# Innovative research method of the fuel injector that allows to evaluate the efficiency of wood chip drive control systems

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**Abstract.** Exceeding air pollution emission standards in large cities leads to a search of methods of reducing emissions and their neutralization. One of the ways to improve air quality is to increase green infrastructure in urban areas. It leads to an increase in the demand for work machines that process waste from tree care is. Mobile chopping shredders for tree branches are driven by internal combustion engines defined in the standard as drives of non-road mobile machines. In the case of spark-ignition internal combustion engines, these provisions are liberal. This leads to a low level of technical advancement of these drives characterized mainly by the carburettor fuel supply system. The article presents an innovative research method of the fuel injector of the injection unit, enabling mechatronisation of the combustion engine's injection system. The measured values make it possible to evaluate the fuel consumption depending on the developed (patent pending) innovative control systems for the chipper drive. Ultimately, the conducted research will enable the increase of the effectiveness of wood chipping grinding processes and reduction of harmful emissions.

**Keywords:** small engine SI, non-road mobile machines, innovative research method of the fuel injector

## 1 Introduction

Energy consumption of chopping branches processes by mobile wood chippers is mainly assessed by fuel consumption [1]. The research on the efficiency of non-road mobile machines [2, 3] (wood chopping machines [1]) and the emissions they generate [1, 4, 5] are important as they significantly influence the assessment of the entire processes in which they are used. Due to the liberal homologation regulations [6-7], these drives are characterized by a carburettor fuel supply system [8-10], which in contrast to modern systems is characterized by limited possibilities of monitoring work parameters [4]. The development of innovative fuel supply systems for this group of engines, using components and control ideas used in automotive vehicles, increases cognitive abilities. Electronic control units allow not only

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to control drives in accordance with modern environmental standards, but also to monitor and record basic drive parameters. The main actuator implementing the drive control processes is an electrically controlled fuel injector whose operation depends on a complex control algorithm stored in the electronic control unit ECU (1 and 2) [11].

$$T_{w_s} = I_{const} \cdot VE(tps, rpm) \cdot AD \cdot C + AE, \tag{1}$$

where:
$T_{w_s}$ – fuel injector opening time signal,
$I_{const}$ – constant dependent on the injector, engine capacity, pressure, intake air temperature, volumetric value, determining the injector opening time enabling reaching the stoichiometric mixture,
$VE(tps, rpm)$ – the value of volumetric efficiency (the ratio of the amount of sucked mixture to the cylinder to its capacity) read from the engine load characteristics and the rotational speed,
$AD$ – percentage difference in relative air density to air density at 21˚C,
$AE$ – enrichment at acceleration,
$C$ – percentage correction of the fuel dose.

$$C = B \cdot T \cdot ASE \cdot EGO \cdot IAT, \tag{2}$$

where:
$B$ – fuel injector opening time signal,
$T$ – constant dependent on the injector, engine capacity, pressure, intake air temperature, volumetric value, determining the injector opening time enabling reaching the stoichiometric mixture,
$ASE$ – the value of volumetric efficiency (the ratio of the amount of sucked mixture to the cylinder to its capacity) read from the engine load characteristics and the rotational speed,
$EGO$ – percentage difference in relative air density to air density at 21˚C,
$IAT$ – enrichment at acceleration.

The correct operation of modern control algorithms requires identified values of operating parameters. The control process carried out in this way, apart from the reduction of fuel consumption and the emission of toxic compounds in the exhaust gas, enables the recording of several signals simultaneously, i.e. for example: rotational speed, engine load, temperature, injection time. The recorded signals allow to carry out analyses of the variables introduced and their impact on the ongoing processes [12, 13]. In addition, it is possible to register measurements of drive parameters under real operating conditions. The registration of such results during the coupling of the drive with the working machine allows the search for new, more effective control systems. One of such systems is to match the work of the wood chipper drive to the operating conditions by changing the rotational speed of the drive depending on the object in the chipper feed channel. These machines are characterized by a periodically variable duty cycle and it is possible to limit fuel consumption during idle operation. An example of such a control is described in the article [14] and the patent application [15]. The assessment of the drive control method of the chipper can be made on the basis of the analysis of one full cycle of the chopping process. For this purpose, it is necessary to determine the injection volume of the fuel during one injection depending on the set injector opening time signal. The article presents the method of determining the injection volume of fuel for one cycle of operation of an internal combustion engine under real operating conditions while maintaining the actual signal generator. The results of an injector working in an upgraded drive system have also been published. The article also indicates the general function of fuel consumption during one operation cycle of the chipper, in which the obtained results are applicable. The test results of the developed method together with other ECU signals will enable the evaluation of the effectiveness of the implemented algorithms and control systems after describing the operating conditions thoroughly during one chip operation cycle.

## 2 Research object

The tests were carried out on a mobile wood chopper driven by a spark-ignition internal combustion engine. The basic drive unit is German GX 390, subject to modernization of the injection-ignition system. The basic change was the replacement of the carburettor fuel supply system with electronically controlled integrated injection-ignition system, characterized by work in feedback and the actuators and sensors indicated in Figure 1. The tested injector is part of the Weber 30 MM4 injection unit [16].

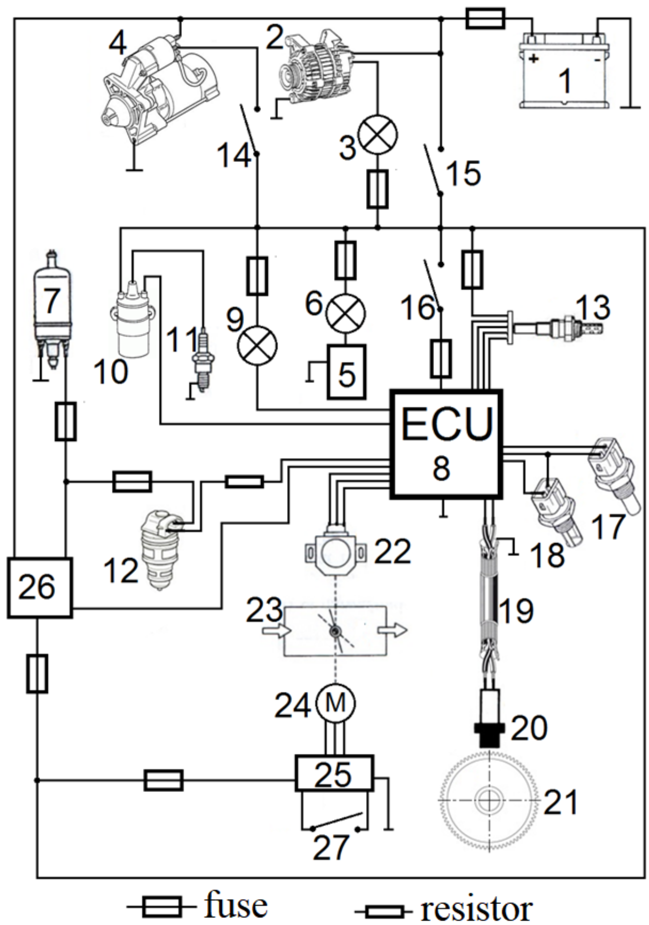


**Fig. 1.** Schematic diagram of the innovative injection-ignition system used in the German GX390 engine: 1 – 12V battery, 2 – 65A alternator, 3 – charging indicator light, 4 – starter, 5 – oil level sensor, 6 – oil level control lamp, 7 – electric fuel pump, 8 – electronic control unit, 9 – malfunction indicator light MIL, 10 – high-voltage ignition coil, 11 – spark plug, 12 – injector, 13 – wide oxygen sensor in the exhaust gas, 14 – starter switch, 15 – circuit switch, 16 – emergency switch, 17 – engine temperature sensor, 18 – sensor temperature of intake air, 19 – shielded cable, 20 – speed sensor and engine crankshaft position, 21 – pulse wheel, 22 – throttle position sensor (TPS), 23 – throttle valve, 24 – servomechanism, 25 – servo controller, 26 – fuel pump and injector relay, 27 – manual engine speed switch

## 3 Research methodology

The tests were carried out using the above-described working machine, the controller of which enables monitoring and registration of test results. An additional function of the controller is the possibility of adjusting the system. The measurement requires a non-invasive transfer of the injector from the inlet manifold suction channel to the measuring cylinder (with an accuracy of 0.1 ml), without disconnecting the electrical and fuel installations. The injector opening time was carried out by the ECU EMU MASTER motor controller. The expected values were entered by the operator. The set time was not less than 1.4 ms because the manufacturer of the injection unit indicates it as a limit when injection can take place [16]. Starting the engine caused impulses simulating the operation of the system. The oscillogram of the signal from the engine speed sensor enabled counting the number of pulses, which was recorded using the DSC Hantek 3064. The system was connected in accordance with Figure 2. Other mechanical, electrical, hydraulic, operational, physico-chemical and atmospheric parameters such as: fuel pressure in the system, air back pressure, injector opening frequency, system voltage, fuel density and temperature, injector geometry, wear, pollution and temperature were constant.

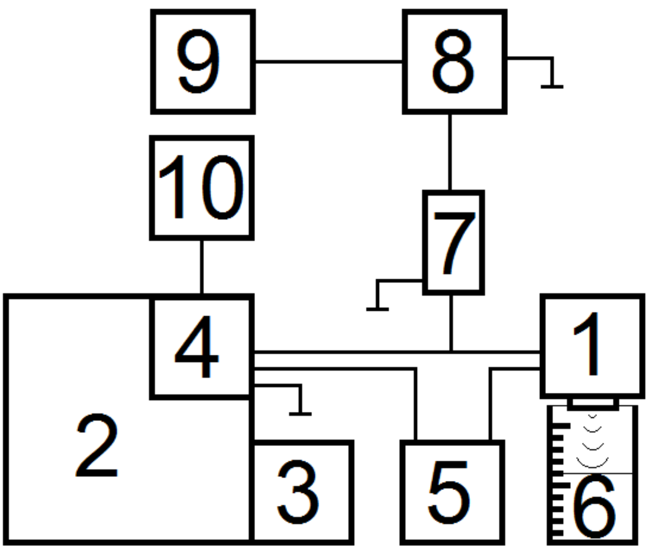


**Fig. 2.** Scheme of the station for measuring the volume of injected fuel dose where: 1 – injector, 2 – internal combustion engine, 3 – motor starter, 4 – electronic engine control unit, 5 – battery, 6 – measuring cylinder, 7 – capacitive measuring probe, 8 – oscilloscope, 9 – PC I with a monitoring and recording program for oscilloscope display, 10 – PC II with a monitoring and recording program and an engine controller programmer

## 4 Research results

The collected results are the total volume of the injected fuel dose, the number of injections made. These values allow to determine the volume of injected fuel dose per one injector opening at a given time of the injector opening signal (Table 1).

**Table 1.** Volume of injected fuel – results of 10 measurement tests

| No | Injector opening time signal set $t_w$ [ms] | Total volume of fuel injected [ml] / The number of injector openings<br>Results of 10 measurement tests: | Average volume of fuel injected during a single injection [ml] |
|---|---|---|---|
| 1 | 1.40 | 0.25 / 71; 0.25 / 70; 0.30 / 86; 0.25 / 72; 0.25 / 71; 0.20 / 57; 0.20 / 58; 0.30 / 85; 0.25 / 71; 0.20 / 58 | 0.0035 |
| 2 | 1.50 | 0.30 / 71; 0.30 / 71; 0.25 / 59; 0.25 / 58; 0.25 / 60; 0.40 / 95; 0.40 / 94; 0.35 / 83; 0.35 / 82; 0.30 / 71 | 0.0042 |
| 3 | 1.60 | 0.35 / 71; 0.35 / 72; 0.35 / 73; 0.35 / 69; 0.40 / 81; 0.40 / 80; 0.25/51; 0.25 / 70; 0.35 / 50; 0.20 / 40 | 0.0049 |
| 4 | 2.10 | 0.60 / 67; 0.50 / 56; 0.60 / 67; 0.60 / 68; 0.40 / 44; 0.40 / 45; 0.60 / 66; 0.50 / 55; 0.60 / 67; 0.60 / 68 | 0.0090 |
| 5 | 2.55 | 0.80 / 71; 0.85 / 75; 0.80 / 73; 0.80 / 69; 0.40 / 35; 0.40 / 36; 0.55 / 49; 0.80 / 70; 0.55 / 47; 0.70 / 62 | 0.0113 |
| 6 | 3.00 | 1.05 / 70; 1.00 / 66; 0.50 / 33; 1.00 / 67; 0.80 / 53; 0.90 / 60; 0.95 / 64; 0.75 / 50; 0.60 / 40; 1.10 / 73 | 0.0150 |
| 7 | 4.00 | 1.50 / 71; 2.00 / 93; 1.90 / 89; 1.50 / 72; 1.50 / 70; 2.00 / 94; 1.80 / 84; 1.70 / 80; 0.75 / 82; 1.65 / 77 | 0.0214 |
| 8 | 5.00 | 2.00 / 71; 1.65 / 58; 1.90 / 67; 1.80 / 64; 1.85 / 66; 1.70 / 60; 2.00 / 72; 1.50 / 53; 1.75 / 62; 1.90 / 68 | 0.0282 |

## 5 Analysis of results

The obtained results allow to determine the characteristics of the injected fuel dose volume for one cycle of the combustion engine operation depending on the set time of the injector opening signal (Fig. 3)

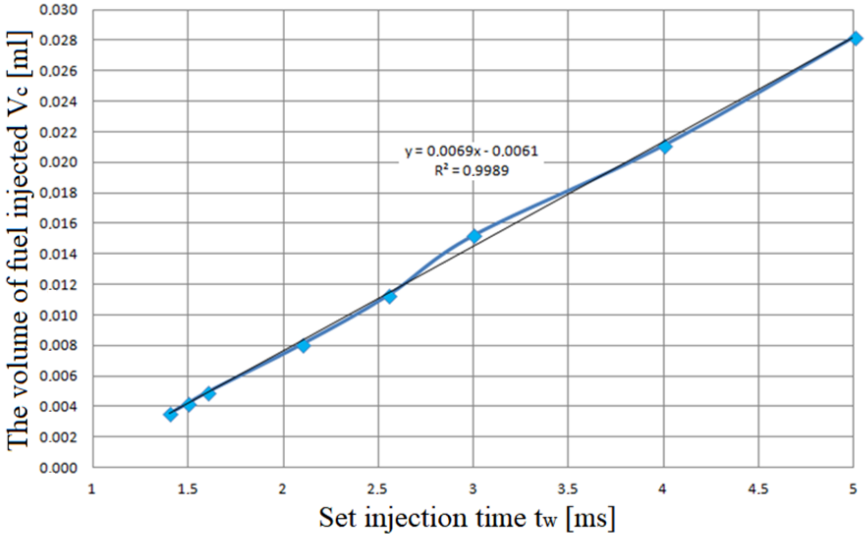


**Fig. 3.** The characteristics of injected fuel dose volume of the chipper drive injection unit for one injector opening cycle as a function of the injector opening time signal

The minimum signal time enabling the injection in accordance with literature sources equals 1.4 ms. It's the time necessary to open the injector and close the injector. The volume of injected fuel dose during a single injection depending on the injector opening time signal is shown in function (3).

$$V_c(t_w) = \begin{cases} 0, & t_w < 1.4 \\ 0.0069 \cdot t_w - 0.0061, & t_w \geq 1.4 \end{cases} \quad (3)$$

where:
$V_c$ – volume of fuel injected during a single injection [ml];
$t_w$ – set signal injection time [ms].

Changing the injection time causes a linear change in the volume of the injected fuel dose. The linearization of the characteristics of the volume of fuel injected as a function of time may allow the derivation of a mathematical model allowing to expand the control possibilities. The performed tests will be used to model the fuel consumption of crushing machines depending on the control method.

## 6 Conclusions

The developed method makes it possible to test injectors of spark ignition internal combustion engines performing indirect injection to the intake duct with an operating pressure of about 0.1 MPa. Injector tests are carried out in conditions close to real, primarily in the aspect of control signals. Injector characteristics can change due to operation and significantly differ from catalog data. The advantage of the method is the ability to test the injection components on the devices in which they are operated and in accordance with their technical condition. The results of these tests may be important for constructors modernizing the structure, working with subassemblies in various technical conditions. The determined characteristics can be used in the developed function enabling determination of fuel consumption of working machines under specific operating conditions. An example of such a function is, for example, the fuel consumption in one operation cycle of the chipper $q_{e_{cr_{jn}}}$ during idling at low speed during the working hour (equation 4).

$$q_{e_{cr_{jn}}} = n_{cr_{jn_s}} \cdot V_{cs_{cr_{jn}}}\left(t_{w_{cr_{jn}}}\right) \cdot 0{,}001 \cdot t_{cr_h}, \quad (4)$$

where :
$n_{cr_{jn_s}}$ – rotational speed of the chipper drive during idling at low speed [rev/s],
$V_{cs_{cr_{jn}}}$ – volume of injected fuel for one cycle of the internal combustion engine during idle operation of the chopper at low speed [ml],
$t_{w_{cr_{jn}}}$ – time of the injector opening preset signal for one cycle of the internal combustion engine during idle chipper operation at low speed [ms],
$t_{cr_h}$ – time of one chip work cycle [s] equal to the working hour.

The time of the injector opening signal, and the rotational speed for the given operating conditions is recorded during the operation of the device. The exemplary function and research results indicated enable empirical and theoretical analyzes of the processes and control systems of non-road mobile machinery drives.

## References

1. M. Manzone, *Energy consumption and CO2 analysis of different types of chippers used in wood biomass plantations*. Applied Energy **156**, 686-692 (2015)
2. S. Gürsoy, B. Kolay, Ö Avşar, A. Sessiz, *Evaluation of wheat stubble management practices in terms of the fuel consumption and field capacity*. Res. Agr. Eng. **61** (3), 116-121, DOI: 10.17221/77/2013-RAE (2015)

3. C. Sağlam, F. Kaplan, R. Polat, *A study on the chopping and mixing of cotton stalks with soil*. African Journal of Biotechnology, **9**(30), 4764-4775, ISSN 1684–5315 (2010)
4. P. Lijewski, P. Fuć, M. Dobrzyński, F. Markiewicz, *Exhaust emissions from small engines in handheld devices*. MATEC Web of Conferences **118**, 00016, VII International Congress on Combustion Engines (2017)
5. D. Mei, W. Hengquan, D. Pengfei, L. Xianming, *A statistical analysis of emission features in non-road small SI engines with the same displacement.* Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, DOI: 10.1177/0954407017729301 (2017)
6. Regulation **2016/1628/UE** of the European Parliament and of the Council of 14 September 2016. On requirements for emission limit values of gaseous and particulate pollutants and type-approval with respect to internal combustion engines for mobile machines non-road, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013 and amending and repealing Directive 97/68/WE
7. J.K. Waluś, Ł Warguła, P. Krawiec, J.M. Adamiec, *Legal regulations of restrictions of air pollution made by non-road mobile machinery- the case study for Europe: a review*. Environmental Science and Pollution Research **25**, 3243-3259, DOI: 10.1007/s11356-017-0847-8 (2018)
8. Ł. Warguła, K.J. Waluś, P. Krawiec, J. Polasik, *Electronic control injection-ignition systems in propulsion of non-road mobile machinery*. Journal of Mechanical and Transport Engineering **70** (1), 61-78, ISSN 2300-3596, DOI: 10.21008/j.2449-920X.2018.70.1.06 (2018)
9. Ł. Warguła, K.J. Waluś, P. Krawiec, M. Kukla, *Research of the ignition advance angle characteristics on the example of a German GX 390 combustion engine*. Autobusy Technika, Eksploatacja, Systemy Transportowe **12**, 1387-1391 (2017)
10. Ł. Warguła, P. Krawiec, K.J. Waluś, M. Kukla, *Conceptual design of adaptation of the mechanical fuel injection unit assembly for electronic control*. Autobusy Technika, Eksploatacja, Systemy Transportowe **12**, 1381-1386 (2017)
11. EMU Engine Management Unit- user manual, [online cit.: 2018-01]. Available from: www.ecumaster.com
12. I. Aygun, E. Cakir, *Development and determination of the field performance of stalk choppers equipped with different blade configurations*. Bulgarian Journal of Agricultural Science, **20** (5), 1273-1276 (2014)
13. İ.S. Dalmış, B. Kayışoğlu, Y Bayhan, F. Toruk, *Determination of the effects of rotation speed and forward speed on combine harvester driven stalk chopper assembly operating performance*. Tarim Bilimleri Dergisi – Journal of Agricultural Sciences **19**, 54-62 (2013)
14. Ł. Warguła, D. Wojtkowiak, K.J. Waluś, P. Krawiec, B. Wieczorek, *The analysis of the efficiency of the control system of Wood chipper's driver with spark-ignition engine based on Skoda combustion engine 1.4 59kW.*, Transport Means 2017 : Proceedings of the 21st International Scientific Conference, September 20-22, 2017, Juodkrante, Lithuania. Part 2, 452 - 458, ISSN 1822-296 X (print), ISSN 2351-7034 (on-line) (2017)
15. Ł. Warguła, P. Krawiec, K.J. Waluś, *The system and method of speed control of wood chipper drive*. (original text in polish: *Układ i sposób sterowania prędkością obrotową napędu rębaka do drewna*), Poznan University of Technology, Poznań, Poland, application number: **P.423369** date of filing 06.11.2017
16. Fiat, Fiat Punto 176, Startprobleme 2, "BOTTOM FEED"-EINSPRITZVENTIL (IWM 523), 1-11 (2006)