Analysis of the costs and cost-efficiency of regeneration of modern fuel injection systems in CI engines

T. Osipowicz

Department of Automotive Vehicles Operation, West Pomeranian University of Technology in Szczecin;
e-mail: tosipowicz@zut.edu.pl

Abstract. This paper presents the analysis of costs and cost-efficiency of the repair of modern fuel injection systems in compression-ignition engines. The requirements for modern Diesel engines are low emission of toxic substances into the atmosphere and low fuel consumption. In order to meet the rigorous standards, the Common Rail fuel injection system has been implemented. By increasing fuel injection pressure to 200 MPa and introducing multi-stage dosing, engine designers have improved the process of air-fuel mixture combustion and engine ecological and economic parameters. The price for these changes is an accelerated wear of fuel injection equipment in modern CI engines.

Regular fuel filter replacement and periodical cleaning of the systems would minimise the risk of damage. Unfortunately, most users do not comply with vehicle servicing times, and come to car repair shops only when a failure occurs, but then it is too late and the repair costs are high.

Key words: Common Rail system, injection pump, fuel injector, high pressure system, low pressure system, Diesel engine.

INTRODUCTION

Accumulator fuel injection systems, called Common Rail (CR) systems, have been introduced in the late 1990s due to ecological and economic reasons. Due to an appropriate organisation of the combustion process in an engine, CI engines with CR system have met more and more rigorous environmental standards and have been consuming less fuel [1].

The use of modern vehicles with CI engines in which a Common Rail fuel injection system has been installed requires certain procedures to be complied with. These procedures are to protect fuel injection equipment from premature wear and tear. The most important factor affecting the service life of all fuel injection system elements is the quality of fuel. Fuel quality refers not only to the type of diesel fuel that is being poured into a fuel tank but also all operations which affect its physicochemical properties after refuelling [2, 3].

PRESENTATION OF THE COSTS ASSOCIATED WITH REGENERATION OF FUEL INJECTION SYSTEMS

The process of testing a vehicle with compression-ignition engine begins with computer diagnostics. During the tests, current parameters of the running engine and possible errors stored in the controller's memory are being read. The test of overflow values should be performed for a vehicle during the operation of engine and fuel injectors. If a failure in fuel injection system is suspected, fuel injectors should be dismounted and tested on a test bench. Furthermore, the pressures at the end of compression stroke in all cylinders should be measured. If the pressures at the end of compression stroke are normal and fuel injectors do not work properly, a decision should be made what needs to be done in order to avoid the excessive costs of vehicle repair. Table 1 presents all the costs of computer diagnostics and possible repair of the Common Rail fuel injection system [18]. If reparable fuel injectors are mounted in a vehicle, they should be disassembled into individual components and analysed under a microscope. During the testing, attention should be paid to the general condition of individual components (corrosion, degree of fouling, presence of metal filings shavings.), also, the condition of the plunger and barrel assembly components and internal seals should be checked. Sometimes it is enough to clean fuel injectors, replace seals, assemble and adjust the volume of fuel injection doses for the engine to start working properly. If there are metal filings shavings and the components of the plunger and barrel assembly are damaged, a complete repair of fuel injection system should be performed [6, 7, 17].

A complete repair of fuel injection system consists of the following steps:
- regeneration of fuel injectors,
- regeneration of fuel injection pump,
- disassembly and cleaning of CR accumulator,

- disassembly and cleaning of high pressure lines,
- disassembly, checking and cleaning of pressure sensor, high-pressure valve, and delivery valve,
- cleaning of low-pressure lines and elements,
- disassembly and cleaning of fuel tank or replacement of fuel tank, if recommended.

A complete repair of fuel injection system makes sense if the above-mentioned steps are met. If any of these steps has been omitted, there is no use to perform the whole procedure. Table 1 presents all the costs of the above operations together with computer diagnostics.

The cost estimate should also include the costs of replacing fuel filter and other possible operations. When analysing the costs of computer diagnostics and repair of accumulator fuel injection systems, it can be concluded that if a vehicle of a total value of approximately PLN 10 thousand is tested, it is more cost-effective to scrap it or sell it for parts because the overall costs are too high.

Fig. 1 presents a diagnostic procedure which is performed during the testing of accumulator fuel injection system. A complete procedure, consisting in the total disassembly of fuel supply system elements, cleaning and regeneration of worn components, is cost-effective only in newer vehicles of a higher market value. The advantage of a complete repair is a guarantee given by an authorised car repair shop for the performed service. However, in case of older vehicles of low market value, it is not cost-effective to carry out the whole procedure due to excessive costs. If the repair cost exceeds 70 % of the vehicle value, it is uneconomic to repair it. Therefore, the author has proposed a procedure that is aimed at detecting the fault and eliminate it at the minimum cost.

Table 1. An example of cost estimate for a complete repair of the Common Rail fuel injection system

Operation	Cost [PLN]
Computer diagnostics of engine system (initial diagnostics, together with fuel injection system)	200
Regeneration of fuel injectors	750 (per unit)
Regeneration of fuel injection pump	1500
Disassembly and cleaning of CR accumulator	50
Disassembly and cleaning of low pressure lines	50
Disassembly, checking and cleaning of pressure sensor, high-pressure valve and delivery valve	100
Cleaning of low pressure lines and elements	100
Disassembly and cleaning of fuel tank or replacement of fuel tank, if recommended	500
Total	5500
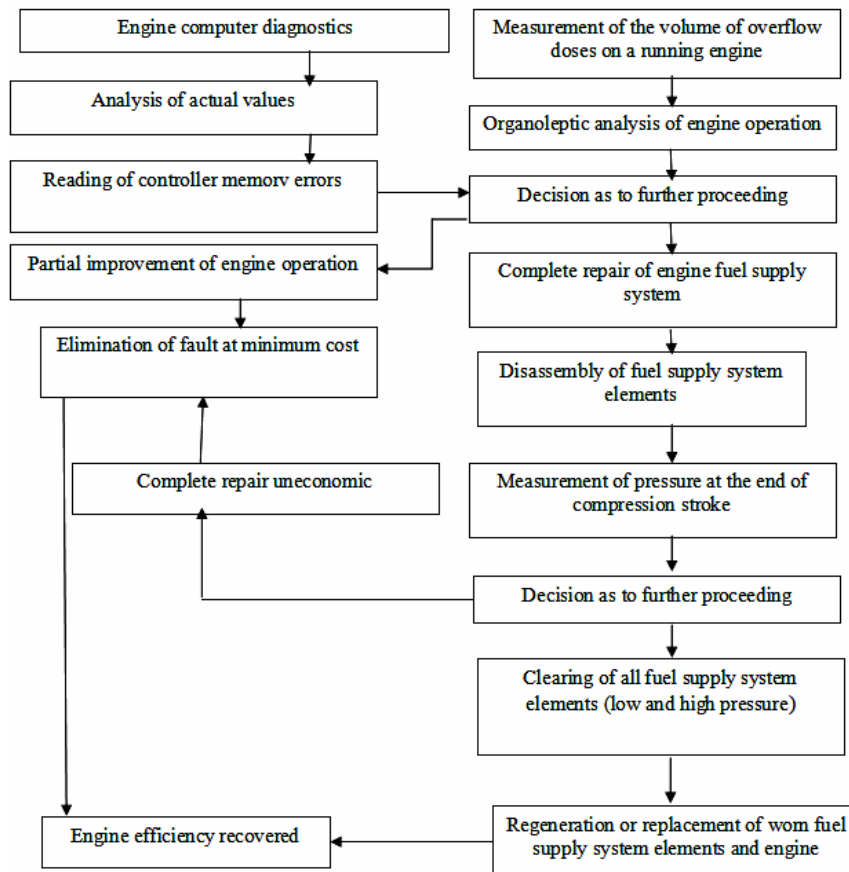
Fig. 1. Diagnostic and repair procedures for a modern Diesel engine

PRESENTATION OF HIGH-PRESSURE SYSTEM TESTING PROCEDURE

After initial diagnostics which has shown a fault in the high-pressure system, the following elements should be dismounted from the engine and tested on a test bench: fuel injectors, pressure and delivery regulators and the pressure sensor [8]. In the first place, pressure and delivery regulators and the pressure sensor are tested, next the test of fuel injectors is performed and finally the fuel injection pump test is done. If the fuel injection pump is worn and it ejects metal filings shavings into the systems, they are visible on the regulator and sensor components. When testing fuel injectors, attention should be paid to the volume of fuel injection and overflow doses, as well as to whether fuel injectors are tight [9]. Electrical parameters, such as resistance, coil inductance or crystal capacitance, should be measured with an appropriate meter, as well as the possibility of short-circuit to earth occurrence is being checked. It is also possible to check pressure regulators by connecting them to an appropriate test bench and testing whether they operate during actuation. If a fuel injection pump is tested, it is not recommended to mount it on a test bench and to carry out the test without prior disassembly and microscopic examination. A fuel injection pump can be a source of metal filings shavings; if a fouled pump is mounted on the test bench, all metal filings shavings enter into the system.

Table 2 presents an example testing protocol of a Bosch solenoid-controlled fuel injector, catalogue No. 0445110025, on a Bosch EPS 200 injector test bench.

Each fuel injector is tested for different operating parameters. Leak test consists in the testing of a fuel injector in terms of its internal leakage at maximum working pressure. Only fuel return dose is tested. This testing shows whether the components of the plunger and barrel assembly and internal seals are not worn. In addition, they are observed for external leakage. During the test of full load quantity (VL), fuel injection and overflow doses are tested. The next step of testing is to test the emission quantity (EM). It is the dose of half load. The LL quantity is the dose of idling, while the VE quantity is the pilot injection dose [14].

The tests showed that the fuel injector had too high fuel injection doses, except pilot injection dose, as well as too high overflow volumes. The next step is to disassemble fuel injector into individual components and to test them under a microscope. The microscopic testing is aimed at checking the technical condition of the components of the plunger and barrel assemblies, testing the condition of internal seals, as well as testing the general condition of fuel injectors for fouling, corrosion or metal filings shavings coming from a high pressure pump [4, 5]. Fig. 3 presents the fuel from the high-pressure rail in which metal filings shavings are to be observed.

Table 2. Protocol of fuel injector testing on a Bosch EPS 200 injector test bench

Type of test	Test parameters			Fuel injection dose [mm³/H]		Return fuel dose [mm³/H]	
	Injection timing [µs]	Pressure MPa	Time of measurement [s]	Set values	Actual values	Set values	Actual values
Leak test	0	140	200	0	0	$35^{+}.35$	27.34
VL	800	135	90	$51.8^{+}.4$	62.97	$47^{+}.30$	148.5
EM	500	80	90	$18.4^{+}.2.5$	24.07		
LL	675	25	90	$4.9^{+}.1.6$	9.34		
VE	160	80	90	$1.5^{+}.1.2$	1.87		
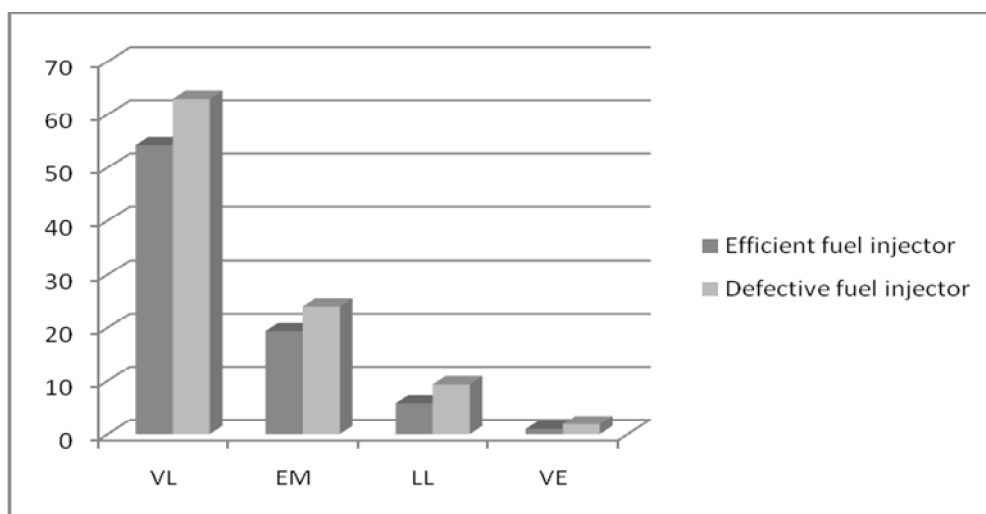
Fig. 2. Graphic depiction of the volume of fuel injection doses for an efficient fuel injector and a defective fuel injector
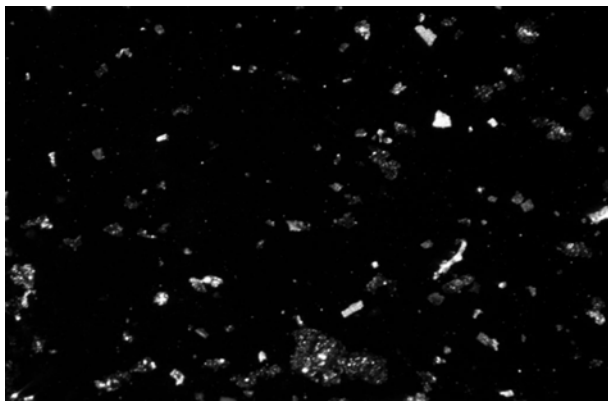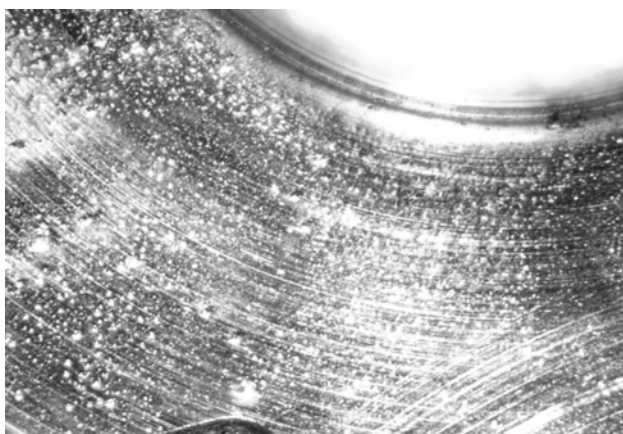
Fig. 3. Fuel from the high-pressure rail under a microscope

Metal filings shavings come from a high-pressure pump Fig. 4 presents a pressure regulator.

**Fig. 4.** Pressure regulator with visible metal filings shavings under a microscope

Fig. 5. Interior of fuel force-feeding pump

Metal filings shavings accumulate in the whole fuel supply system. Starting from the fuel injection pump, through the CR rail, pressure sensor and regulators, they enter into the low pressure system, pass through the fuel filter and accumulate in it [15].

The source of metal filings shavings is the roughing pump installed on the fuel injection pump and the raceway of main shaft that drives the high pressure section into the fuel injection pump. Fig. 5 presents the interior of fuel force-feeding pump.

On the raceway of gear wheels, metal filings shavings visible in Fig. 4 develop as a result of friction. Fig. 6 presents a fragment of main shaft raceway in a fuel injection pump.
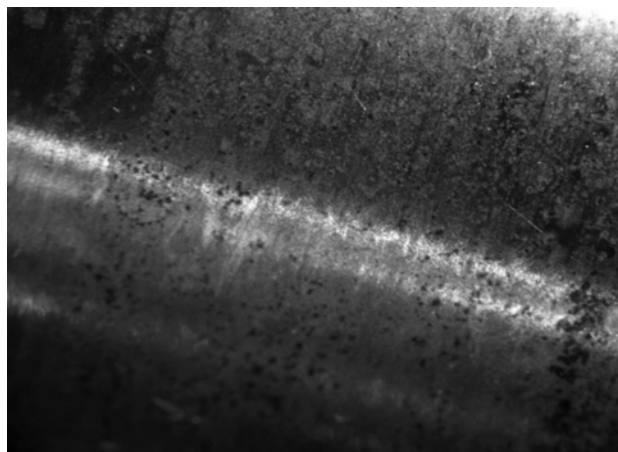
Fig. 6. Raceway of the main shaft of fuel injection pump

The plungers of high pressure section are driven into a fuel injection pump. As a result of temperature, friction and poor fuel quality, seizures as well as corrosion occur locally on the surface [20]. The result of these phenomena is different types of fuel supply system fouling and metal filings shavings. Fig. 7 presents the surface of a high pressure section plunger.

Fig. 7. Surface of a high pressure section plunger

The fouling and metal filings shavings deface the plunger surface. The effect of wear is lower fuel delivery volumes and lower efficiency of fuel injection pump [13].

Fig. 8 presents the characteristics of fuel delivery for efficient and worn fuel injection pumps. Fig. 9 presents

the efficiency characteristics of efficient and worn fuel injection pumps.

If the efficiency of fuel injection pump is lower than 80%, it should be disassembled and tested.

The fuel fouling and metal filings shavings migrate with fuel into fuel injectors. The job of fuel injector is to spray and distribute an adequate fuel quantity in the engine's combustion chamber. If the elements responsible for proper operation have been fouled, damaged or they have undergone accelerated wear, fuel injection doses will be changed and, as a result, the engine will stop working properly.
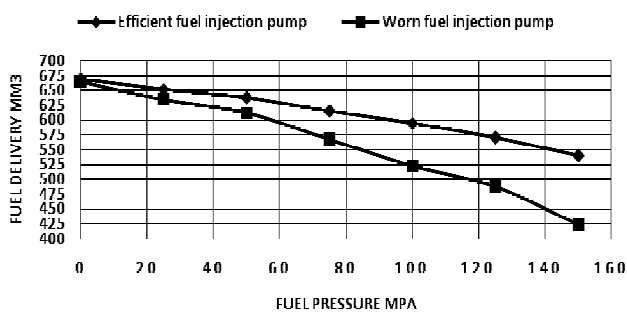
OPERATING CHARACTERISTICS OF CR FUEL INJECTION PUMP

Fig. 8. The operating characteristics of fuel delivery of a fuel injection pump

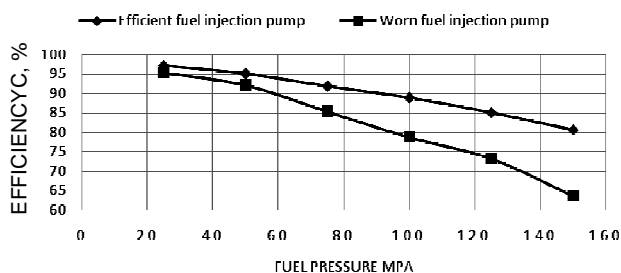## CHARACTERISTICS OF CR FUEL INJECTION PUMP EFFICIENCY

Fig. 9. The characteristics of fuel injection pump efficiency

If this occurs, the following should be carried out:
- regenerate fuel injectors,
- regenerate fuel injection pump,
- clean the CR rail, pressure regulators, pressure sensor and high pressure lines,
- clean the low pressure system together with the fuel tank,
- replace the fuel filter.

The high price of regeneration of modern fuel injection systems is due to the fact that the whole system should be completely regenerated to carry out the repair process in accordance with all the procedures so that a guarantee can be given for the performed service [16]. Unfortunately, this process is time-consuming and costly due to the prices of spare parts and work time. Most vehicle users want to have the repair made as cheaply as possible; therefore, the method has been developed by

which a fault is detected and eliminated during computer diagnostics. Most often, this method repairs the effect of the fault and not its cause, but it is cheap and so popular with customers [10, 11].

When analysing the above-described case, only the cleaning and regulation procedure is conducted after the testing of fuel injectors and their disassembly [19]. Next, the pressure regulator, pressure sensor, CR rail and high pressure lines are cleaned. The fuel injection pump is left as it is. Its efficiency is approximately 78% at 100 MPa. Then, the system is assembled, the fuel filter replaced and the final computer diagnostics performed. If the engine operates properly, the repair process is to be finished. A vehicle has been repaired but the reason of failure has not been removed. It is difficult to estimate how long the engine will efficiently operate. This may be 20 thousand kilometres, or perhaps 1000 kilometres. Customers usually choose this method despite no guarantee for the performed service due to its price. The total cost of this repair is approximately PLN 1000. When compared to the standard procedure at approximately PLN 5500, this is a big difference [12].

CONCLUSIONS

The analysis has shown that the performance of complete regeneration of fuel injection systems is only cost-effective in the case of vehicles of high market value. Usually, these are higher-class vehicles or new ones, in which the failure occurred due to the owner's fault (use of poor quality fuel). The repair is uneconomic when the repair cost exceeds approximately 70% of the vehicle value. The objective of the proposed method is to maximally reduce the repair costs. This method only eliminates the effects of failure and makes the engine efficient again. The main reason of modern CI engine troubles is poor fuel quality and lack of compliance with the operating procedures by users. Regular fuel filter replacement and periodical cleaning of the systems would minimise the risk of damage. Unfortunately, most users do not comply with vehicle servicing times, and come to car repair shops only when a failure occurs, but then it is too late and the repair costs are high.

REFERENCES

1. **Ambrozik A., Ambrozik T., Łagowski P. 2015.** Fuel impact on emissions of harmful components of the exhaust gas from the CI engine during cold start-up. Eksploatacja i Niezawodność – Maintenance and Reliability, Vol. 17, No. 1, pp. 95–99.
2. **Boychuk P., Boychuk Kh., Nahorski Z., Horabik J. 2012.** Spatial inventory of greenhouse gas emissions from the road transport in Poland, Econtechmod an international quarterly journal on economics in technology, New technologies and modelling processes, Vol. 1, No. 4, pp. 9–16.
3. **Dolinskii A., Draganov B., Kozirskii V. 2012.** Nonequilibrium state of engineering systems, Econtechmod an international quarterly journal on economics in technology, New technologies and modelling processes, Vol. 1, No. 1, pp. 33–34.
4. **Dziubiński M., Czarnigowski J. 2011.** Modelling and verification failures of a combustion engine injection

system. TEKA Commission of Motorization and Energetics in Agriculture, Vol. XIC, PAN Lublin.

5. **Kirichenko I., Strilets O., Koshovy M. 2012.** Piezo actuators injector of Common Rail fuel injection system. TEKA Commission of Motorization and Energetics in Agriculture, Vol. 12, No. 3, PAN Lublin.

6. **Kuzmin O., Kostsyk R. 2015.** Specifics of self – commercialization of innovative products by machine – buildings companies. Econtechmod: an international quarterly journal on economics in technology, New technologies and modelling processes, Vol. 4, No. 1, pp. 61–66.

7. **Lamtyugova S. N., Sidorov M. V. 2014.** Numerical analysis of the problem of flow past a cylindrical body applying the r-functions method and the galerkin method, Econtechmod an international quarterly journal on economics in technology, New technologies and modelling processes, Vol. 3, No. 3, pp. 43 – 50.

8. **Osipowicz T. 2015.** Diagnosing Common Rail fuel injectors using fuel micro – doses. TEKA Commission of Motorization and Energetics in Agriculture, Vol. 15, No. 3, PAN Lublin.

9. **Osipowicz T. 2015.** Testing of modern fuel injection pumps. TEKA Commission of Motorization and Energetics in Agriculture, Vol. 15, No. 3, PAN Lublin.

10. **Osipowicz T. 2015.** Research and analysis technical parameters not repair Diesel injectors, Autobusy, Technika, Eksploatacja, Systemy Transportowe, No. 6.

11. **Osipowicz T. 2015.** Analysis of opportunities unit injectors repair, Autobusy, Technika, Eksploatacja, Systemy Transportowe, No. 6.

12. **Osipowicz T., Abramek K. 2014.** Catalytic treatment in Diesel engine injectors. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 2014, 16 (1): pp. 22–28.

13. **Osipowicz T., Abramek K., Stoeck T. 2015.** Testing of modern Common Rail fuel injectors. Combustion Engines. 162 (3), pp. 688–694.

14. **Osipowicz T., Kowalek S. 2014.** Evaluation of Modern Diesel Engine Fuel Injectors. TEKA Commission of Motorization and Energetics in Agriculture, Volume XIV, No. 3, PAN Lublin.

15. **Osipowicz T., Stoeck T. 2015.** Analysis of diagnose possibilities common injection pumps, Autobusy, Technika, Eksploatacja, Systemy Transportowe, No. 6.

16. **Osipowicz T., Stoeck T., Gołębiewski W. 2015.** Influence of fuel pollutant on operating parameters of contemporaty fuel injector, Journal of KONES and Powertrain and Transport, Vol. 22, No. 3, pp. 169–174.

17. **Shapovalov Yu., Mandziy B. and Bachyk D. 2013.** Optimization of linear parametric circuits in the frequency domain, Econtechmod an international quarterly journal on economics in technology, New technologies and modelling processes, Vol. 2, No. 4, pp. 73–77.

18. **Shpak N., Kyrylych T. 2013.** Sales channels selection for small industrial enterprises based on qualitative quantitative characteristic criteria, Econtechmod an international quarterly journal on economics in technology, New technologies and modelling processes. Vol. 2, No. 4, pp. 79–89

19. **Stoeck T., Osipowicz T., Abramek K. F. 2014.** Methodology for the repair of Denso Common Rail solenoid injectors. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 2014, 16 (2): pp. 270–275.

20. **Stoeck T. Osipowicz T. 2013.** Analysis of damages Common Rail injectors using in Diesel engines commercial vehicles. Logistyka. Instytut Logistyki i Magazynowania, No. 6.