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The impact of changing engine's operational parameters on its emission

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Abstract. The share of vehicles powered by compression ignition engines is constantly growing. The roots of this tendency are mainly of economic nature: diesel fuel is cheaper than petrol, and additionally compression ignition engines have higher efficiency than spark ignition engines. The growing number of vehicles also means that they start to impact the environment significantly. The vehicle-related emission of harmful substances is regulated by EURO emission standards in Europe. To satisfy them, engines must be equipped with additional exhaust aftertreatment systems such as exhaust gas recirculation (EGR) systems, catalytic reactors or diesel particulate filters (DPF). The fuel injection system, and more specifically its control strategy, responsible for controlling the time, manner and quantity of fuel delivered to the combustion chamber, significantly affects the emissions. When faced with problems in satisfying the requirements of the exhaust gas emission standards, many manufacturers attempt to limit the emissions by modifying the engine control strategy. The article discusses the problem related to the evaluation of the possible ways of limiting the emissions by modifying the engine's control parameters as performed by one of the leading car makers. The emissions of a car with an engine for which the manufacturer prepared a software control update aiming to curb the emission were measured in real life conditions. The tests were performed with the standard software and after its update. The results have shown that emissions of certain compounds can be limited without worsening operational parameters.

1. Introduction

The necessity to limit the negative impact on the environment is one of the basic factors impacting the development of automotive. This obligation burdens car makers who must run multiple approval tests to make sure their cars are approved for sale. Despite the high expenses on their development, they cannot adequately reflect real traffic conditions. The producers often use the stationary nature of the approval tests and adjust the engine operation control strategy so that the emissions of harmful compounds are within the limits specified by the standard in force. The tests conducted in real traffic conditions show that the emissions of a new car may differ from the emissions measured during approval tests [1,2]. The main, underlying reason is that in real life operation the engine operates in unspecified conditions (variable load and RPM). The competition in the automotive is very stiff and forces car makers to regularly introduce new models. This shortens the time allocated for fine tuning the engine operation control. The car makers mainly focus on satisfying emission requirements specified in the car's approval procedure, not on the car's emissions in real life conditions. Very often, this comes to life only once the car is licensed for operation and mass produced. At such time it is difficult to introduce any design changes to hundreds of cars put into operation. Fine tuning of the engine operation control software is one of the most common ways of limiting negative impact on the environment. Although the underlying reasons may be different, car makers use this solution very often. It also happens that real-life operation shows that the operation of the exhaust aftertreatment system differs from its initial assumptions made during design works and tests.

Many tests [3,4,5] were performed in recent years, showing that various injection strategies (changing the injection time or fuel pressure) may produce specific engine operation parameters. Delaying the injection time shortens the time window during which the fuel evaporates and mixes with air. Local oxygen shortages are created that way, leading to the creation of soot. On one hand, by accelerating the injection time, more time is allowed for evaporating and mixing of air with fuel, the consequence of which is less soot, but on the other hand the charge ignites sooner, which raises temperature and pressure inside the chamber (created by the still ongoing compression stroke), ultimately creating conditions in which nitrogen oxides are prone to form [6,7]. The selected solution determines the application of additional exhaust aftertreatment systems outside the engine and the development of a suitable strategy of managing their operation.

2. Subject and methodology of tests

The topic discussed in the article covers the solution applied by Volkswagen in passenger cars powered by engine of the EA189 family. The evaluation of the possibility of limiting harmful compounds emissions was performed while measuring emissions in real traffic conditions. Volkswagen Jetta MK6 was selected to be the test subject, whose main parameters are shown in Table 1.

Table 1. The tested car's main parameters.

Parameter	Value
Engine type	R4 2.0 TDI CR DPF
Gear box	Automatic 6-gear DSG
Displacement	1968 cm^3
Maximum power	140 HP at 4200 RPM
Maximum torque	320 NM at 1750-2500 RPM
Emission standard	EURO 5
Mileage	235,000 km

Contemporary cars feature very elaborate systems that control the engine's operating parameters. Since the testes car is driven daily, it was necessary to evaluate its technical condition and the correctness of operation of the engine's systems. Computer diagnostics was run to this end and it showed no errors saved in the controller's memory.

The examination of the impact of modified engine operation control parameters was performed with the following test and measurement devices:

- MAHA dynamometer - for measuring the car's engine power and torque,
- GPS receiver - for pinpointing geographical location,
- SEMTECH DS analyser - for measuring the emission of CO, HC, NO_x and CO_2,
- Micro Soot Sensor - for measuring the emission of diesel particulates.

As it was necessary to update the car's software at an authorized workshop, the tests were performed on two consecutive days. On the first day, the tests were done with the standard engine control software, and on the second day with the software modified by the car maker to limit the emissions.

Given the fact that the producer modified the engine control strategy, it was necessary to analyse the introduced changes. The control software was read from the controller's memory for this purpose and then WinOLS software was used to compare the control parameters and to identify the introduced changes.

The car’s engine power and torque were measured before resting the emissions in real traffic conditions. The measurements were made for the default control software and after it has been modified. The resulting characteristics allowed to determine whether the changes introduced to the engine control strategy affect the change of the engine's operational parameters.

In order to perform the tests in a wide range of traffic conditions, the route, during which the emissions were measured in real traffic conditions, was designed to cover segments matching urban and extra-urban traffic. The course of the selected route, covering 12 km in total, is presented in Fig. 1.

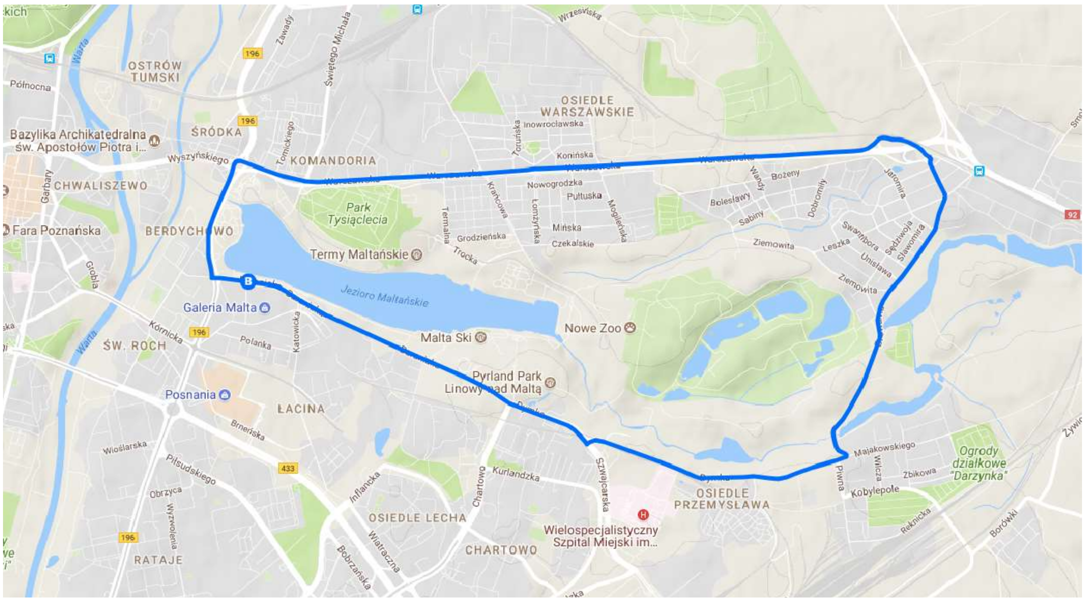

Figure 1. The course of the test route

3. Measurement results

Due to the complexity of the research, the results were divided into three parts. The first part presents a comparison of control strategies. The second part contains a comparison of the vehicle's operational parameters. The last part presents the results of emission measurements.

3.1. Comparison of engine operation strategies.

The analysis of the engine control software showed that the car maker modified the engine control strategy with the aim to limit the emissions. The most significant changes were identified in the EGR control maps, as shown in Fig. 2a and 2b. The map controlling the opening of the EGR valve was almost completely redesigned. The red colour in the chart and in the table indicates that values increased in relation to their originals, while the blue colour indicates decreased values of control parameters.

-(Injection Quantity,Engine speed)/-

rpm \ mg	5	8	10	13	15	20	25	30	35	40
1200	8900	8900	8900	8900	8900	8900	8900	8900	8900	8900
1500	4000	4200	4400	4700	5200	5800	6600	7200	7800	8900
2000	4100	4250	4400	4700	5200	5750	6550	7150	7800	8900
2500	4300	4350	4400	4700	5100	5551	6050	6800	7600	8900
3000	4300	4350	4450	4600	4800	5250	5650	6500	7300	8850
3500	4300	4350	3950	3550	3750	4150	4650	6400	7200	8600
4000	4500	4550	4125	3700	3900	4250	4650	6350	7000	8300
4500	4700	4800	4400	4000	4200	4450	4900	6550	7200	8152
5000	5000	5000	5000	5300	5600	6000	6550	7000	7600	8500
5500	5400	5400	5400	5750	6100	7000	7700	8200	8700	9900
6000	11000	11000	11000	11000	11000	11000	11000	11000	11000	11000

Figure 2a. Exhaust gas recirculation parameters.

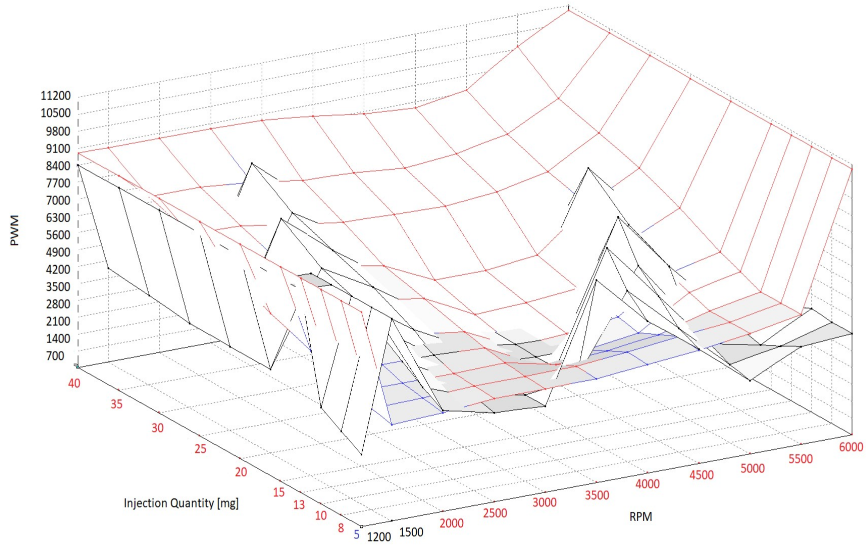

Figure 2b. Exhaust gas recirculation control maps.

It should be noted that for large doses and high RPM values, the ERG valve control parameters have higher values, which corresponds to the increased rate of closing that results in reduced recirculation of exhaust gases. However, it should be note that for selected points in low and medium loads, the EGR valve control parameters have lower values, resulting in the increased rate of recirculation of exhaust gases.

The turbo control strategy was also altered. The analysis of the turbo control map (Fig. 3a and 3b) shows that the supercharging pressure was reduced for medium RPM. This was probably done to reduce the pressure in the combustion chamber for that RPM range, which leads to limited formation of nitrogen oxides.

-(Injection Quantity,Engine speed)/-

rpm \ mg	0	5	10	15	20	25	30	35	40	45	50	55	60
600	1025	1040	1050	1080	1120	1200	1250	1300	1380	1400	1430	1480	1500
1000	1025	1040	1050	1080	1120	1200	1250	1300	1380	1400	1430	1480	1500
1250	1030	1020	1040	1120	1170	1205	1315	1415	1485	1590	1625	1665	1715
1500	1043	1040	1070	1150	1230	1306	1455	1570	1640	1795	1850	1900	1950
1750	1067	1090	1100	1200	1304	1425	1610	1760	1885	2120	2190	2240	2255
2000	1090	1108	1140	1265	1389	1525	1716	1887	2070	2270	2350	2350	2350
2250	1115	1147	1190	1331	1465	1655	1852	2021	2198	2315	2350	2350	2350
2500	1160	1208	1255	1396	1540	1725	1915	2075	2255	2350	2350	2350	2350
2750	1200	1250	1295	1451	1580	1750	1950	2095	2280	2350	2350	2350	2350
3000	1220	1290	1340	1481	1600	1750	1960	2086	2265	2350	2350	2350	2350
3500	1230	1300	1371	1510	1600	1750	1925	2030	2195	2300	2300	2300	2300
4000	1230	1300	1380	1500	1600	1750	1900	2020	2147	2180	2180	2180	2180
4200	1230	1300	1380	1500	1600	1750	1880	1990	2112	2120	2120	2120	2120
4500	1230	1300	1380	1500	1600	1750	1860	1950	2039	2040	2040	2040	2040
4800	1230	1300	1380	1500	1600	1750	1850	1850	1850	1850	1850	1850	1850
5400	1230	1300	1380	1500	1600	1750	1750	1750	1750	1750	1750	1750	1750

Figure 3a. Boost pressure control parameters.

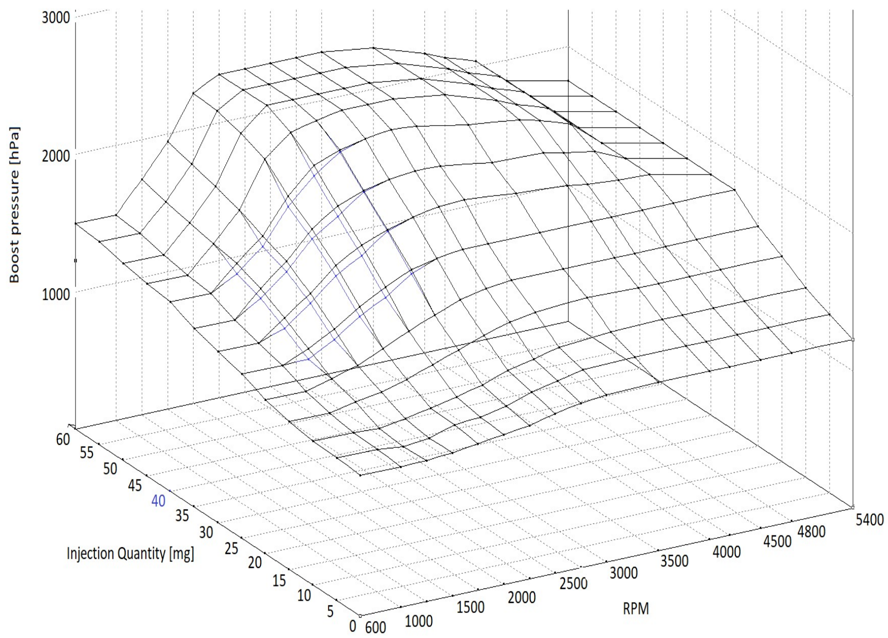

Figure 3b. Boost pressure control maps.

The last notable change in the engine's software concerned the maximum torque limiter. When analysing Fig. 4a and 4b, which shows the torque limiter's parameters and 2D map, we noted that the maximum torque limit was increased for RPM values of over 1750 RPM. The increased value of this parameter mainly affected the car's performance.

-(Torque, Engine Speed)/

rpm	0	500	600	1000	1250	1500	1750	1900	2000	2250	2500	2750	3000	3250	3500	3750	4000	4200	4400	4800	5000	5400	5500
	0	0	160	200	270	316	350	353	353	356	358	355	354	337	323	310	298	287	280	245	186	66	0

Figure 4a. Torque limiter parameters.

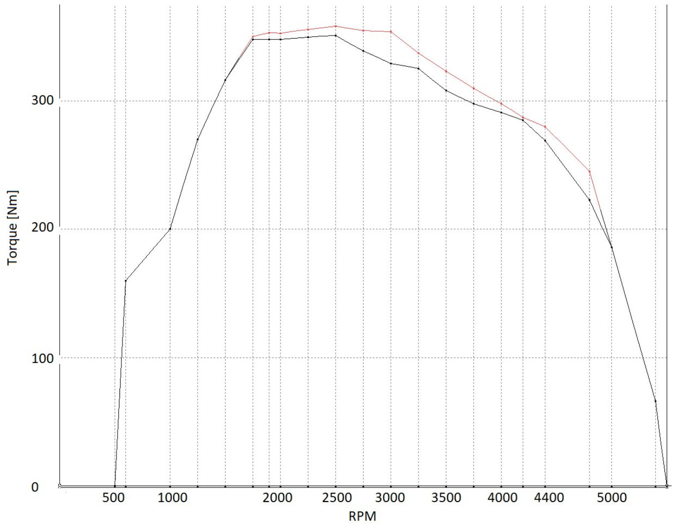

Figure 4b. Boost pressure control maps.

3.2. Comparison of power and torque characteristics.

The objective of the modification was to limit the emission of toxic compounds in the exhaust gases, without worsening the car's utility parameters. To confirm this objective has been fulfilled, the car's engine power and torque were measured for both control strategies. The results are presented in Fig. 5.

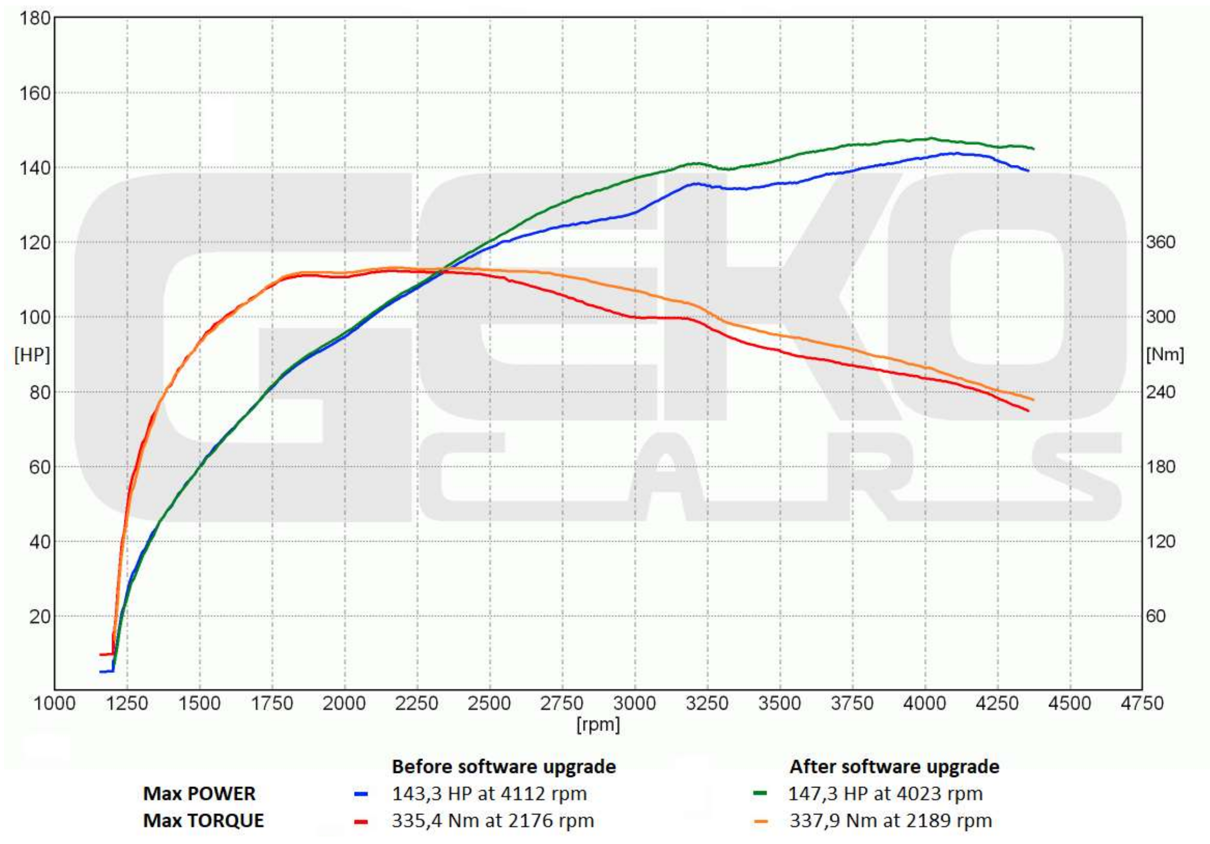

Figure 5. Comparison of the performance of the tested vehicle.

The chart above shows that the maximum torque curve is similar to the values specified in the control software.

3.3. Measuring emissions in real traffic conditions.
The key part of the test was the measurement of the car's emissions in real traffic conditions. Aiming to limit the impact of the driving technique on the emissions, all test runs were done by the same driver. The car's automatic gear box made it easier to ensure comparable operating parameters. The atmospheric conditions during the test runs are presented in Table 2.

Table 2. Atmospheric conditions during test runs.

Parameter	Before software upgrade	After software upgrade
Average ambient temperature	18.5 °C	18.5 °C
Average ambient pressure	1011.1 hPa	1009.5 hPa
Average ambient humidity	58.77 %	40.1 %
Average absolute humidity	7.78 g/kg dry air	7.1 g/kg dry air

Each test run started at the same time, which allowed to minimize any differences in traffic intensity that would have a significant impact on the total emission of harmful compounds recorded throughout the test run. The test run along the designated route showed that the changed engine control strategy results in increased fuel consumption. The average fuel consumption for the car with updated software increased by 0.3 l / 100 km. The duration and distance covered in the test run were comparable (Table 3).

Table 3. Summary of results of measurement of emissions in real traffic conditions.

Parameter	Before software upgrade	After software upgrade
Total distance travelled	12.087 km	12.036 km
Total fuel consumed	0.627 dm^3	0.660 dm^3
Overall fuel economy	5.185 dm^3/100 km	5.482 dm^3/100 km
Total test duration	1,056 s	1,067 s
Total work	3 kW-h	3 kW-h

The increased fuel consumption translates directly into increased CO_2 emission, as confirmed by the results presented in Fig. 6. The mass of CO_2 generated by the engine before the modification was similar to the value specified by the car maker during approval tests, but following the modification, this limit was markedly exceeded. The changes introduced to the engine control strategy resulted in decreased nitrogen oxides emissions during the second measurement. The amount of NOx emitted by the car's engine was reduced by 30%, yet this value would still exceed the limits specified in EURO5 by over 8 times. The emission of carbon monoxide was also reduced, although it should be noted that the limits specified by the exhaust emission standard were not exceeded, both before and after loading the modified control software. The total emission of hydrocarbons during the first series of tests showed that the permissible values were exceeded almost two times. The car maker's modifications improved the process of preparing the mixture, consequently reducing HC emissions during the second run. The only toxic component of exhaust gases whose increase was recorded during the tests were the diesel particulates. Following the modification, the specific emission of PM rose by around 40%. This, however, did not result in exceeding the permissible EURO 5 limits.

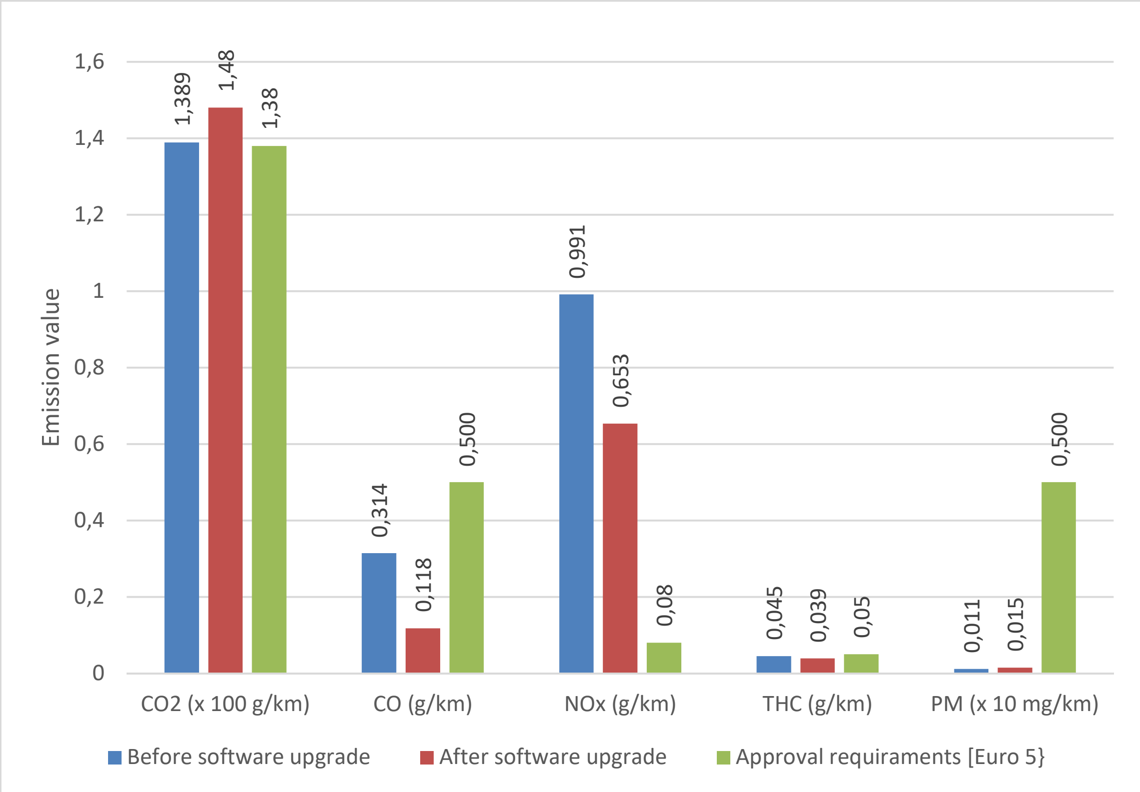

Figure 6. Comparison of emission results and existing limits.

4. Summary

Car makes have been tackling problems related to satisfying the increasingly stringent exhaust gases standards for years. To satisfy these standards, engines have been equipped with additional systems for reducing emissions. The shortened product life means that manufacturers who are under the pressure of time do not spend enough resources on fine tuning their control systems, just like in the situation of the manufacturer of the tested car.

Our deliberations showed that changing such parameters as exhaust recirculation, supercharging pressure or maximum torque limits, allows to limit the emissions of toxic compounds.

Despite the significant reduction of NOx emissions, the results obtained during the tests exceeded the limits specified in EURO5. Nevertheless, it should be noted that vehicles licensed for operation subject to this standard are approved using a stationary NEDC test which reflects real traffic conditions only to a limited extent.

The dynamometer measurements showed that changing the engine operation control strategy in order to limit toxic compounds emissions may be done not only without limiting the performance but may even increase it.

The analysis of the changes introduced to the engine operation control software was performed on the basis of generally available knowledge and may not cover all significant changes introduced to the engine's software by the car maker. Still, the assumed result, namely the reduced emissions of harmful compounds without worsening of operational parameters, has been achieved.

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