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Chiptuning impact on emissions in driving tests

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The article presents the results of engine tests aimed at assessing the impact of modifications to engine control software on emission parameters and fuel consumption. Experiments were conducted on a 1.3 L MultiJet compression-ignition engine compliant with the Euro 6 standard. The electronic control unit's EEPROM was extracted and re-calibrated by a leading chiptuning company. Two operating scenarios-factory calibration and the modified calibration-were executed on an engine test bench equipped with a dynamic dynamometer. To ensure repeatability and comparability, the dynamometer governed engine speed and load in accordance with the New European Driving Cycle (NEDC) homologation procedure. Analysis of the revised calibration maps revealed substantive alterations, chiefly to the boost-pressure characteristic, the maximum-torque map, and the maximum fuel-injection-quantity map as a function of air mass. The resulting emission data demonstrate that chip-tuning exerts a pronounced impact on the engine's emission profile, elevating the release of toxic exhaust constituents, most notably nitrogen oxides.

Key words: *chiptuning, combustion engine, emission, ecology*

1. Introduction

The passenger car market has undergone significant changes over the past decade. Automobile companies are struggling with rising production costs, which are caused, among other things, by increasing environmental requirements forcing them to meet increasingly stringent emission standards. The cost of approving power units constitutes a significant part of the total cost of developing and producing a car; manufacturers therefore decide to reduce the number of engine variants available in production vehicles (Table 1). This trend is noticeable, among other things, in the change in the number of available engine variants between the current and previous model generations. For example, for the previous generation of the Fiat Scudo, engines with 3 different displacements and 4 power variants were available, while for the VW Caddy, two engines (1.6 dm^3 and 2.0 dm^3) with 5 power variants were available.

Table 1. Comparison of available powertrain units of urban vans [1, 2]

<table>
<tr><th></th><th colspan="5">Generation IV</th><th colspan="3">Generation V</th></tr>
<tr><td rowspan="2">Fiat Doblo</td><td colspan="2">1.3 MJ</td><td colspan="2">1.6 MJ</td><td>2.0 MJ</td><td colspan="3">1.5 BlueHDI</td></tr>
<tr><td>75 HP</td><td>90 HP</td><td colspan="2">105 HP</td><td>135 HP</td><td>105 HP</td><td colspan="2">131 HP</td></tr>
<tr><td rowspan="2">VW Caddy</td><td colspan="2">1.6 TDI</td><td colspan="3">2.0 TDI</td><td colspan="3">2.0 TDI</td></tr>
<tr><td>75 HP</td><td>102 HP</td><td>110 HP</td><td>140 HP</td><td>122 HP</td><td>75 HP</td><td>102 HP</td><td>122 HP</td></tr>
</table>

The latest generation no longer offers a choice of engine capacities, only different power variants. Technically, the units offered do not differ significantly in construction or equipment. Regardless of the variant, they are equipped with identical fuel, supercharging, cooling or exhaust after-treatment systems. The differences are most often in the power transmission system used (different clutch diameters, the presence or absence of a dual-mass flywheel, or the number of gear ratios). Thus, the different power variants result from different engine control programs implemented by the ECU.

Changing engine control strategies and thus providing different power variants is not only the domain of the latest generation of vehicles. Such solutions were already used on a smaller scale in the previous generation, as exemplified by the 1.6 TDI engine used in the VW Caddy or the 1.3 MJ in the Fiat Scudo.

The ability to change parameters in the ECU makes it so that it is not only the manufacturer, at the stage of designing and adapting the engine to meet certain emission standards, who has the ability to influence the setpoints and shape the torque and power output characteristics, but anyone with the appropriate equipment that allows reading and writing the microcontroller's memory [7].

Currently, there are many programmers on the market that allow ECU programming. Among the most popular are Flex – Magic Motorsport, Autotuner, Dfox – DFB Technologies and KESS 3 – Alientech. The listed devices allow programming using non-invasive methods that do not require physical access to the microcontroller, i.e., through the OBD diagnostic connector or directly through the engine controller connector (BENCH), and invasive methods that, depending on the microcontroller chip or hardware architecture used in the engine controller, require physical access to the PCB and microcontroller leads (BOOT).

Almost all engine controllers manufactured in recent years support programming via the OBD connector, as this is how dealers deliver software patches via service diagnostic interfaces [13]. Manufacturers of stand-alone programmers use modified instructions in factory communication protocols that allow them to skip checking the digital signature of the controller's batch file, thereby allowing the controller to be programmed with any modified batch [11].

Simplifying the programming procedure for connecting the appropriate device to the OBD port has made it easier to access the controller's memory, speeding up reverse engineering and allowing experimentation with parameter modifications in the ECU. This has increased knowledge of engine control algorithms, demonstrated the potential to change engine performance by modifying the control program, and subsequently increased the popularity of software-based engine performance enhancement services called chiptuning.

At present, there is no data to say unequivocally how many cars in operation in Poland have modified software. However, given the dynamics of the chiptuning market and the growing number of workshops offering such services, it can be concluded that the number of vehicles with modified engine controller software may be significant and continue to increase.

Given that cars are homologated with specific engine control software, any change to that software could result in the vehicle losing its homologation and, consequently, being unable to legally operate on public roads. Considering a situation in which the controller is modified to increase torque and maximum power, it can be concluded that this undoubtedly also changes the emissions of harmful compounds generated by the engine, which is one of the standardized parameters. Given the very small number of scientific articles describing this issue, it is worthwhile to better understand the relationship between modifications to vehicle engine controllers and emissions of harmful compounds.

2. Research test benchmark

A test stand consisting of an AVL dynamic engine dynamometer and a Fiat 1.3 MultiJet compression-ignition engine mounted on it was used for the study.

The dynamic dynamometer is a three-phase asynchronous electric brake (AVL DynoRoad type) with a maximum power of 120 kW and braking torque of up to 509 Nm, capable of operating over the full range of motor speeds (0–8000 rpm). The use of an electric machine enables loading the engine (converting its mechanical energy into electrical energy returned to the grid) and conducting tests under both steady-state and dynamic engine loads. The engine mounted on the bench is a four-cylinder turbocharged unit with a displacement of 1.3 dm^3, equipped with a common-rail direct injection system and meeting the Euro 6 emission standard (maximum power of about 70 kW, torque up to 200 Nm) [14, 20]. The high-pressure common-rail fuel system is fed directly from an AVL weighing fuel gauge [5]. The bench also has a forced-circulation liquid-cooling system, a radiator and temperature control of the liquid and oil. The engine uses its factory Magneti Marelli MJD9 ECU (Fig. 1), which has been suitably adapted for dynamometer operation (including an interface for remote control of operating parameters and data reading via OBD interface) [3]. The bench has built-in safety features – including guards for moving parts and exhaust extraction systems – and the test software monitors critical parameters (such as oil pressure, maximum rpm or torque) [17], preventing the exceedance of limit values that could threaten engine or dynamometer failure.

Advanced AVL PUMA software is used to control the operation of the bench – it is a dynamometer automation system that allows load setting, test run control and real-time measurement data acquisition. The dynamometer software includes modules for simulating vehicle operation; this allows mapping on a stationary bench the real conditions of engine operation in a vehicle, including the realization of standard driving tests (such as the European NEDC cycle or other homologation procedures) [4] and freely definable waveforms of dynamic loads. Using built-in algorithms and physical models, it is possible, among other things, to simulate the vehicle's driving resistances (mass, aerodynamics, rolling resistance), the operation of the power transmission system, and even to interfere with the way gears are shifted – thanks to this, the workstation acts as a "vehicle simulator" for the tested engine [8, 12]. The AVL PUMA program interfaces with the engine control system (ECU) via CAN/OBD diagnostic interfaces (among others, the SIRIUS CAN interface is used, which allows reading and writing parameters from the CAN bus online) [6, 19].

Fig. 1. Magneti Marelli MJD9 ECU for 1.3 MultiJet

The communication process of the Autotuner device used in the tests with the MJD9 ECU, which controls the engine under test, varies depending on the selected mode, but some elements remain common. Reading the controller begins with identifying the ECU. Autotuner automatically detects the controller and software version, and checks if a VR file is available in the online database. If the file is not in the database, reading the memory through the OBD connector may take a long time, or even be impossible if the controller is locked. In this case, it is necessary to read the flash memory using BENCH or BOOT mode. In addition, OBD mode reads only the calibration (map) area, not the entire low-level batch – so the file read by OBD is sometimes smaller than the physical memory capacity of the microcontroller. Importantly, when reading OBD, Autotuner does not create a full memory backup, including dflash and iflash memory. In bench or boot modes, the device can perform a full dump of ECU memory. Autotuner writes a so-called backup file (ZIP) containing all memory segments (iFlash/dFlash, etc.) of the controller. Such a full readout allows EEPROM data to be preserved (e.g. immobilizer codes, injector configurations, DTC errors, DPF counters, etc.), which is important especially for safety purposes and possible restoration of the factory state. It is recommended to backup the ECU in BENCH or BOOT mode before modification to protect any unique configuration data.

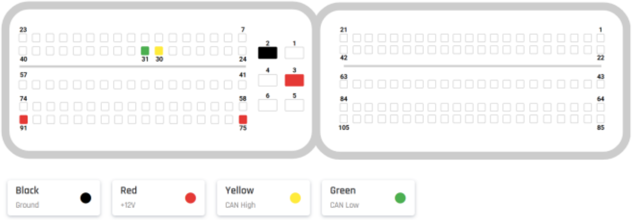

Fig. 2. Autotuner BENCH connection pinout for Magneti Marelli MJD9 ECU

Reading the memory of the microcontroller of the tested engine was performed with the Autotuner equipment using BENCH mode. This equipment allows programming the MJD9 controller through the OBD-II diagnostic connector, which is brought out on the dynamometer bench near the control panel. Reading and writing in this mode is done through the standard CAN diagnostic bus using the UDS protocol. This is the most convenient method: you just need to connect the Autotuner interface to the OBD-II port, and the device will read the microcontroller's memory and let you upload the modified map. The OBD mode is usually used to quickly read/write engine calibration as part of standard modifications, as long as the controller allows it. The MJD9 ECU used in the engine under test is on the list of those supported in OBD mode, but due to the adaptation of the system to the test bench, there were unidentified communication problems and it was not possible to read the memory using this method. For some newer controllers (e.g., Marelli MJD9DF version HW002), Autotuner downloads VR files after the driver identification process, but the file suitable for the tested driver was not on the server. In practice, when tuning the MJD9 for the first time, there is a need to read the ECU in order to unlock it using the BENCH or BOOT mode (the file read by this method can be sent to the Autotuner manufacturer for inclusion in the online database, where it will be available to other users in the future) [15, 16]. After such an operation, OBD can already perform further modifications. In the case in question, since the reading through the OBD connector failed and there was no corresponding VR file on the server, it was necessary to read the contents of the memory in BENCH mode by connecting the appropriate wires directly to the driver's connector. A diagram showing how to connect the appropriate wires to the corresponding pins of the controller is shown in Fig. 2. For the reading, it is necessary to connect the power supply (12V and GND), the two wires corresponding to the CAN-Low and CAN-High lines, and the wire supplying power to the controller to simulate that the ignition is turned on. This reads the entire contents of the microcontroller's memory (full backup), including both the iFlash area (where calibrations are stored) and the dFlash area (where settings and variable parameters are stored).

3. Methods

The read-out file containing the calibration was sent to one of Europe's leading tuning companies, offering remote file modification services. The order involved a typical power increase referred to in the service catalog as STAGE 1. It was decided to outsource the modification to replicate real-world conditions as closely as possible, with the tuning company performing it on an actual car. The modified file was analyzed in StageX software, which allows comparison of changes in calibration files. The software has mappacks defined for a specific driver type. By mappack is meant a special set of data describing the structure of one-, two- and three-dimensional characteristics stored in the memory of the controller. This data describes the location of a given characteristic in memory, its size-axis description, and appropriately scaled values. The mappack categories used during the calibration analysis are listed in Table 2.

After importing the original and modified ECU files into StageX, the software identifies calibration groups in which differences were detected. These groups are marked in orange in Fig. 3. Note that the engine torque limiter maps, engine desired torque maps, transmission torque limiter, injection system and boost pressure have been modified.

Table 2. StageX software mappack category with description

Category	Description
Air control	Airflow management maps, such as through the EGR throttle or MAF.
Engine torque limiters	Torque limits – e.g., temperature-dependent, gear-dependent, ESP-dependent.
Engine torque request	Torque demand from the gas pedal, cruise control, etc.
Exhaust gas temperature EGT	Monitoring and limiting exhaust gas temperatures – for example, for DPF or turbo protection.
Gearbox torque limiter	Torque limiter due to transmission.
Idle speed RPM	Idle speed – maps that set the resting speed.
Injection system	A wide range of injection maps: times, number of doses, temperature corrections, etc.
Rail pressure	Fuel pressure maps in the fuel rail (common rail).
Smoke limitation	Limits the amount of fuel to not exceed emissions (MAF or MAP sensor).
Start of SOI injection	Injection advance maps - key to performance, combustion and emissions
Turbo boost pressure	Target charge pressure maps
Turbo boost control	Maps controlling the turbo valve/actuator (e.g., N75, VGT, WG).

Fig. 3. Mappack category with difference sign for MJD9DF ECU in StageX software

Engine speed /

RPM	750	1000	1450	2100	2500	3200	3600	4000
0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0

Fig. 4. Example of engine torque limiter maps modified in MJD9 ECU

Engine speed /

RPM	1000	1250	1500	1750	2000	2250	2500	3000	3250	3500	3750	4000	4500	4750	5200	5700
0	135.0	180.0	258.5	260.7	261.5	263.9	263.6	266.2	256.5	243.8	230.0	213.7	159.1	146.2	126.0	0.0

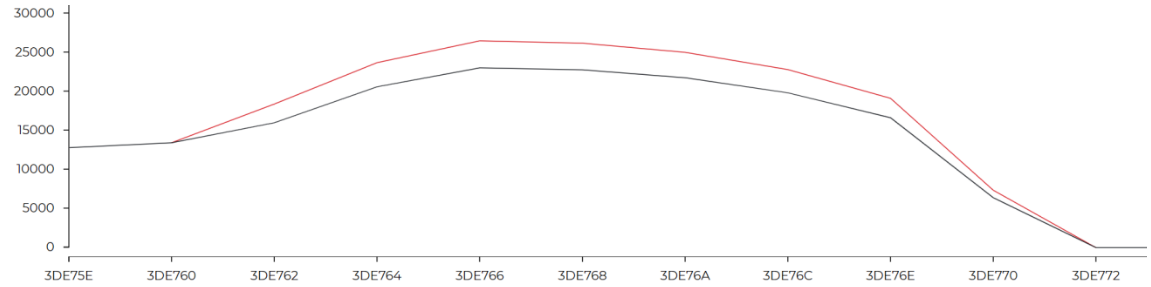

Fig. 5. Main engine torque limiter characteristic modified in MJD9 ECU shown in characteristic table and visualized in raw flash file

Engine speed / Pedal position

% \ RPM	600	800	1250	1750	2250	2750	4000	5200	5700
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	17.0	16.6	15.1	13.1	11.1	1.3	0.0	0.0	0.0
20	45.0	43.3	40.8	36.0	29.9	18.4	3.7	0.0	0.0
30	69.8	66.8	64.3	60.8	56.1	45.2	24.8	9.4	0.0
40	89.0	88.7	88.1	86.5	81.9	71.9	49.8	29.1	0.0
50	100.0	112.5	116.2	117.2	115.0	102.4	74.8	49.8	0.0
70	122.4	196.8	197.9	200.5	196.3	180.2	145.6	109.4	0.0
90	124.8	208.8	262.1	267.1	265.7	249.4	196.8	163.2	0.0
100	126.0	210.0	302.4	312.0	312.0	312.0	225.9	186.4	0.0

Fig. 6. Engine torque request depending on accelerator pedal position and engine speed, modified in the MJD9 ECU

Engine speed / Internal torque

Nm \ RPM	700	800	1000	1250	1500	1750	2000	2250	2500	2750	3000	3500	4000	4500	5000	5500
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20.0	4.88	4.60	4.34	4.04	3.50	3.50	3.52	3.80	4.24	4.26	4.46	4.50	4.52	4.54	4.70	5.00
30.0	7.30	7.06	6.24	5.72	5.08	5.10	5.12	5.46	5.88	5.92	6.30	6.74	6.76	7.06	7.42	8.46
40.0	9.48	9.36	8.30	7.56	6.96	6.88	6.98	7.18	7.46	7.48	7.90	8.44	8.46	8.48	8.50	9.02
50.0	11.60	11.58	10.66	9.56	8.74	8.70	8.78	8.88	9.02	9.10	9.74	10.22	10.24	10.26	10.60	11.44
60.0	13.50	13.42	12.94	11.66	10.78	10.62	10.68	10.72	10.74	10.76	11.46	12.02	12.04	12.06	12.40	13.50
70.0	15.66	15.62	14.72	13.70	12.86	12.68	12.58	12.56	12.64	12.80	13.30	13.52	13.54	13.56	14.34	15.70
80.0	19.10	18.34	17.44	15.92	15.12	14.50	14.02	14.36	14.80	14.92	15.14	15.16	15.18	15.54	16.78	18.32
100.0	28.20	25.40	23.32	20.98	19.72	18.94	18.30	18.78	19.10	19.12	19.22	19.24	20.12	21.32	22.58	23.68
120.0	37.80	34.80	31.86	27.62	26.12	25.08	24.06	24.54	25.00	25.02	25.16	25.16	26.64	28.42	29.62	30.66
140.0	41.08	41.08	41.08	36.64	30.62	29.40	28.80	28.80	29.08	29.08	29.10	29.32	31.50	33.60	36.00	37.70
160.0	47.18	47.18	47.18	41.92	38.62	37.10	34.20	32.76	32.70	31.46	31.60	33.60	36.64	39.80	43.44	45.42
180.0	52.56	52.56	52.56	50.86	43.44	41.38	40.08	39.46	39.24	38.98	39.08	40.06	42.72	47.38	50.30	53.50
200.0	58.14	58.14	58.14	54.26	49.12	47.18	45.92	45.94	46.04	46.04	46.12	48.24	50.50	53.60	59.02	62.64
220.0	67.88	67.88	67.88	58.62	55.02	52.58	50.70	49.40	49.78	51.38	51.40	51.42	53.40	58.22	59.64	62.66
240.0	83.52	83.52	83.52	67.12	58.10	55.12	54.82	54.52	54.72	54.74	57.02	60.74	60.78	61.26	61.56	62.68

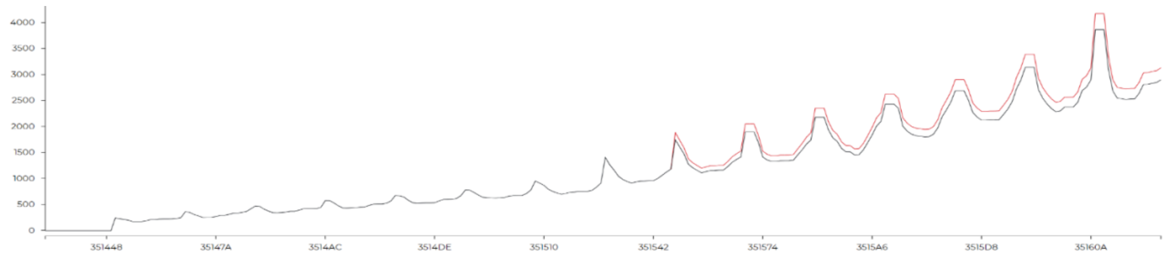

Fig. 7. Example of engine torque to injection quantity conversion maps modified in MJD9 ECU shown in the characteristic table and visualized in raw

One of the modified maps was the torque limiter characteristic. In the modified calibration, the torque limit at 750–1450 rpm was increased to 200 Nm, as shown in Fig. 4.

The main torque limiter, which shapes the engine torque characteristic, was modified over the 1250–4000 rpm range. The modified values of the main torque limiter are presented in Fig. 5.

Calibrations that limit the maximum fuel dosage relative to engine temperature, among other things, allow shaping the course of thermodynamic processes and managing the thermal management of the engine. The modified file also includes changes in the scope of these characteristics. The maximum fuel quantity map was increased by approximately 25% across the entire analyzed range, as shown in Fig. 8. The factory characteristics allow the highest doses in the temperature range from –30°C to 115°C; above this temperature, the maximum values are reduced to protect the engine from overheating. In the modified file, the values above this temperature have been modified by the same value.

The desired torque map was also modified. The changes mainly affected the values at high accelerator pedal positions, as shown in Fig. 6. The values at the maximum accelerator pedal setting were changed. The maximum desired torque in the range shown was increased by 20%.

The engine calibration modifications carried out included, for the most part, characteristics from the "Injection System" group. This group primarily contains a set of calibrations that specify the maximum fuel dose as a function of speed, a characteristic that converts torque to fuel dose based on speed, and an injection duration characteristic that specifies the injector opening time as a function of fuel pressure and injection dose. In the modified file, this group accounted for the largest number of changes, mainly because the aforementioned characteristics, in a slightly modified form, occur repeatedly, and the algorithm uses different versions for different engine operating states (e.g., depending on DPF filling, DPF regeneration, etc.).

The torque-to-fuel dose conversion maps were also modified. An example of such a modification is presented in Fig. 7. The fuel dose values corresponding to torque values in the range of 120–240 Nm were increased by approximately 8%.

Another characteristic that has been modified within the "Injection system" group is Injection Duration. The map includes an injector flow calibration that determines the injector opening time required to inject a specific volume of fuel, depending on the fuel pressure in the CR rail. The injection duration map was modified for fuel doses from 25 mm^3 to 55 mm^3 and rail pressures from 600 bar to 1800 bar, as shown in Fig. 9. The opening times have been increased by 8%, with the consequence that more fuel is physically injected into the combustion chamber than the parameters processed by the engine controller would suggest.

Changing the parameters primarily responsible for the amount of fuel delivered to the combustion chamber is not the only modification that was made to the calibration file under review. The last set of characteristics in which modifications were made includes a group related to boost pressure control. In the "Turbo boost pressure" tab of the StageX software, the following maps have been identified that have been modified relative to the original:

– turbo boost pressure request – containing characteristics of the desired boost pressure in different engine modes
– turbo boost pressure limit – containing the limits of boost pressure relative to speed
– turbo boost pressure limit by ATM – containing limits of boost pressure relative to atmospheric pressure.

The tuner's modification to the boost pressure request map increased the boost pressure setpoint over the engine speed range from 1500 to 4500 rpm. This characteristic defines the requested boost pressure as a function of engine speed and load, expressed by the injected fuel quantity. As shown in Fig. 10, the boost pressure setpoint was increased by approximately 6% for loads above about 150 Nm. In addition, the characteristics limiting the value of boost pressure have been modified so that the permissible pressure values therein are higher than the desired pressure values. Similarly, the maps limiting boost pressure relative to atmospheric pressure have been modified. The injection duration and boost pressure request maps discussed above are presented together in Fig. 9 and Fig. 10.

The effect of software modifications on environmental parameters was determined using PEMS equipment, specifically the AXION R/S mobile exhaust gas analyzer. The measurement range and methods used are shown in Table 3.

Table 3. AXION R/S analyzer measurement characteristics [2]

Substance	Measurement range	Relative measurement accuracy	Resolution	Measurement method
HC	0–4000 ppm	±3%	1 ppm	NDIR
CO	0–10%	±3%	0.01 vol.%	NDIR
CO_2	0–16%	±4%	0.01 vol.%	NDIR
NO	0–4000 ppm	±3%	1 ppm	E-chem
PM	0–300 mg/m^3	±2%	0.01 mg/m^3	Laser Scatter

The emission measurements were performed as a single comparative test series for the factory and modified ECU calibration. Therefore, the repeatability of the complete test procedure could not be determined experimentally, and no standard deviation for repeated test runs was calculated [18]. For this reason, the results should not be interpreted as a full statistical assessment of emission variability, but rather as a comparative case study showing the direction and scale of emission changes resulting from ECU calibration modifications.

The measurement uncertainty was assessed on the basis of the declared accuracy of the AXION R/S analyzer. According to the instrument specification, the relative measurement accuracy was ±3% for HC, CO and NO, ±4% for CO_2 and ±2% for PM. Since both calibrations were tested using the same engine, test bench, analyzer, sampling configuration and NEDC-based operating cycle, the systematic component of the instrumental error affected both measurements similarly [9, 10].

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Engine speed / Engine temp

deg C \ RPM	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500	3750	4000	4500	5000	5250
-30.0	54.80	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
-10.0	48.54	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
10.0	42.50	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
20.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
30.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
40.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
50.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
60.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
70.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
80.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
90.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
100.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
110.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
115.0	39.82	55.00	60.10	61.36	59.40	59.70	58.86	58.74	58.20	54.62	52.04	49.04	46.64	41.32	35.96	0.00
120.0	16.50	20.00	31.20	35.46	35.40	34.00	32.52	28.92	26.84	25.00	25.54	27.14	28.20	29.22	27.66	0.00
125.0	12.92	11.54	9.64	9.12	8.30	7.72	7.14	6.80	6.74	6.82	7.62	8.42	8.84	9.26	9.80	0.00

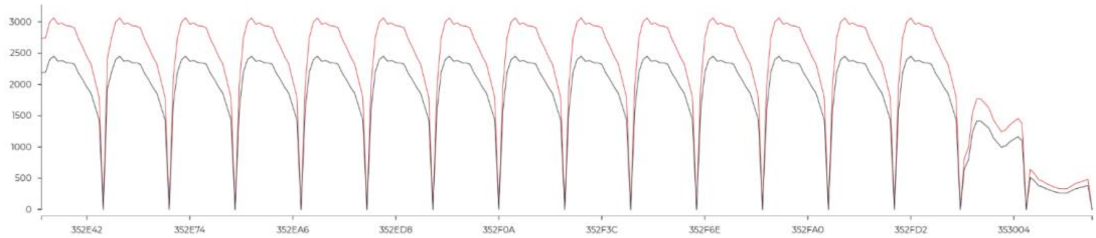

Fig. 8. Example of maximum fuel quantity injected by engine temperature characteristic modified in MJD9 ECU shown in characteristic table and visualized in raw flash file

Consequently, the comparison was based primarily on relative differences between the factory and modified calibration. If the observed change in a given emission component exceeded the declared accuracy of the analyzer, it was interpreted as an indication of a real change in emission behavior. Nevertheless, the lack of repeated test runs is a limitation of the study and should be taken into account when interpreting the results. Future work should include repeated test cycles to determine repeatability, standard deviation and statistical significance of the observed differences.

Using the capabilities of the dynamic dynamometer and AVL PUMA software, the NEDC test was reproduced, including the Urban and Extra-Urban phases. Although WLTP and RDE procedures are currently used for the emission assessment of light-duty vehicles, the NEDC cycle was selected in this study to ensure repeatable and directly comparable engine speed and load conditions on the dynamic engine test bench. The aim of the study was not to reproduce the complete vehicle type-approval procedure, but to isolate the influence of ECU calibration modification under identical operating conditions. For this reason, the results obtained should be interpreted as a comparative assessment of the impact of the Stage 1 ECU modification, rather than as a direct homologation result.

The lack of WLTP- and RDE-based measurements is a limitation of the present study. Future work should include WLTP-based test-bench procedures and PEMS-based RDE measurements to assess the effect of ECU modification under more representative transient and real-driving conditions.

The modified injection duration and boost pressure request maps are shown in Fig. 9 and Fig. 10. These figures are placed after the measurement equipment characteristics due to formatting and readability constraints.

4. Results and discussion

4.1. Emission results for the complete NEDC cycle

Comparative tests of the Fiat 1.3 MultiJet engine on a dynamic engine dynamometer before and after ECU software modification showed clear changes in the emission of toxic exhaust components over the complete NEDC cycle. The specific emission values measured over the complete NEDC cycle are presented in Fig. 11. After the Stage 1 modification, an increase in NO_x, PM and HC emissions was observed in comparison with the factory calibration. This indicates that performance-oriented ECU modification deteriorated the emission characteristics of the tested engine under the analysed operating conditions.

The increase in emissions was directly related to the changes introduced into the calibration file. The fuel dose as a function of desired torque was increased by approximately 8%, and the injection duration was increased by a similar value. As a result, more fuel was delivered to the combustion chamber. This increased the combustion energy and local combustion temperature, which promoted NO_x formation. At the same time, local oxygen deficiency and transient enrichment contributed to higher PM and HC emissions. Although the boost pressure setpoint was also increased by approximately 6% under high-load conditions, this change only partially compensated for the increased fuel quantity.

Fuel rail pressure / Injection quantity

mm3/inj \ bar	0.0	100.0	200.0	250.0	300.0	400.0	500.0	600.0	700.0	800.0	900.0	1000.0	1200.0	1400.0	1600.0	1800.0
0.00	0.00	170.00	170.00	170.00	170.00	160.00	150.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00
0.20	0.00	559.00	327.00	304.00	292.00	278.00	271.00	267.00	264.00	262.00	261.00	260.00	258.00	257.00	256.00	255.00
0.50	0.00	728.00	412.00	359.00	333.00	307.00	294.00	287.00	282.00	279.00	276.00	274.00	272.00	270.00	268.00	267.00
1.00	0.00	859.00	525.00	437.00	393.00	349.00	328.00	316.00	307.00	302.00	297.00	294.00	290.00	286.00	284.00	282.00
1.50	0.00	990.00	561.00	484.00	438.00	388.00	360.00	343.00	332.00	324.00	317.00	313.00	305.00	301.00	297.00	294.00
2.00	0.00	1111.00	603.00	525.00	476.00	419.00	387.00	367.00	353.00	342.00	335.00	328.00	319.00	313.00	308.00	305.00
20.00	0.00	2895.00	1620.00	1366.00	1196.00	984.00	856.00	771.00	711.00	665.00	630.00	602.00	559.00	529.00	506.00	489.00
25.00	0.00	3296.00	1847.00	1555.00	1359.00	1114.00	967.00	885.00	813.00	759.00	717.00	684.00	633.00	597.00	570.00	548.00
30.00	0.00	3632.00	2048.00	1727.00	1512.00	1241.00	1078.00	987.00	908.00	890.00	841.00	801.00	742.00	700.00	668.00	643.00
35.00	0.00	4000.00	2302.00	1919.00	1668.00	1359.00	1176.00	1077.00	987.00	970.00	916.00	875.00	812.00	768.00	735.00	709.00
40.00	0.00	4000.00	2358.00	2008.00	1769.00	1464.00	1276.00	1171.00	1078.00	1056.00	997.00	950.00	879.00	827.00	789.00	756.00
45.00	0.00	4000.00	2531.00	2162.00	1908.00	1581.00	1378.00	1264.00	1161.00	1137.00	1073.00	1020.00	941.00	885.00	841.00	808.00
50.00	0.00	4000.00	2688.00	2311.00	2048.00	1704.00	1487.00	1363.00	1251.00	1221.00	1150.00	1092.00	1003.00	937.00	889.00	850.00
55.00	0.00	4000.00	2867.00	2470.00	2191.00	1823.00	1590.00	1456.00	1334.00	1301.00	1223.00	1159.00	1061.00	989.00	935.00	892.00

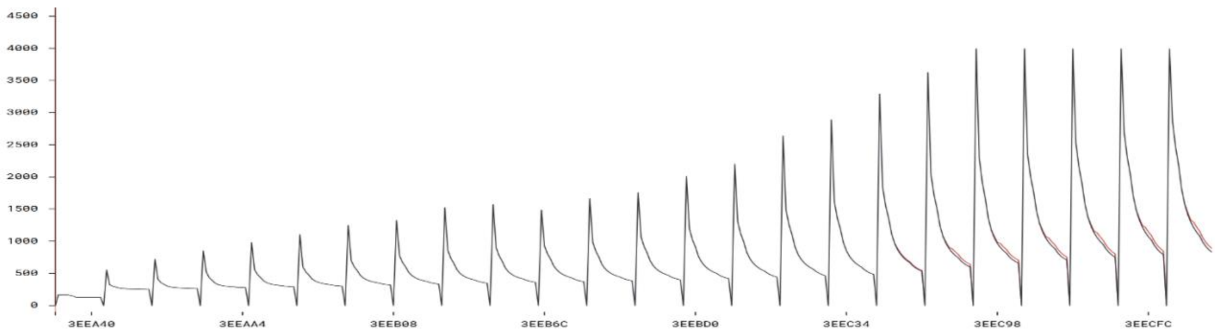

Fig. 9. Injection duration characteristics modified in MJD9 ECU shown in the characteristic table and visualized in the raw flash file

Engine speed / Injection quantity

mg/hub \ RPM	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500	3750	4000	4250	4500	4750
5.00	910.0	940.0	960.0	1010.0	1070.0	1110.0	1175.0	1225.0	1265.0	1295.0	1315.0	1335.0	1340.0	1340.0	1315.0	1265.0
8.00	960.0	990.0	990.0	1040.0	1100.0	1165.0	1225.0	1280.0	1315.0	1350.0	1370.0	1390.0	1395.0	1395.0	1365.0	1315.0
11.00	1000.0	1020.0	1040.0	1120.0	1170.0	1225.0	1265.0	1325.0	1365.0	1405.0	1435.0	1455.0	1455.0	1455.0	1440.0	1395.0
14.00	1060.0	1080.0	1120.0	1180.0	1250.0	1290.0	1325.0	1380.0	1425.0	1465.0	1495.0	1515.0	1515.0	1515.0	1495.0	1445.0
17.00	1200.0	1215.0	1220.0	1260.0	1320.0	1370.0	1415.0	1465.0	1505.0	1545.0	1565.0	1585.0	1585.0	1575.0	1555.0	1515.0
20.00	1270.0	1290.0	1310.0	1355.0	1405.0	1445.0	1490.0	1545.0	1585.0	1615.0	1645.0	1655.0	1655.0	1645.0	1615.0	1560.0
23.00	1360.0	1400.0	1415.0	1475.0	1515.0	1565.0	1615.0	1655.0	1690.0	1720.0	1730.0	1740.0	1720.0	1690.0	1670.0	1620.0
26.00	1465.0	1500.0	1525.0	1595.0	1655.0	1710.0	1760.0	1790.0	1810.0	1810.0	1810.0	1810.0	1780.0	1750.0	1715.0	1700.0
29.00	1560.0	1600.0	1645.0	1710.0	1770.0	1820.0	1860.0	1880.0	1890.0	1875.0	1875.0	1875.0	1840.0	1810.0	1785.0	1780.0
32.00	1600.0	1720.0	1770.0	1820.0	1880.0	1920.0	1960.0	1970.0	1950.0	1935.0	1935.0	1925.0	1895.0	1870.0	1845.0	1820.0
35.00	1600.0	1840.0	2006.0	2132.0	2174.0	2205.0	2237.0	2126.0	2100.0	2090.0	2084.0	2069.0	2042.0	2021.0	1969.0	1820.0
38.00	1600.0	1900.0	2153.0	2279.0	2321.0	2342.0	2352.0	2168.0	2147.0	2137.0	2132.0	2111.0	2090.0	2032.0	1969.0	1820.0
41.00	1600.0	1940.0	2268.0	2363.0	2363.0	2363.0	2363.0	2205.0	2189.0	2179.0	2174.0	2147.0	2090.0	2032.0	1969.0	1820.0
43.00	1600.0	2000.0	2363.0	2363.0	2363.0	2363.0	2363.0	2237.0	2226.0	2216.0	2210.0	2147.0	2090.0	2032.0	1969.0	1820.0
45.00	1600.0	2040.0	2363.0	2363.0	2363.0	2363.0	2363.0	2263.0	2258.0	2231.0	2210.0	2147.0	2090.0	2032.0	1969.0	1820.0
50.00	1600.0	2100.0	2363.0	2363.0	2363.0	2363.0	2363.0	2310.0	2258.0	2231.0	2210.0	2147.0	2090.0	2032.0	1969.0	1820.0

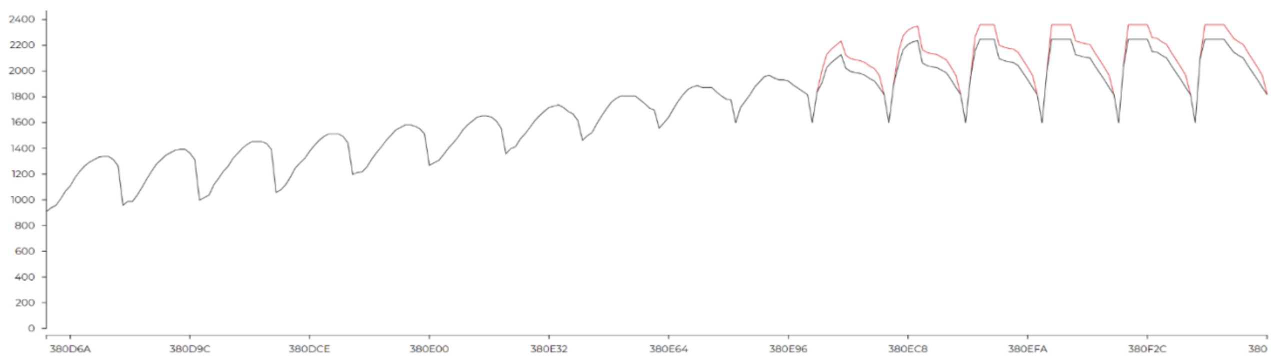

Fig. 10. Request boost pressure characteristics modified in MJD9 ECU shown in the characteristic table and visualized in the raw flash file

4.2. Emission results for the urban phase

The Urban phase of the NEDC cycle is characterized by low vehicle speeds, frequent stops and repeated acceleration events. Under these conditions, an increase in exhaust emissions was also observed after uploading the Stage 1 ECU modification. The specific emission values recorded during the Urban phase are presented in Fig. 12. However, the differences between the factory and modified calibration were less pronounced than in the Extra-Urban phase, because the engine operated less frequently under high-load conditions.

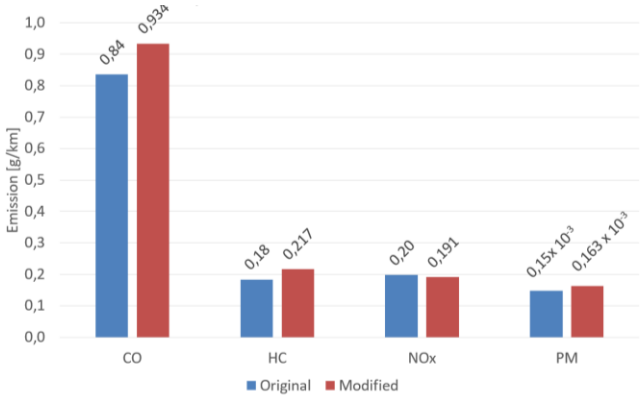

Fig. 11. Specific emission in the complete NEDC cycle for the 1.3 MultiJet Euro 6 engine with factory and modified ECU calibration

The increase in PM and HC emissions in the Urban phase can be associated with transient enrichment during acceleration. Under low-speed and rapidly changing load conditions, the required boost pressure is not always achieved immediately due to the dynamic response of the turbocharger. Consequently, the additional fuel resulting from the modified injection maps may not be fully burned, promoting soot and unburned hydrocarbon formation.

NO_x emissions in the Urban phase also increased, although to a lesser extent than in the high-load part of the cycle. This may be due to the exhaust gas recirculation system remaining active during low-load urban operation, partially limiting NO_x formation. Nevertheless, the increased fuel quantity and higher local combustion temperatures led to higher NOx emissions than under factory calibration.

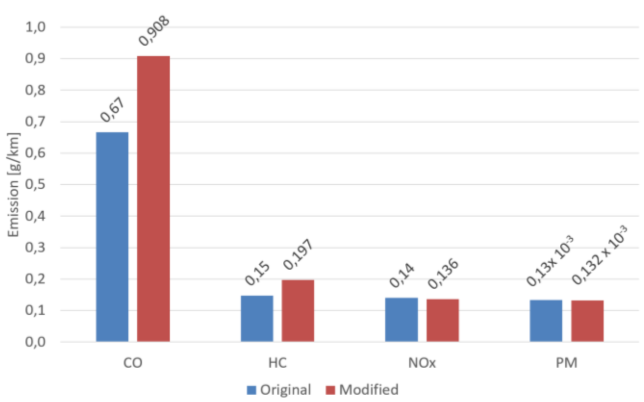

Fig. 12. Specific emission in the Urban phase of the NEDC test for the 1.3 MultiJet Euro 6 engine with factory and modified ECU calibration

4.3. Emission results for the extra-urban phase

The specific emission values obtained for the Extra-Urban phase are presented in Fig. 13. In this part of the NEDC cycle, the differences between the factory and modified calibration were more pronounced due to higher engine speeds and loads. After uploading the modified software, the engine generated significantly higher NO_x and PM emissions during high-speed operation.

The increase in NO_x emissions was mainly associated with higher combustion temperatures resulting from increased fuel delivery and higher boost pressure under high-load conditions. The modified torque limiters and torque-to-fuel quantity maps allowed higher fuel quantities in the engine speed range where the Extra-Urban phase requires higher torque. In addition, the increase in maximum fuel quantity limits over the temperature range reduced the protective effect of factory calibration strategies intended to limit thermal load.

PM emissions in the extra-urban phase also increased due to the extended injection duration and increased fuel quantity. Although the boost pressure setpoint was increased to provide more air for combustion, the relative mixture became richer than in the factory calibration, especially during transient load changes. This promoted soot formation. The DPF present in the Euro 6 engine retains most particulate matter, but increased engine-out soot production may lead to faster filter loading. Since the DPF loading state was not recorded during the tests, this should be considered a limitation of the study.

5. Conclusions

Analysis of the exhaust emission results for the Fiat 1.3 MultiJet engine, comparing the factory calibration with the modified ECU software, showed a marked increase in NO_x, PM and HC emissions. These changes were particularly evident in the extra-urban phase of the NEDC cycle, where the engine operates at higher speeds and loads. The increase in emissions was a direct result of changes to the calibration maps, which included an increase in torque limits, fuel dosage, injection duration and desired boost pressure.

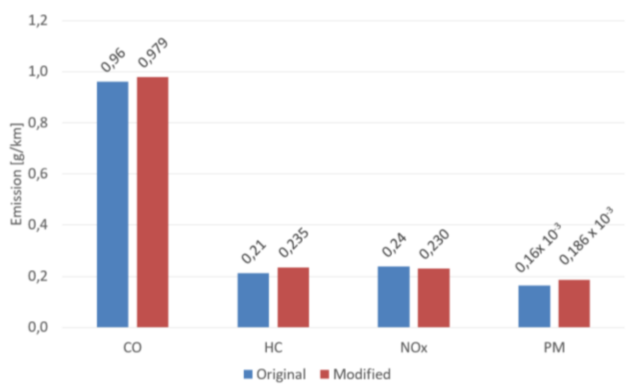

Fig. 13. Specific emission in the Extra-Urban phase of the NEDC test for the 1.3 MultiJet Euro 6 engine with factory and modified ECU calibration

It is worth noting, however, that the modification was performed by an independent tuning company, and there are currently no standardized guidelines or procedures that specify how to safely and sustainably perform this type of modification. As a result, the results of calibration can vary significantly depending on the level of expertise, experience and tools used by the contractor in question. There is a real chance that other companies could achieve better results. At the same time, less knowledgeable or unskilled operators could cause even greater deterioration of combustion and emission characteristics and even jeopardize the life of the drive unit.

Importantly, some irregularities and simplifications are noticeable in the analyzed modification, indicating a lack of in-depth analysis of the impact of changes on engine operation. In particular, increasing the values in the maps by a fixed percentage (e.g. +8% for injection timing, +25% for maximum doses) does not take into account the actual technical capabilities of the equipment (injectors, turbocharger, cooling system or DPF). Such an approach suggests that the modification was carried out in a template fashion, without individual adjustment to a specific drive unit. Failure to consider temperature limitations, DPF regeneration conditions, mechanical tolerances or controller protection strategies can result not only in increased emissions in the long run but also in the risk of engine or component damage.

In conclusion, the results presented underscore the need for caution when deciding on chiptuning and, above all, signal that, as the popularity of such services increases, it will be necessary to examine more closely the environmental impact of modified vehicles.

Without proper procedures for validating modifications, analyzing their impact on the entire powertrain, and accounting for environmental consequences, such interference can do more harm than good. Given the lack of industry regulation, it seems reasonable to develop quality standards for independent ECU modification services, taking into account operational safety and environmental compatibility. Since the measurements were performed as a single comparative test series, the results should be interpreted as a case study indicating the direction and approximate scale of emission changes, rather than as a full statistical assessment of ECU modification effects.

Nomenclature

DI	direct injection
ECU	engine control unit
HC	hydrocarbons
NO_x	nitrogen oxides
NEDC	New European Driving Cycle
PM	particulate matter

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