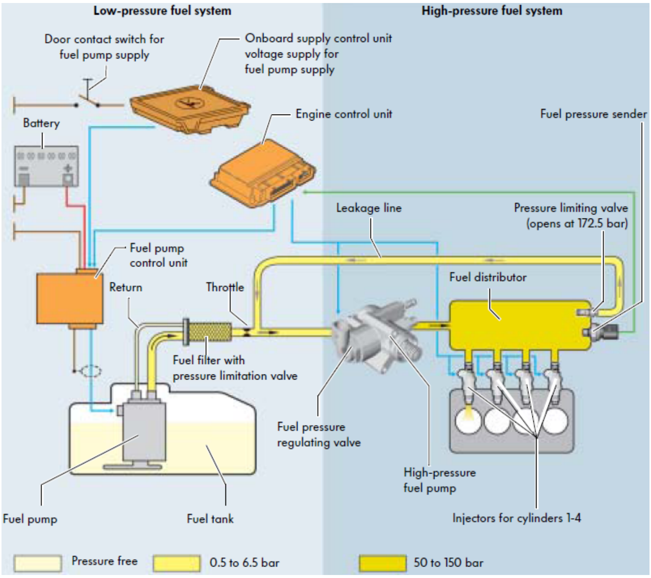

Fig. 11. Fuel system diagram in 1.8 TSI engine [5]

The high pressure pump has a one-piston structure and it is powered with a quadruple cam from the exhaust camshaft. The pump piston is moved by means of a roll pusher. This solution assures lower power losses which leads to quieter operation, reduced part wear, and fuel savings. Thanks to the use of a quadruple cam, it was possible to reduce the dimensions of the pump.

In one engine operation cycle, four forcing strokes which produce the same level of pressure as a bigger pump powered with a dual cam in the FSI engine are possible. This has considerably reduced pressure pulsation and improved the regulation dynamics (faster achievement of the desired pressure level). What is more, it became possible to regulate the pressure in the fuel collector tank after every injection which means that injection optimization can occur separately for every cylinder. In this way, it is possible to improve lambda regulation and reduce fuel consumption [5].

The fuel collector tank is made of high-grade stainless steel and it distributes fuel to every injector. Its dimensions and shape are designed in such a way so as to minimize pressure pulsations after every injection. A high-pressure sensor is installed inside the collector. On the basis of the signal from the sensor, the controller manages the operation of the regulation valve.

New injectors in the TSI engine have 6 openings in the nozzle through which the fuel is injected in a cone-shaped stream (*fig. 2*). The total apex angle of the stream is 50° (in TFSI, there is one opening with the angle of 10°). Such a way of spraying fuel is supposed to assure better mixture formulation in the combustion chamber. It also reduces the emission of hydrocarbons and solid particles (soot) and practically eliminates knocking. The control voltage of the injectors is still 65 V, and 15 V is enough to keep the injector open. The injection can still happen both during the intake stroke as well as during the compression stroke [5].

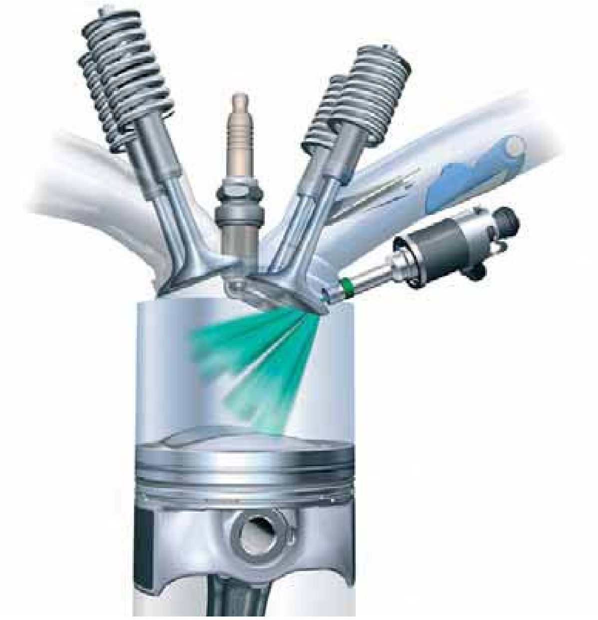

Fig. 2. The shape of the atomized fuel stream in 1.8 TSI engine [5]

Power supply system in the TSI system

The air supply system is very similar to the system used in the TFSI engine. It consists, respectively, of an air filter, a flow meter integrated with a temperature sensor, an electronically controlled throttling valve, and an intake manifold with flaps that control the air flow.

An anemometric flow meter integrated with an intake air temperature sensor is used to measure the amount of air. The frequency modulated signal from it is provided to the controller. The air mass is determined on the basis of a value table recorded in the controller memory. The frequency can change from 1,2 kHz (which corresponds with the air flow value of 4 kg/h) to 3,6 kHz (640 kg/h). The temperature sensor informs about the air temperature which is used to correct the air mass set [5].

The intake manifold is made as a two-part polyamide cast. The throttling valve, the fuel collector, the fuel tank deaeration check valve, and the pneumatic actuator controlling the air flow are fitted to it. The construction of the inlet manifold is presented in the *fig.* 3.

Control of the air flow is performed by means of the flaps with the shape of flat pans which are placed out of the axes of the intake tunnels. This makes it possible to improve the intake air flow, especially when the flaps are lowered. When the flaps are raised, the air starts to flow through the upper part of the intake tunnels which improve the production of the mixture in the cylinders. The flaps are controlled by means of a pneumatic actuator through a double electrovalve. The actuator changes the position of the shaft to which the intake manifold flaps are fitted and a potentiometer that transmits information about the position of the flaps to the controller. The position of the flaps is dependent on the rotational speed of the engine. They are raised when the speed is below 3000 r/min, and they are lowered when the speed is higher in order not to obstruct the air flow [5].

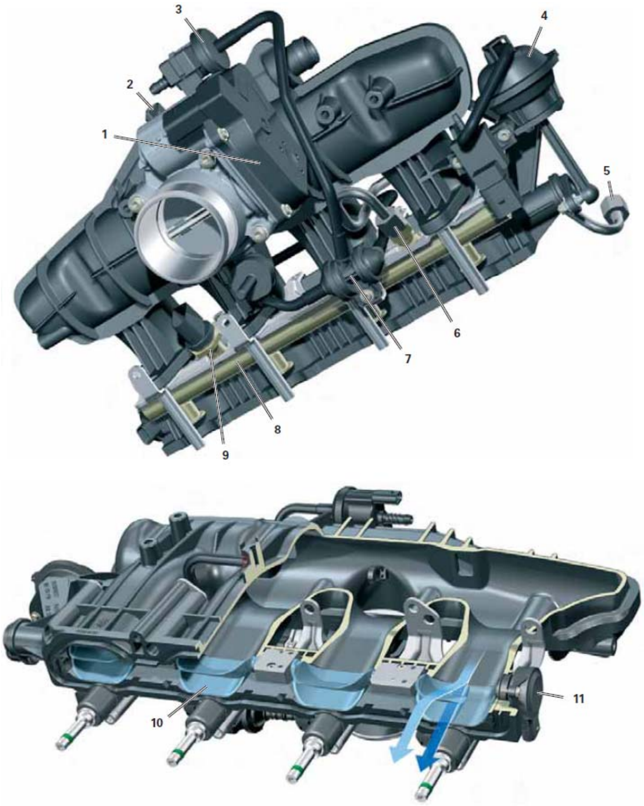

Fig. 3. Air intake manifold module in1.8 TSI engine [5]
1 – throttle valve control module, 2 – intake air temperature (IAT) sensor, 3 - evaporative (EVAP) emission canister purge regulator valve, 4 – vacuum motor for intake manifold flap changeover, 5 – fuel port, high-pressure pump, 6 – fuel port, high-pressure fuel rail, 7 – double check valve for EVAP system, 8 – high-pressure fuel rail, 9 – fuel pressure sensor, 10 - intake manifold flaps, 11 - intake manifold runner position sensor

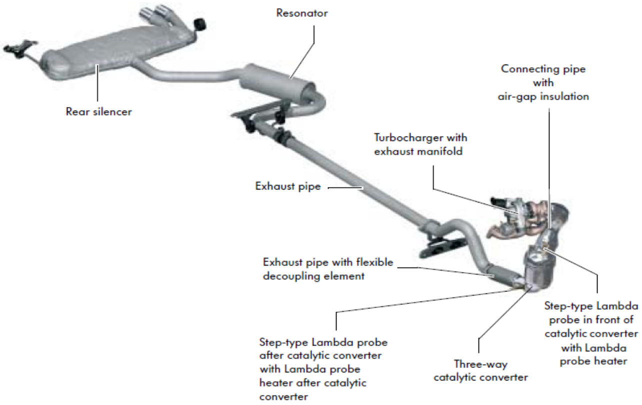

Fig. 4. Exhaust system in 1.8 TSI engine [5]

Exhaust and reduction system in TSI engine

The fume exhaust and reduction system in the TSI engine is constructed in a relatively simple way. A preliminary catalytic converter is placed directly behind the engine, then a two-step Lambda probe is fitted, and the main three-way catalytic converter is placed directly behind it (*fig.* 4). A broadband probe before the preliminary catalytic converter was not used, as it was replaced with a set of characteristics programmed in the controller memory. Such a solution became possible thanks to the use of uniform mixture (λ=1) for the full range of engine speed (with the exception of the start of a cold engine). In this way, Lambda regulation was considerably simplified [5].

1.8 TSI engine supercharging

The level to which the cylinders are filled with fresh air in the TSI engine is increased by means of a supercharger. It is designed in such a way so as to increase the dynamics and, at the same time, to reduce fuel consumption. The supercharger makes it possible to achieve the highest torque value when it is needed the most, that is in any range of rotational speed values. 80 % of maximum torque can be achieved as early as at 1250 r/min, and 100 % - at 1500 r/min. This is achieved thanks to the fact that the moment of inertia of the moving parts of the supercharger is maintained on the lowest possible level. The most significant difference in comparison to the existing turbo charging systems is the use of an intake air cooler cooled with water from the engine cooling circuit, placed in the intake [2, 5].

The supercharger is built into the exhaust manifold. It is equipped with two connections on the intake side: to the crankcase deaeration system and to the fuel vapor exhaust from the fuel tank. It is cooled with water from the engine cooling circuit, and it is greased with motor oil. An interference muffler which reduces the noise produced as a result of pressure pulsations is fitted at the supercharger exhaust. Two valves are connected with the supercharger:

a) the charge pressure control electrovalve connected with a pneumatic actuator that opens the fume bypass tunnel,

b) closed air circuit electrovalve that opens the connection between the intake side and the compression side of the turbocharger during engine braking.

The operation of the supercharger is relatively simple. The fumes flowing from the cylinders power the turbine which is connected with the wheel of the supercharger increasing the intake air pressure. Charge air pressure is controlled by means of a charge pressure control valve on the basis of the signals from intake air pressure and temperature sensors. The maximum charge air pressure can reach 0,18 MPa. The supercharge charging system is presented in the *fig.* 5 [2, 5].

Variable engine timing phases in the 1.8 TSI engine

In the TSI engine, identically to the earlier generations of direct fuel injection systems manufactured by the Volkswagen concern, it is possible to shift the position of the intake camshaft. It is only the construction of the Shift system that is different. By shifting the camshaft, it is possible to adjust the torque to the engine operation phase and improve the composition of the fumes. The intake shaft can be shifted by 30 ° or 60 ° in relation to the crankshaft.

Three values influence the possibility of shifting camshaft position and the extent to which it can be shifted: the intake air mass, the rotational speed of the crankshaft and the temperature of the engine (as a correction parameter). The engine controller controls the operation of the camshaft shift electrovalve which generates pressure changes in the shift actuator. Control is performed by means of frequency modulated signal (PWM) [5].

The shifter consists of a rotor, a stator, a diverter valve and a lock pin. The rotor is permanently connected with the camshaft to which the diverter valve is also connected. The timing chain is placed on the toothed stator. The pin is used to lock the rotor and the stator when the oil pressure is lower than 50 kPa (engine start). The control signal induces a shift in the position of the diverter valve anchor. In this way, motor oil fills different shifter chambers.

When the rotational speed is lower than 1800 r/min, the shifter remains in the rest position. Above this value, the position of the intake camshaft is shifted by the angle selected on the basis of the characteristics programmed in the controller memory. The opening and closing angles are selected in such a way so that the filling of the cylinders is optimal. In the case of a failure in the camshaft shifting system, the lock pin locks the rotor with the stator and the camshaft operates in the same way as in systems without a shifter. The torque reached by the engine is lower in such conditions [5].

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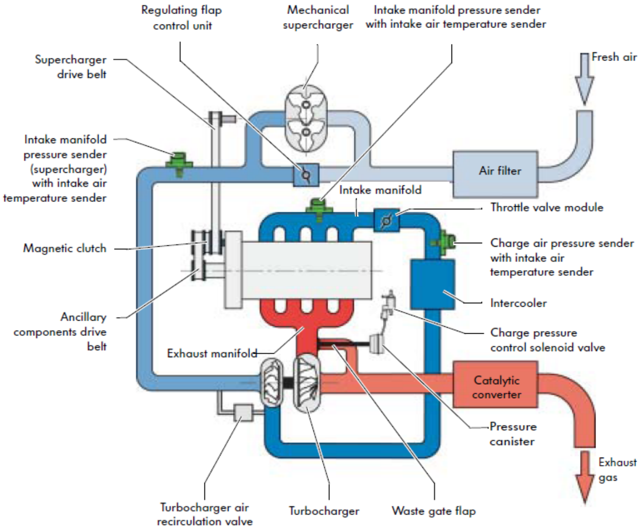

Fig. 5. Schematic diagram of all supercharging components in 1.8 TSI engine [5]

Direct fuel injection control in the 1.8 TSI engine

The 1.8 TSI engine uses the Bosch MED 17.5 engine control module (*fig. 6*). The hardware and software components have been developed so that they can be used for future projects both for gasoline and diesel engine applications. This allows maximum use with regards to functions and vehicle interfaces independent of the engine combustion configuration. Examples of this include the Electronic Pedal Control and radiator fan activation strategies.

A new feature of the MED 17.5 is the deletion of the continuous-duty oxygen sensor. Now, a nonlinear oxygen sensor is installed. The sensor is located between the close-coupled pre-catalyst and the underbody catalytic converter. The function of the continuous-duty pre-cat sensor has been mapped by the new functions of the engine control module. These maps are generated by conducting appropriate tests during engine development. Advantages [5]:

a) fewer potential sources of fault,

b) more cost-effective,

c) requirements of ULEV are met without continuous-duty oxygen sensor,

d) no adjustments needed in customer service or for exhaust emission inspections.

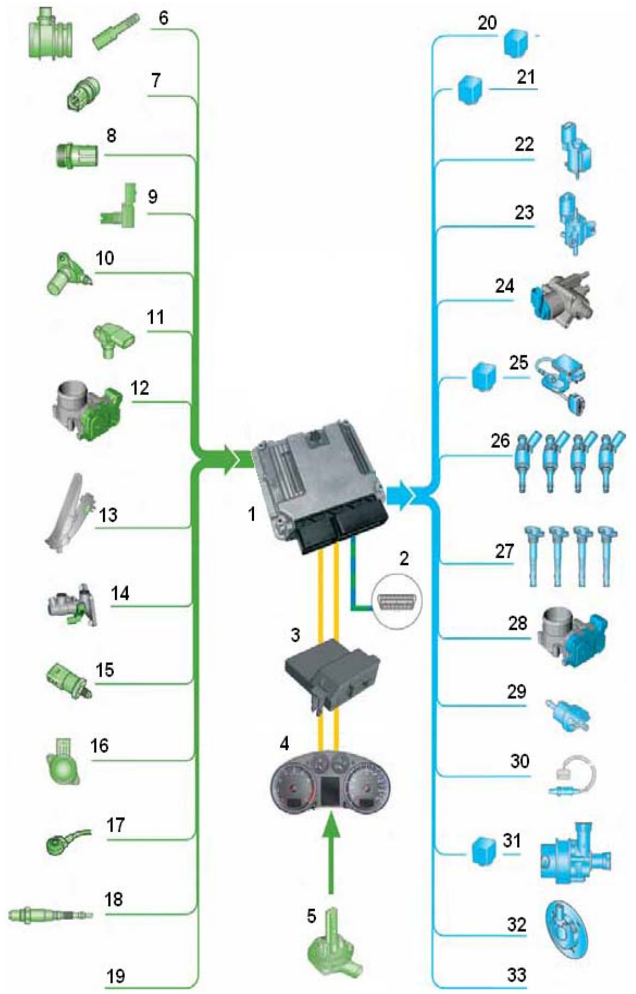

Fig. 6. Overview of Bosch MED 17.5 system [5]
1 - Engine Control Module with Ambient Pressure Sensor, 2 - Diagnostic Link Connector, 3 – Data Bus On Board Diagnostic Interface, 4 – Instrument Cluster Control Module, 5 - Oil Level Thermal Sensor, 6 - Mass Air Flow Sensor with Intake Air Temperature Sensor, 7 - Engine Coolant Temperature Sensor, 8 - Engine Coolant Temperature Sensor, 9 - Change Air Pressure Sensor, 10 - Engine Speed Sensor, 11- Camshaft Position Sensor, 12 - Throttle Valve Control Module with Throttle Drive Angle Sensor 1 and Throttle Drive Angle Sensor 2, 13 - Throttle Position Sensor and Accelerator Pedal Position Sensor 2, 14 - Brake Pedal Switch with Clutch Position Sensor, 15 - Fuel Pressure Sensor, 16 - Intake Manifold Runner Position Sensor, 17 - Knock Sensor 1, 18 - Heated Oxygen Sensor with Oxygen Sensor 2 Behind Three Way Catalytic Converter, 19 - DFM Generator, Cruise Control ON/OFF, 20 - Motronic Engine Control Module Power Supply Relay, 21 - Engine Component Power Supply Relay, 22 - Intake Manifold Runner Control Valve, 23 - Wastegate Bypass Regulator Valve, 24 - Fuel Pressure Regulator Valve, 25 - Fuel Pump Control Module with Transfer Fuel Pump, 26 - Cylinder Fuel Injectors 1-4, 27 - Ignition Coils with Power Output Stages, 28 - Throttle Valve Control Module with Throttle Drive for Electronic Power Control, 29 - Evaporative (EVAP) Emission Canister Purge Regulator Valve, 30 - Oxygen Sensor Heater, 31 - Coolant Circulation Pump Relay with After-Run Coolant Pump, 32 - Camshaft Adjustment Valve 1, 33 - Radiator Fan Setting 1 with PWM Signal Leak Detection Pump

In all operating ranges of the engine, except directly after starting (when the fuel-air mixture is slightly richer), the mixture composition is set to lambda 1. The following operating modes are implemented:
a) in start phase: high-pressure – start of fuel-air mixture,
b) for several seconds after start: HOSP,
c) following warm-up phase: engine map controlled dual injection cycle,
d) at coolant temperatures of 80°C or higher: fuel injection synchronous with intake cycle only.

In the Bosch MED 17.5 engine control module is used new IFX Tricore processor family. It has sufficient capacity in reserve to accommodate future advancements in order to meet market requirements. Hardware used in the engine control module [5]:
a) infineon – IFX Tricore 1766 (Leda Light),
b) 80 MHz system frequency,
c) 1.5 MByte internal flash,
d) single chip system.

Tests and analysis of the performance of the TSI engine

In order to test the performance of the 1.8 TSI engine, nominal power, torque, exhaust emission and fuel consumption tests were performed on the engine. At the same time, the 1.8 T indirect fuel injection engine was tested in order to obtain comparison. Both engines were fitted in the Skoda Superb model with the sedan body type [1].

All the tests were performed in accordance with the European Directive 98/69/EC, on the chassis test stand of one of the vehicle diagnostics point in Poznań.

The NEDC driving test constituted the first part of the tests conducted. It made it possible to determine the amount of pollution emitted and the fuel consumption (*table 1*). The NEDC test is a simulation of a car drive in the city and outside of the city. Before the test the vehicle tested should not run for 6 h. After the vehicle is started, the test begins immediately and the measuring devices are activated [3].

Table 1 Summary of the results of the tests performed and comparison with the data provided by the manufacturer and with Directive 98/69/EC [3, 5]

Parameters		Test results		Manufacturer's	
		1.8 TSI	1.8 T	1.8 TSI	1.8 T
Nominal power [kW]		120,2 (5250)	110,8 (5500)	118 (5000)	110 (5500)
Torque [N·m]		251,5 (1500)	211,2 (2000)	250 (1500)	210 (1750)
Fuel consumption according to the NEDC test	City [dm^3/100 km]	10,2	11,4	10,4	11,5
	Road [dm^3/100 km]	6,3	6,6	6,0	6,5
	Average [dm^3/100 km]	7,5	8,7	7,6	8,3
Fume emission according to the NEDC test	CO_2 [g/km]	181	210	180	202
	CO [g/km]	0,184	0,426	< 1,0	< 1,0
	HC [g/km]	0,097	0,068	< 0,1	< 0,1
	NO_x [g/km]	0,069	0,030	< 0,08	< 0,08

The first part referred to as UDC (Urban Driving Cycle) is a simulation of a drive in the city. It usually consists of 4 identical cycles lasting for 195 s each and conducted without any time break in between. The discussed part of the test is characterized with frequent accelerations, braking, and stops. In total, the vehicle covers the distance of a bit more than 4 km in 780 s, and the maximum speed is 50 km/h. Just after the city cycle, the out of the city part referred to as EUDC (Extra Urban Drive Cycle) is conducted. Here, the maximum speed is 120 km/h. The distance covered in nearly 7 km, in 400 s. In total, the distance covered during the whole NEDC test, which is 19 minutes and 40 seconds long, is 11,007 km. Changes in drive dynamics are presented in the *fig. 7* and the basic information about test is provided in the *table 2.*

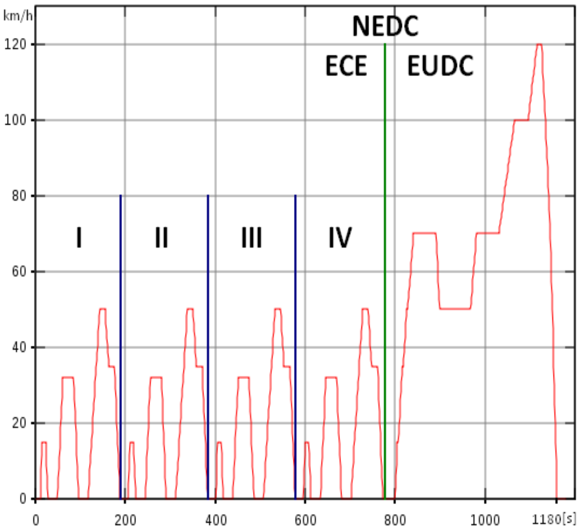

Fig. 7. A chart showing the progress of the NEDC driving test [3]

Table 2 Basic parameters in the NEDC test [3]

Parameter	Unit	ECE	EUDC	NEDC
Distance	km	4×1,013=4,052	6,955	11,007
Duration	s	4×195=780	400	1180
Average speed	km/h	18,7	62,6	33,6
Maximum speed	km/h	50	120	120

In the course of the test, the appropriately prepared fumes were collected into the so-called measurement sack. Fume preparation involves cooling them and mixing them with a certain amount of air so as to achieve the desired pressure and temperature values.

Fume analyzers (CO2, CO, HC i NO_x) performed measurements of momentary content of a given component of the fumes contained in the measurement sack every second and recorded the results as values modulated appropriately in relation to the engine load. Finally, momentary values were added up, giving the full result of the measurement performed in the NEDC test. A simplified view of the test stand is presented in the *fig. 8* [3].

Tested cars were produced in 2004 (with engine 1.8T) and 2005 (with the 1.8TSI engine) year. The manufacturer has adapted them to meet the requirements of Euro 4 Standards (CO – 1,0 g/km HC – 0,1 g/km and NOx - 0.08 g/km). By 2009, for engines with gasoline direct injection, was not required to measure the concentration of particulate matter in the exhaust gas, which is why during this study there were no measurement of this component and it was not included in this study.

The second part of the tests involved determining the speed characteristics of direct injection engines (*fig. 9*) and indirect injection engines (*fig. 10*) including the determination of the maximum nominal power and the maximum torque. The characteristics determined in accordance with Directive 98/69/EC.

The vehicle was accelerated to the maximum rotational speed. The nominal power and the torque transferred to the car wheels were measured at that point. Next, the clutch was disconnected and the car started to slow down freely until it was fully stopped. The nominal power and the torque of the driver unit were measured at that point. The final performance of the engine itself is the sum of the values measured earlier. The whole test was relatively short; it took about 5 minutes of free rolling until the car stopped [3, 4].

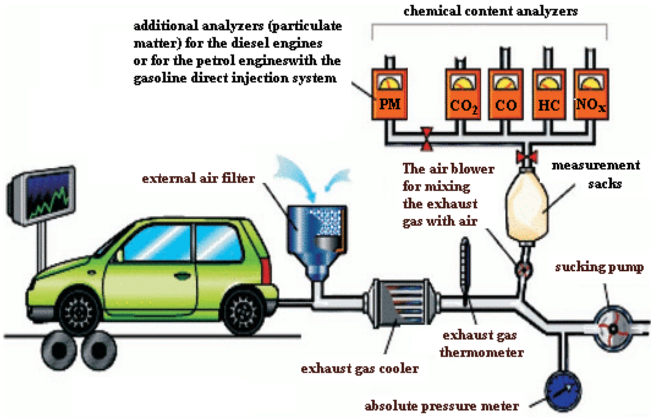

Fig. 8. A simplified diagram of the measurement stand used to conduct the NEDC test [1]

Before performing the measurement in the vehicle, the engine was warmed up. Next, it was placed on the test stand roller and appropriately secured. Further preparation to the measurement involved determining the transmission gear and the main gear transmission on which the test was to be performed (in this case it was the fourth gear). Next, the dynamic radius of the vehicle tires was verified. The data determined was entered into the chassis test stand program and the measurements could be started.

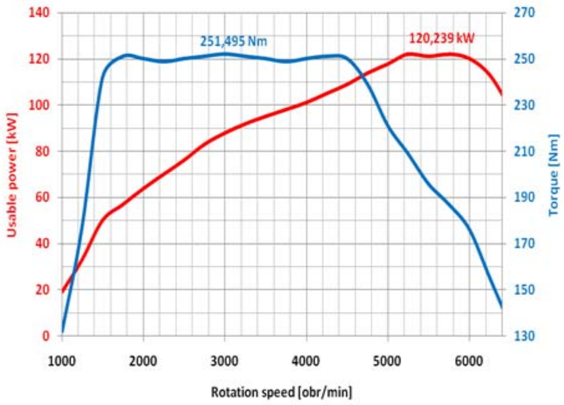

Fig. 9. Skoda Superb 1.8 TSI engine speed characteristics [8]

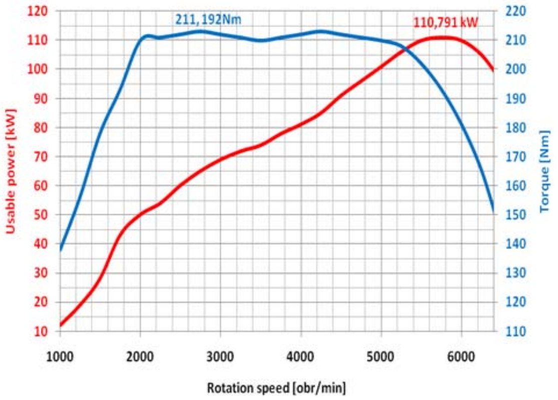

Fig. 10. Skoda Superb 1.8 T engine speed characteristics [8]

The tests conducted make it possible to perform the analysis in two different ways. Firstly, the results can be compared with the data provided by the manufacturer. In this case, a clear similarity can be observed (table 1). The engine nominal power and torque characteristics depending on the rotational speed determined on the chassis test stand reflect the charts published by the Volkswagen Group concern. Slight differences between the results of the tests performed and the data provided by the manufacturer should be explained, most of all, with differences in the test stands used and with the fact that the cars examined already had a certain mileage greater than zero (about 130 thousand km) – material wear or aging.

In the second case, a comparison of two types of engines was performed: an engine with direct fuel injection and an engine with indirect fuel injection. The analysis shows clearly that the parameters of the engine with indirect fuel injection are worse than the parameters of the engine with direct fuel injection. The nominal power and the torque values are considerably higher for the 1.8 TSI engine [8].

In certain cases, fuel consumption differs considerably from the data provided by the manufacturer both for the car with direct fuel injection as well as for the one with indirect fuel injection. However, even considering the differences in comparison to manufacturer data, the 1.8 TSI engine consumes, on average, 1,2 dm^3/100 km less petrol than the 1.8 T engine.

Pollution emission with reference to hydrocarbons and oxides of nitrogen is considerably lower for the car with indirect fuel injection. Despite that fact, higher pollution emission levels for the engine with direct fuel injection are well within the limits specified in the standard. Carbon dioxide emission for both engines does not meet the requirements of the standard but the engine with direct fuel injection is comparatively better. It is worth noticing that the emission of carbon monoxide is over two times lower in the 1.8 TSI engine in comparison to the 1.8 T engine [8].

Summary

The analysis of the nominal power and torque characteristics obtained leads to a clear statement that the characteristics demonstrated by the engine with direct fuel injection are better. Cars equipped with this type of engines are characterized by improved dynamics and flexibility which has a positive influence on the driving comfort.

The tests conducted and the comparative analysis of their results performed showed that direct fuel injection systems are superior to indirect fuel injection systems. The present work has proved that it is possible to achieve higher engine nominal power and torque values at relatively lower fuel consumption and lower carbon monoxide emission to the atmosphere.

Direct fuel injection engines are now becoming more and more popular. More and more automotive concerns start to use this type of engines in their cars. The advantages of direct fuel injection systems presented in the present work indicate that they can replace indirect fuel injection systems and become serious competition for diesel engines with respect to fuel consumption and fume emission [1, 6, 7].

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