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IMPLICATIONS FOR THE ENVIRONMENTAL-ENGINEERING COMPROMISE AS A RESULT OF THE AFTERMARKET OPTIMIZATION OF A DIESEL ENGINE

POSLEDICE ZA OKOLJSKO-INŽENIRSKI KOMPROMIS ZARADI OPTIMIZACIJE DIZELSKEGA MOTORJA

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Keywords: calibration, tuning, fuel prices, performance, fuel consumption

Abstract

New IC engines contain many systems that ensure better engine performance, while satisfying increasingly strict environmental norms and exhaust emission standards in what is known as an environmental-engineering compromise. However, controlling, calibrating, and subsequently optimizing high-performance engines in which the trade-offs between performance, economy and emissions take precedence, is a challenge for even the most experienced automotive engineers, as it includes major implications. With the rise of fuel prices however, in recent years, more and more transport companies and fleet owners have looked to improve their vehicles' economy through different aftermarket optimizations of the vehicles` engines, rarely

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taking into account the impact of such changes on the overall balance imposed through the environmental-engineering compromise. This paper investigates the required changes into the engines` electronic control units to achieve higher power output and lower fuel consumption, while analyzing the benefits and shortcomings brought by these optimizations on the engines` short and long-term operation.

Povzetek

Novi motorji z notranjim zgorevanjem imajo številne sisteme, ki zagotavljajo boljše delovanje, hkrati pa izpolnjujejo vse strožje okoljske norme in standarde emisij izpušnih plinov v tako imenovanem okoljsko-inženirskem kompromisu. Vendar so krmiljenje, umerjanje in posledično optimiziranje visokozmogljivih motorjev, pri katerih imajo prednost kompromisi pred zmogljivostjo, ekonomičnostjo in emisijami, izziv tudi za najbolj izkušene avtomobilske inženirje. Zaradi dviga cen goriva si v zadnjih letih vse več prevozniških podjetij in lastnikov voznih parkov prizadeva izboljšati ekonomičnost svojih vozil z različnimi poprodajnimi optimizacijami motorjev vozil, pri čemer le redko upoštevajo vpliv takih sprememb na splošno ravnotežje, uvedeno s kompromisom okoljskega inženiringa. Ta prispevek raziskuje potrebne spremembe v elektronskih krmilnih enotah motorjev za doseganje večje izhodne moči in manjše porabe goriva, hkrati pa analizira prednosti in pomanjkljivosti, ki jih prinašajo te optimizacije na kratkoročno in dolgoročno delovanje motorjev.

1 INTRODUCTION

In the 1980s road transport started bringing up major environmental concerns which have gained in relevance continuously [1-2], so most Western European countries, USA, Japan and others, started introducing maximum allowable concentrations of the exhaust emissions of internal combustion (IC) engines, first limiting their exhaust opacity, and later introducing limits on the quantity of: carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx), particulate matter (PM), sulfur dioxide (SO2), volatile compounds (VOCs), and unburned fuel [3]. Today, IC engines contain many electronically controlled systems that ensure better engine performance, while satisfying the increasingly strict environmental norms and exhaust emissions standards in what is known as an environmental-engineering compromise. The technological advances toward cleaner combustion at the very least include high-pressure fuel injection, exhaust gas recirculation, turbocharging and cooling the air ahead of the intake manifold [4]. This brings up the complexity of engine control, since each additional system increases the number of inputs in the control matrix, which possess a challenge for fast calibration and optimization of the engine's working parameters, which, in turn, is indivisible from new engine design [5-7].

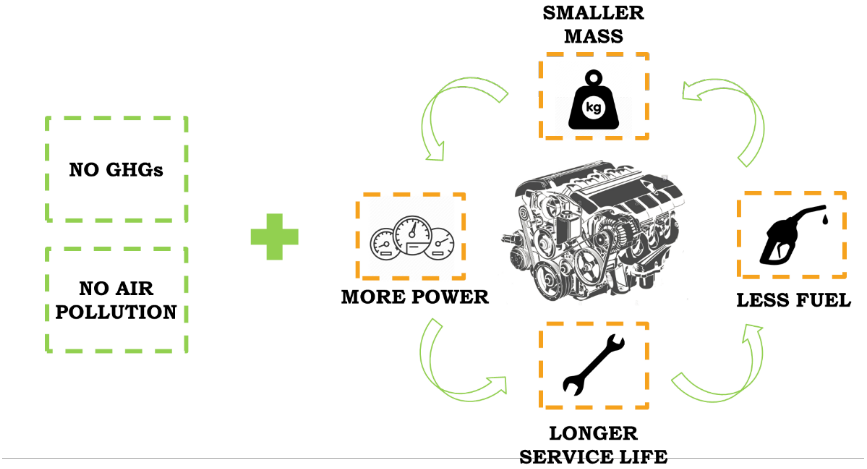


Figure 1: *The environmental-engineering compromise*

Fuzzy-logic control and altering the control maps in the engine's electronic control unit (ECU) also offer tempting aftermarket performance opportunities [8]. Although tuning an engine, along with other physical engine modifications is almost standard practise with automotive enthusiasts, more recently its application has gained in popularity with transport companies with large vehicle fleets, and even private owners looking to gain the most out of their vehicles [9]. In fact, one of the most recurring control modifications offered by licensed services (and often unlicensed servicing entities as well), is the possibility to increase engine power and torque while reducing fuel consumption [10], also known as POWER and ECONOMY optimizations.

In the available referent literature, [11] analyzes the different aftermarket engine calibration approaches available, while [12] reports on the use of a fuzzy logic controller to maintain engine operation within the most optimal boundaries, but none provide input on the subsequent implications or drawbacks associated with these approaches. Reference [13] is more thorough in this aspect, by proposing a new tuning method and listing its commercial benefits However, it does not cover the challenges that such modifications bring, such as their impact on the engine components' life or exhaust emissions` quantities. Reference [14] reviews multiple studies of engine calibration problems from the perspective of optimization of three different engines (gasoline, diesel and hybrid), and suggests a more efficient approach to engine calibration. Although the article covers the research on both off-board and on-board engine calibration, it fails to identify the parameters and quantify the results that indicate the negative impact of the procedure.

While soaring fuel prices brought by the ongoing conflict in Ukraine have acted as a catalyst for transport companies and fleet owners to look into increasing their vehicles' economy through aftermarket optimization, account is rarely taken of the potentially negative impact of such modifications. With this in mind, this paper's aim is to detail the required changes in the engine and its system's operation, and understand and quantify both the advantages, but, foremost, the disadvantages in terms of exhaust emissions and engine service life following aftermarket POWER and ECONOMY optimizations of a diesel engine's operation.

2 MATERIALS & METHODS

2.1 Test engine

Passenger vehicles in the Western Balkans (Albania, Bosnia and Herzegovina, Kosovo, North Macedonia, Montenegro and Serbia) have an average age of just above 11 years, with the share of new vehicles being particularly low [15]. With legislative restrictions in place on importing passenger vehicles driven by IC engines that do not comply with the Euro 4 environmental Standards, it is safe to say that most vehicles found within this region will be driven by IC engines that fall within the Euro 4 bracket, or on the transition to Euro 5 [16]. The research and testing is performed on a sufficiently modern diesel engine - the 1.9 dm^3, in-line, four-cylinder, four stroke, turbocharged direct injection (TDI) engine, manufactured by the VW group from 2005-2009. It employs such technological advancements as direct injection, a variable turbine geometry turbocharger, a charge intercooler, water-cooled exhaust gas recirculation and a BOSCH EDC 16 electronic control unit.

The vehicle used for the purpose of the research was a SEAT Leon Mk2 driven by the 1.9 TDI engine, which, in its factory setting, can deliver 78 kW of power at 4000 rpm and 250 Nm of torque at 2300 rpm. (Figure 2) Additionally, its combined fuel economy (urban and highway) is 6.6 l/100 km (Figure 3). Furthermore, upon measuring the quantity of the different components found in the vehicle's exhaust emissions that fall under the legal frameworks of the Republic of North Macedonia, and, in particular, the Rule book for the technical inspection of vehicles [17] in the Republic of North Macedonia, per its factory settings, the engine emits 3.43% of CO_2 per volume of exhaust emissions.

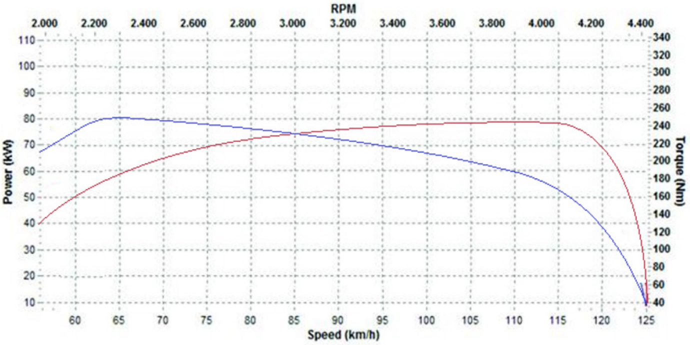


Figure 2: *Power and torque curves of the non-optimized 1.9 TDI engine (Engine ID Code: BKC/BLS BXE)*

***Figure 3:** Fuel consumption per the engine's factory settings (board computer read out)*

2.2 Testing and measuring equipment

The equipment used to monitor and measure the engine's output operational characteristic has included the TEXA SpA IDC 5 Car diagnostics software and Ross-Tech's VCDS diagnostics software for vehicles of the VW group. Both softwares are suitable for technicians familiar with the basics of self-diagnosis, as these toolkits provide the most detailed techniques for the most advanced features available with the new generations of electronic control units adopted on most modern vehicles. Aside from their monitoring and diagnostics capability, the VCDS software was also used to perform the tuning and optimization of the operating parameters of the Seat Leon's 1.9 TDI engine, to achieve better engine performance and reduced fuel consumption. Although the TEXA IDC 5 also allows performing permanent adjustments or reprograming some actuators through the functions provided by the control unit, this software was used primarily to monitor the engine data once the optimizations were completed. Additionally, a BrainBee AGS 688 Gas Analyzer (Figure 4) equipped with an exhaust probe (Figure 5), was used to measure and compare the before and after emissions` footprint of the test-engine.

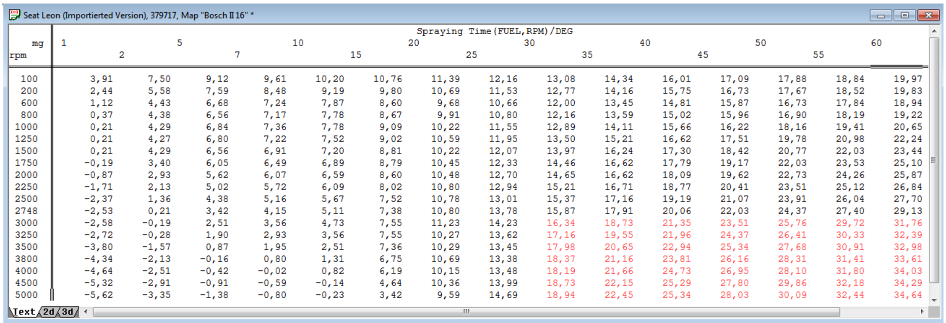
Figure 4: *BrainBee AGS 688 Gas Analyzer*

Figure 5: *Exhaust probe*

2.3 Optimization of the engine's output operating characteristics

Car manufacturers base their engines` ECUs on fuzzy logic, and the BOSCH EDC 16 ECU paired with the 1.9 TDI engine is no exception. The fuzzy logic maps used as lookup tables within the ECU hold predetermined values that the engine should achieve, namely, power (kW), torque (Nm) and the quantity of pollutants in the exhaust emissions, expressed as a percentage (%) of the volume of total exhaust emissions. All the maps are uploaded to a .hex file (HEX – hexadecimal source file) within the ECU's EEPROM (electrically erasable programmable read-only memory), but to get them to the desired state requires hard work and many precise calculations (as a safety measure that protects the manufacturer from amateurs damaging the engine and causing expensive and often irreversible defects).

Performing the ECONOMY and POWER aftermarket engine optimizations includes changing more than 50 control surfaces or maps, only a part of which will be provided in this paper. To achieve reduced fuel consumption and CO_2 emissions, the goal of these optimizations is to increase engine power for the same amount of fuel (Figure 6) that would be injected into the non-optimized engine. Practically, this would mean that the engine would consume less fuel to overcome the same resistance (the sum of forces that oppose the vehicle's motion), and, consequently, it would lead to lower CO_2 emissions. This optimization also requires advancing the start of injection (Figure 7), but, at most, up to 20^o BTDC, since, according to [18-19], the consequences of early injection will lead to engine knock, and a significant increase in combustion temperature.



Spraying Time (FUEL,RPM)/DEG

rpm \ mg	1	2	5	7	10	15	20	25	30	35	40	45	50	55	60
100	3,91	7,50	9,12	9,61	10,20	10,76	11,39	12,16	13,08	14,34	16,01	17,09	17,88	18,84	19,97
200	2,44	5,58	7,59	8,48	9,19	9,80	10,69	11,53	12,77	14,16	15,75	16,73	17,67	18,52	19,83
600	1,12	4,43	6,68	7,24	7,87	8,60	9,68	10,66	12,00	13,45	14,81	15,87	16,73	17,84	18,94
800	0,37	4,38	6,56	7,17	7,78	8,67	9,91	10,80	12,16	13,59	15,02	15,96	16,90	18,19	19,22
1000	0,21	4,29	6,84	7,36	7,78	9,09	10,22	11,55	12,89	14,11	15,66	16,22	18,16	19,41	20,65
1250	0,21	4,27	6,80	7,22	7,52	9,02	10,59	11,95	13,50	15,21	16,62	17,51	19,78	20,98	22,24
1500	0,21	4,29	6,56	6,91	7,20	8,81	10,22	12,07	13,97	16,24	17,30	18,42	20,77	22,03	23,44
1750	-0,19	3,40	6,05	6,49	6,89	8,79	10,45	12,33	14,46	16,62	17,79	19,17	22,03	23,53	25,10
2000	-0,87	2,93	5,62	6,07	6,59	8,60	10,48	12,70	14,65	16,62	18,09	19,62	22,73	24,26	25,87
2250	-1,71	2,13	5,02	5,72	6,09	8,02	10,80	12,94	15,21	16,71	18,77	20,41	23,51	25,12	26,84
2500	-2,37	1,36	4,38	5,16	5,67	7,52	10,78	13,01	15,37	17,16	19,19	21,07	23,91	26,04	27,70
2748	-2,53	0,21	3,42	4,15	5,11	7,38	10,80	13,78	15,87	17,91	20,06	22,03	24,37	27,40	29,13
3000	-2,58	-0,19	2,51	3,56	4,73	7,55	11,23	14,23	16,34	18,73	21,35	23,51	25,76	29,72	31,76
3250	-2,72	-0,28	1,90	2,93	3,56	7,55	10,27	13,62	17,16	19,55	21,96	24,37	26,41	30,33	32,39
3500	-3,80	-1,57	0,87	1,95	2,51	7,36	10,29	13,45	17,98	20,65	22,94	25,34	27,68	30,91	32,98
3800	-4,34	-2,13	-0,16	0,80	1,31	6,75	10,69	13,38	18,37	21,16	23,81	26,16	28,31	31,41	33,61
4000	-4,64	-2,51	-0,42	-0,02	0,82	6,19	10,15	13,48	18,19	21,66	24,73	26,95	28,10	31,80	34,03
4500	-5,32	-2,91	-0,91	-0,59	-0,14	4,64	10,36	13,99	18,73	22,15	25,29	27,80	29,86	32,18	34,29
5000	-5,62	-3,35	-1,38	-0,80	-0,23	3,42	9,59	14,69	18,94	22,45	25,34	28,03	30,09	32,44	34,64

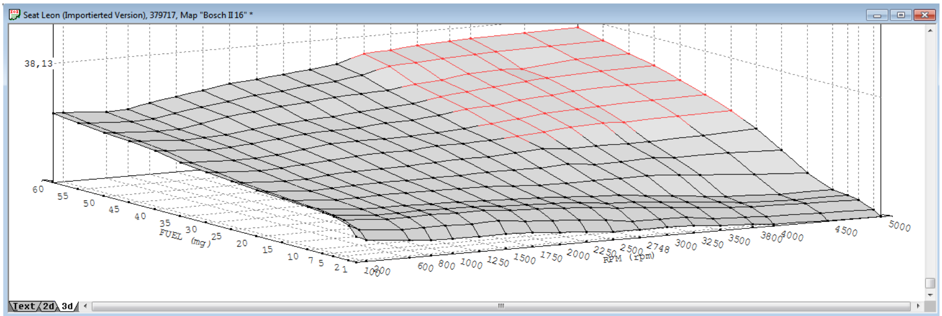
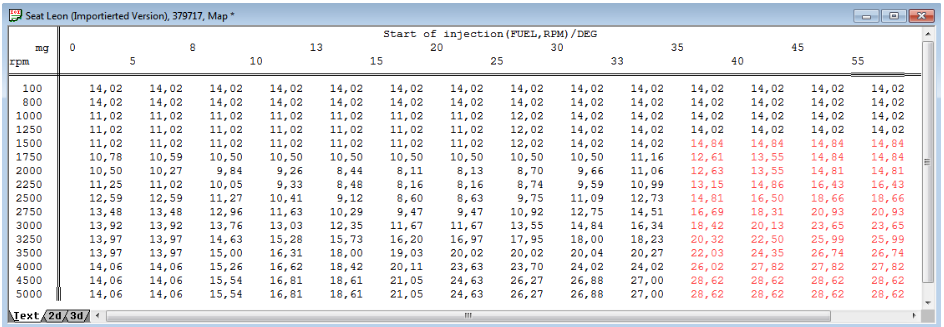


Figure 6: *ECONOMY optimization – Injection duration (Fuel, RPM/DEG)*



Start of injection(FUEL,RPM)/DEG

rpm \ mg	0	5	8	10	13	15	20	25	30	33	35	40	45	55
100	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02
800	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02	14,02
1000	11,02	11,02	11,02	11,02	11,02	11,02	11,02	11,02	12,02	14,02	14,02	14,02	14,02	14,02
1250	11,02	11,02	11,02	11,02	11,02	11,02	11,02	11,02	12,02	14,02	14,02	14,02	14,02	14,02
1500	11,02	11,02	11,02	11,02	11,02	11,02	11,02	11,02	12,02	14,02	14,02	14,84	14,84	14,84	14,84
1750	10,78	10,59	10,50	10,50	10,50	10,50	10,50	10,50	10,50	10,50	11,16	12,61	13,55	14,84	14,84
2000	10,50	10,27	9,84	9,26	8,44	8,11	8,13	8,13	8,70	9,66	11,06	12,63	13,55	14,81	14,81
2250	11,25	11,02	10,05	9,33	8,48	8,16	8,16	8,16	8,74	9,59	10,99	13,15	14,86	16,43	16,43
2500	12,59	12,59	11,27	10,41	9,12	8,60	8,63	8,63	9,75	11,09	12,73	14,81	16,50	18,66	18,66
2750	13,48	13,48	12,96	11,63	10,29	9,47	9,47	9,47	10,92	12,75	14,51	16,69	18,31	20,93	20,93
3000	13,92	13,92	13,76	13,03	12,35	11,67	11,67	11,67	13,55	14,84	16,34	18,42	20,13	23,65	23,65
3250	13,97	13,97	14,63	15,28	15,73	16,20	16,97	16,97	17,95	18,00	18,23	20,32	22,50	25,99	25,99
3500	13,97	13,97	15,00	16,31	18,00	19,03	20,02	20,02	20,02	20,04	20,27	22,03	24,35	26,74	26,74
4000	14,06	14,06	15,26	16,62	18,42	20,11	23,63	23,63	23,70	24,02	24,02	26,02	27,82	27,82	27,82
4500	14,06	14,06	15,54	16,81	18,61	21,05	24,63	24,63	26,27	26,88	27,00	28,62	28,62	28,62	28,62
5000	14,06	14,06	15,54	16,81	18,61	21,05	24,63	24,63	26,27	26,88	27,00	28,62	28,62	28,62	28,62

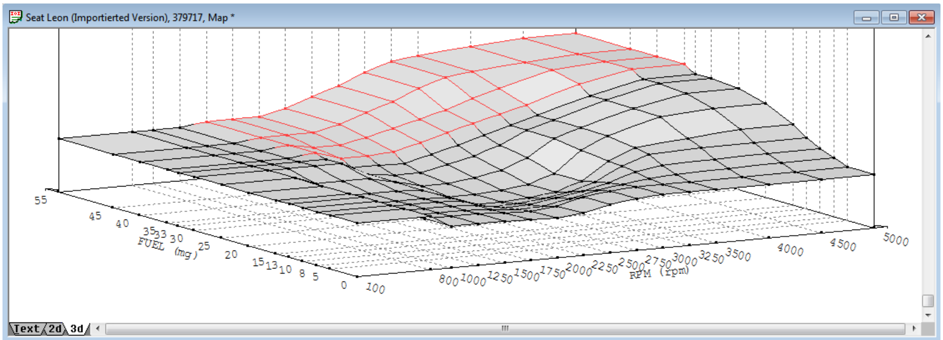
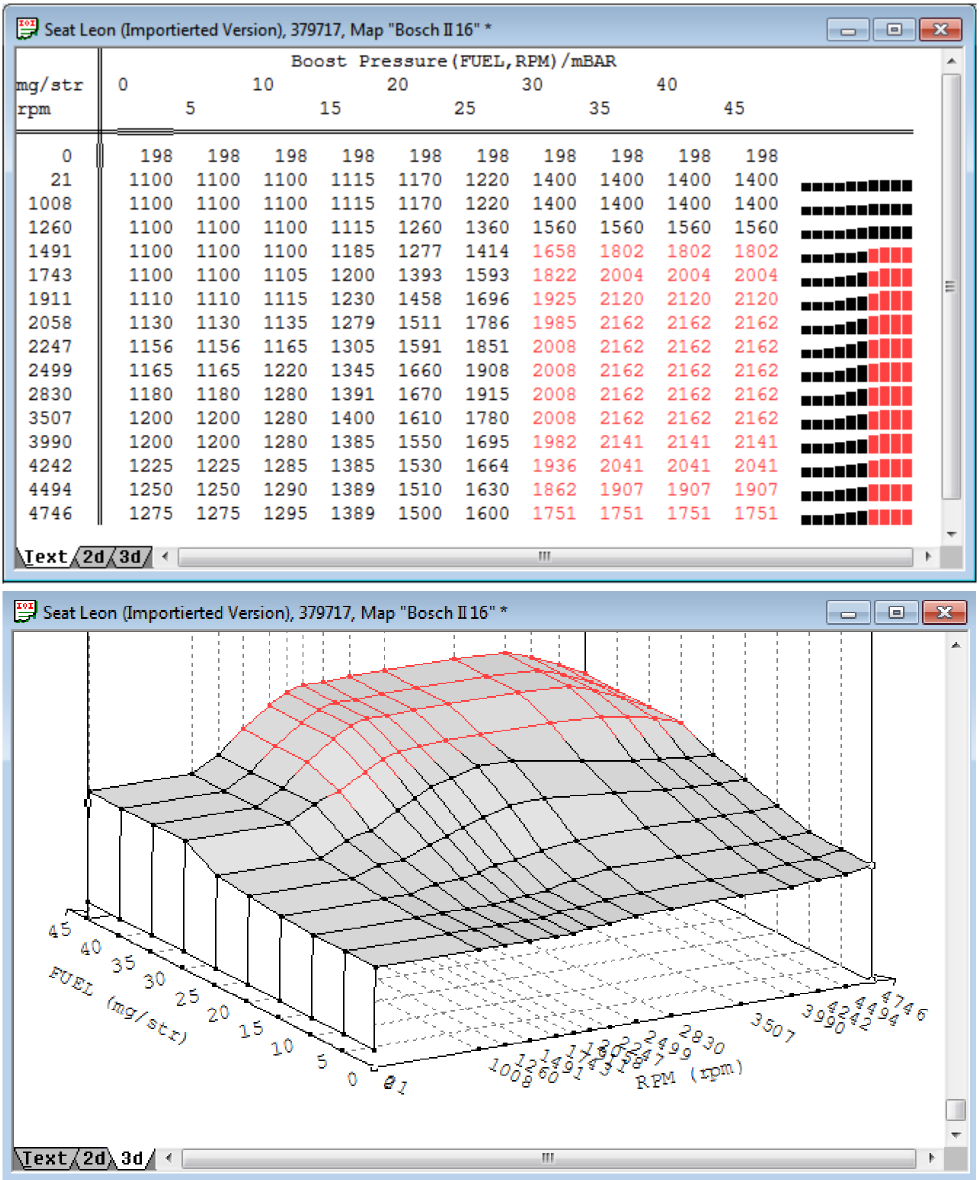


Figure 7: *ECONOMY optimization – Start of Injection (Fuel, RPM/DEG)*

However, the output engine power can be increased further by changing the angle of attack of the variable geometry turbine blades. Reducing the cross-section of the exhaust gas flow to the turbine will result in a higher speed of the exhaust gas flow, which will lead to a higher rotational speed of the turbocharger, and an increase in the boost pressure and the density of the intake charge (Figure 8).



Seat Leon (Importierted Version), 379717, Map "Bosch II 16" *

Boost Pressure(FUEL,RPM)/mBAR

mg/str rpm	0	5	10	15	20	25	30	35	40	45
0	198	198	198	198	198	198	198	198	198	198
21	1100	1100	1100	1115	1170	1220	1400	1400	1400	1400
1008	1100	1100	1100	1115	1170	1220	1400	1400	1400	1400
1260	1100	1100	1100	1115	1260	1360	1560	1560	1560	1560
1491	1100	1100	1100	1185	1277	1414	1658	1802	1802	1802
1743	1100	1100	1105	1200	1393	1593	1822	2004	2004	2004
1911	1110	1110	1115	1230	1458	1696	1925	2120	2120	2120
2058	1130	1130	1135	1279	1511	1786	1985	2162	2162	2162
2247	1156	1156	1165	1305	1591	1851	2008	2162	2162	2162
2499	1165	1165	1220	1345	1660	1908	2008	2162	2162	2162
2830	1180	1180	1280	1391	1670	1915	2008	2162	2162	2162
3507	1200	1200	1280	1400	1610	1780	2008	2162	2162	2162
3990	1200	1200	1280	1385	1550	1695	1982	2141	2141	2141
4242	1225	1225	1285	1385	1530	1664	1936	2041	2041	2041
4494	1250	1250	1290	1389	1510	1630	1862	1907	1907	1907
4746	1275	1275	1295	1389	1500	1600	1751	1751	1751	1751

Seat Leon (Importierted Version), 379717, Map "Bosch II 16" *

***Figure 8:** ECONOMY optimization – Intake Manifold Boost Pressure (Fuel, RPM/mBAR)*

3 RESULTS

Analyzing the results for the engine's power output (Figures 9 and 10), the POWER/ PERFORMANCE optimization led to a 36% increase in engine power (78 to 106 kW) while the ECONOMY optimization, which was aimed primarily at a decrease in fuel consumption and a climate-friendly improvement of the environmental map of the engine, maintained an increase in engine power of 23 % (78 to 96 kW). Both optimizations led to an increase in the power output, with room to improve the engine's fuel economy, or otherwise reduce fuel consumption. The POWER optimization led to a 9% decrease in fuel consumption (6.6 to 6.0 l/100 km) while the ECONOMY optimization, understandably led to an even larger, 13.5% decrease in fuel consumption (6.6 to 5.7 l/100 km).

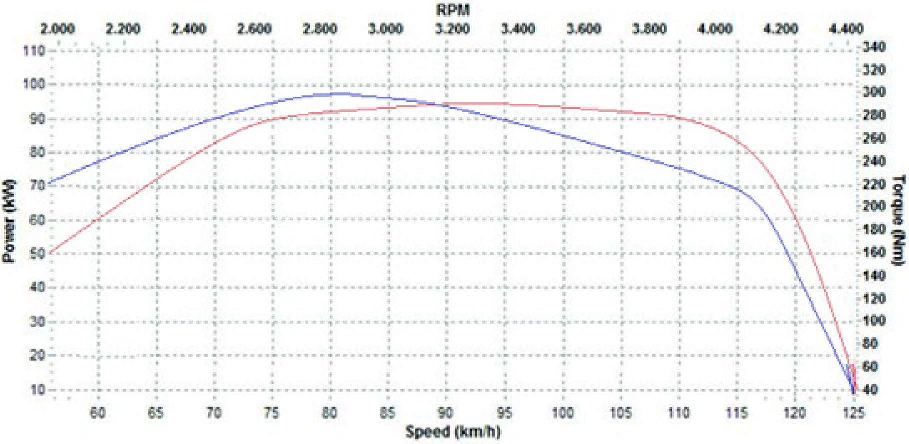


Figure 9: *Power output following the ECONOMY optimization*

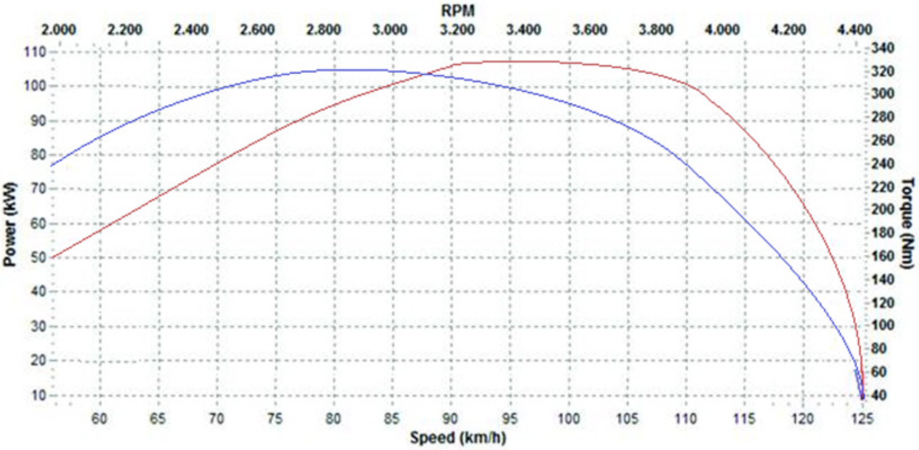
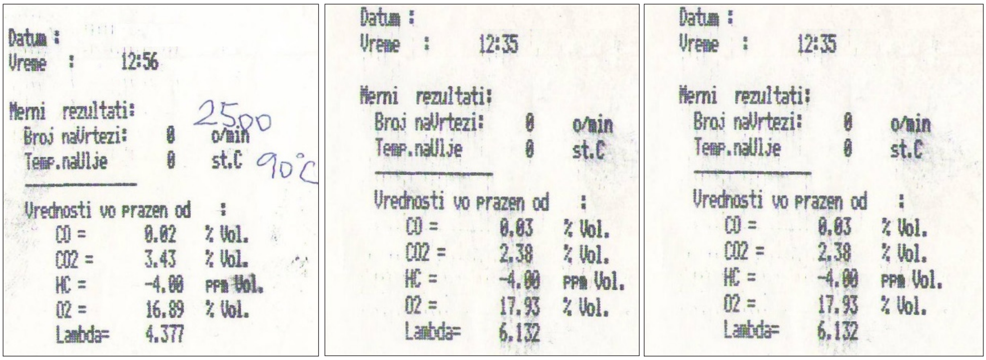


Figure 10: *Power output following the POWER optimization*

Figure 11: *Fuel consumption – POWER optimization*

Figure 12: *Fuel consumption – ECONOMY optimization*

The quantity of harmful exhaust components was measured following both optimizations. The results showed a major difference between the non-optimized engine and the same engine following the POWER, and especially the ECONOMY optimization (Figure 11, 12) regarding the CO_2 emissions. Due to the lowered fuel consumption, a more climate-friendly exhaust footprint from the 1.9 TDI engine was achieved as a direct consequence, and included a 42% decrease in CO_2 emissions (3.43% to 1.99% of the total volume of exhaust gases). Furthermore, even the POWER optimization led to a 30% reduction in CO_2 emissions (3.43% to 2.38% of the total volume of exhaust gases).



```
Datum :
Vreme   :      12:56

Merni  rezultati:                2500
  Broj naVrtezi:      0     o/min
  Temp.naVlje         0     st.C  90°C
  ______________

  Vrednosti vo prazen od      :
      CO =          0.02    % Vol.
      CO2 =         3.43    % Vol.
      HC =          -4.00   PPm Vol.
      O2 =          16.89   % Vol.
      Lambda=       4.377
```

a)

```
Datum :
Vreme   :      12:35

Merni  rezultati:
  Broj naVrtezi:      0     o/min
  Temp.naVlje         0     st.C
  ______________

  Vrednosti vo prazen od      :
      CO =          0,03    % Vol.
      CO2 =         2,38    % Vol.
      HC =          -4.00   PPm Vol.
      O2 =          17.93   % Vol.
      Lambda=       6.132
```

b)

```
Datum :
Vreme   :      12:35

Merni  rezultati:
  Broj naVrtezi:      0     o/min
  Temp.naVlje         0     st.C
  ______________

  Vrednosti vo prazen od      :
      CO =          0,03    % Vol.
      CO2 =         2,38    % Vol.
      HC =          -4.00   PPm Vol.
      O2 =          17.93   % Vol.
      Lambda=       6.132
```

c)

Figure 13: *Exhaust emissions: a) Unoptimized; b) Economy; c) Power*

4 DISCUSSION

The results show that the test-engine is designed to have a higher power output than what the factory control setting allows it. However, taking account of the market where the particular vehicle driven by this engine is being sold, the control maps chosen will reflect specific legal norms, such as environmental Standards, traffic safety norms, conditions for the technical approval of vehicles, taxation conditions, etc., in the countries that make the biggest part of the vehicle's market. The most attention is paid to the environmental norms, since they are controlled easily at the annual technical inspection of the vehicle, by measuring the quantity of harmful components in the vehicle's exhaust emission.

Both the POWER and ECONOMY optimizations are performed primarily by advancing the fuel injection timing. Immediately following the optimization, and according to the results, the engine demonstrates significantly better fuel economy, and, with it, a reduction in CO_2 emissions, but the advanced fuel timing will also inevitably lead to an increase in combustion temperature, which will lead to a rise in NOx emissions. Nevertheless, following both aftermarket optimizations, in the short-term the engine satisfies the required environmental norms in full, while the test-vehicle continues to meet the Euro 4 Emission Standards.

In theory, it is likely that long-term operation will lead to higher wear of certain components, but within the limits predicted by the manufacturer. The performed optimizations following prolonged operation, with great certainty, will lead to a more pronounced decrease in injection pressures and delayed fuel injection timing, which would increase the particulate matter (PM) emissions while decreasing NOx. It should be noted however, that engine emissions can be affected (sometimes significantly) even as the engine deteriorates due to normal wear and/or lack of proper service. This means that, even if the amount of NOx and PM in the exhaust emissions changes over time, the manufacturer predicted that it is highly unlikely that the vehicle's ecological standard will drop in the Euro 3 Standard.

It should be noted that gauging and evaluating the effect of the components' wear on the emissions quantity for engines with modern after treatment systems (Euro 5 and 6 Emission Standard) is considerably more complex, since these engines rely very heavily on the after treatment system to limit emissions, especially for NOx and PM.

5 CONCLUSION

The ongoing conflict in Ukraine and the current geopolitical state of the world have slowed down the economic recuperation following the COVID 19 pandemic significantly. This translates to a new economic crisis, and with-it rising fuel prices. Additionally, one of the positive consequences of the pandemic, the drop in CO_2 emissions in 2020 and 2021, is now on the rise as societies are getting back to their pre-COVID functioning. In response, the research conducted in preparation for this paper sought to analyze the implications of taking advantage of engine control and diesel engine aftermarket optimizations, which have the potential to minimize fuel consumption and reduce the GHG exhaust footprint of a diesel IC engine.

By performing a POWER and ECONOMY optimization on a sufficiently modern, 1.9 dm^3, in-line, four-cylinder, four stroke, turbocharged direct injection engine, that complies with the Euro 4 Emission Standards, this paper proved that it is perfectly plausible to improve fuel economy, and, as a direct consequence, make the engine more climate friendly. At the same time, each of the optimizations maximized the power output of the engine, thereby meeting the operational needs of the engine and vehicle tested.

The major trade-offs for the environmental-engineering compromise are related to engine wear, which, in the short term, will be insignificant, but as this optimization required advancing the fuel injection timing, it will lead to an increase in local NOx emissions due to higher combustion temperatures. In the long term, as engine wear becomes more pronounced and results in decreased injection pressures and delayed fuel injection timing, the amount of PM emissions is likely to increase, while the NOx emissions will drop. It should be stressed that neither optimization will lead to larger engine wear than the one predicted by the manufacturer, or at least not in the short-term, which, consequently, means that the test vehicle and engine will continue to meet the Euro 4 Emission Standards.

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