International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-9 Issue-1, October, 2019

Economic Evaluation of Turbogenerators in Cargo Vehicles

V. G. Chirkin, D. A. Petrichenko, A. S. Nekrasov, V. S. Korotkov

Abstract*: Insufficient development of energy saving technologies in the field of transport and cargo carrying, as well as the necessity to improve efficiency of vehicle power generating units promote development of heat recovery systems. Challenging trends of implementation of these technologies are road and railroad cargo vehicles due to continuous loads on the modes similar to steady states. In order to achieve the mentioned tasks, it is possible to apply heat recovery systems based on turbogenerators which increase performances of overall power generating unit and decrease fuel consumption. This article discusses technical and economical performances of vehicle power generating units based on turbogenerators, positive and negative effects as well as reasonability of their application. Competitive variants of developed heat recovery system are analyzed, their advantages and disadvantages are compared and discussed. Consumer properties of the developed turbogenerator are determined for wide scale and long-term application with accounting for payback periods.

Keywords*: fuel efficiency, heat recovery system, piston engine, power generating unit, turbogenerator, vehicle efficiency improvement.

I. INTRODUCTION

About 90% of all energy used by humans is produced by internal combustion engines, herewith, the balance of environmental pollution is as follows: 50.4% - internal combustion engines, 15.7% - thermal power plants, 14.1% - industrial enterprises [1], [2]. About 70% of harmful emissions are generated by automobiles. Increase in price of hydrocarbon fuels and technogenic environmental impact are the major factors promoting active implementation of power saving technologies and upgrading of norms of harmful emissions with exhaust gases of various power generating units. At present the most rigid requirements to harmful emissions are applied to passenger cars due to their high concentration in megalopolises. The norms of emissions for freight, railroad and marine transport are significantly lower [3]-[6].

Revised Manuscript Received on October 30, 2019.
* Correspondence Author
Hemlata Pal*, School of Electronics, Devi Ahilya University, Indore, India. Email: hemlatapal099@gmail.com
Dr. Abhay kumar, Head of department of School of Electronics, Devi Ahilya University, Indore, India. Email: dr.abhaykumar @gmail.com

Freight trucks and diesel locomotives operate for sufficiently long periods which can be referred to as steady, thus, it is possible to consider possibility of application of exhaust gas heat recovery systems for these vehicles. Heat recovery systems based on turbogenerators are characterized by compact sizes, high specific power and efficiency, which is especially important for existing vehicles for which they are intended. The main purpose of such systems is decrease in fuel consumption [7]-[9]. If in the case of railroad vehicle, the electricity produced by turbogenerator can be used directly by propulsion electric motors using power converters, then for freight trucks, the produced electricity will be useful for refrigerating or other units, or as a component of hybrid electromechanical power generating unit. The research in the field of heat recovery systems for small scale and distributed power generation are sufficiently intensive, which confirms the importance of this type of energy saving.

II. PROPOSED METHODOLOGY

A. General Description

Freight trucks and diesel locomotives constitute preferable market segment for application of turbogenerators.
Russian market of freight rucks in addition to domestic manufacturers proposes mainly European models: Volvo, Scania, MAN, Mercedes, DAF, Iveco, as well as numerous Chinese lorries. Freight trucks were always engine of commerce; this is especially important for large countries where huge distances should be covered for goods delivery. Truck fleet in Russia is comprised of more than 3.8 million units including more than 86% of very large cargo carriers, and 867 thousand KamAZ trucks [10]. Freight trucks manufactured in various countries are characterized in general by common specifications; most models are equipped with supercharged diesel engines with displacement of 12–16 l and average power of 350–500 HP, this is sufficient power for application of exhaust gas heat recovery systems for electricity production. The obtained electricity can be used for provision of own needs of vehicle, for use in refrigerators, and for power supply of hybrid drives.
Hybrid power generating units for freight trucks become more and more popular. Experimental models with combined drive were developed and manufactured by most global car manufacturers [11]:

- I-SAM Volvo FE Hybrid is comprised of Deutz D7F300 7L diesel engine combined with 120 kW electric engine and lithium ion battery cells of the last generation;

- Iveco Eurocargo Hybrid with full weight of 7.5 t is equipped with diesel electric hybrid transmission of parallel type. The EEV diesel engine with maximum power of 180 HP operates in combination of 60 HP electric motor–generator. The hybrid lorry equipped with start/stop system saves up to 30% of fuel depending on traffic mode;

- DAF LF Hybrid with full weight of 12 t is equipped with electric hybrid drive comprised of PACCAR FR 118 kW engine integrated with starter–generating device charging lithium ion cells. This concept saves from 10 to 20% of fuel;

- Renault Premium Distribution Hybrys Tech: 19 t and 26 t hybrid trucks equipped with Deutz DXi7 120 kW diesel engines. Battery cells can supply the truck electric drive in order to move up to 1.5 km using only the electric drive. Fuel saving of Renault Premium Distribution Hybrys Tech reaches 20%;

- Mercedes-Benz Atego BlueTec Hybrid is a 12 t delivery truck equipped with OM 924 LA 4.8L diesel engine with the power of 160 kW (218 HP) at 2,200 rpm and Eaton electric transmission. The 44 kW AC electric motor is installed between clutch and six-speed automatic gearbox;

- MAN TGL 12.220 Hybrid is a 12 t truck equipped with MAN D0834 220 HP engine and ZF hybrid transmission combining 80 HP electric motor and ASTronic Light six-speed automatic gearbox. The MAN engineers report 15% fuel saving;

- Peterbilt Model 335 is equipped with Paccar PX-6 4.5L engine with the power of 136 kW (185 HP), electric motor with the function of generator: Eaton Hybrid Electric Power System, and six-speed automated gearbox. Electricity produced by the generator is supplied to lithium ion cells and stored for further use. This provides 25% fuel saving;

- Hybrid KamAZ is equipped with diesel engine with 12-speed automated gearbox (ZF). The front drive is activated by 90 kW electric machines with maximum torque of 250 N*m [12].

Therefore, hybrid freight trucks attract more and more attention, the advances of electricity storage onboard vehicles and power electronics would permit to increase the number of hybrid vehicles in Russian market in the nearest future.

Nowadays the fleet of locomotives in Russia is comprised of more than 20 thousand units including about 10 thousand diesel engines, 35% of them are freight diesel locomotives. Most diesel locomotives exceeded their performance potential and should be replaced soon. According to RBC data, for 2018 the sales of electric and diesel locomotives in Russian market amounted to 704 units, which was lower than the pre-crisis sales. Electric locomotives prevail in the structure of sales in kind: 54.9% in average for five-year period. Herewith, it should be mentioned that the sales of diesel locomotives were more stable, and in 2014–2018 varied in the range of 268-294 pieces. According to forecasts by BusinesStat [13], in 2019–2023 further increase in the sales of electric and diesel locomotives in Russian market is expected. Herewith, the increment rates will decrease gradually to 3.7% in 2023, which mainly will be stipulated by continuing stagnation of Russian economy. Electric and diesel engines will be mainly purchased for replacement of failed machinery. Thus, in the nearest future OAO RZhD plans to modernize already operating electric and diesel locomotives, which would permit to decrease the necessity of cardinal renovation of the fleet. As a consequence of the mentioned factors, significant increase in sales of electric and diesel locomotives should not be expected. In 2023 the sales amount is forecasted to be 839 pieces, which is by 19.2% higher than that in 2018.

Efficiency increase of power generating units of trucks and diesel locomotives first of all improves their consumer properties due to power increase and decrease in fuel consumption, which in its turn can reduce transportation costs, improve competitiveness and reliability of freight vehicles. The power generating units of these vehicles are diesel engines, their efficiency at present is about 30–40% depending on operating modes, charging rate, and parameters of fuel injection equipment. The remaining portion of heat energy (more than 60%) is distributed between lubricating and cooling system (10–35%), exhaust gas system (20–45%), and frictional energy (up to 10%). A portion of exhaust gas energy can be converted into electricity by means of turbogenerator which is installed in exhaust gas system and makes it possible to produce usable electric energy by conversion of some heat energy of spent gases, producing minor increase in output resistance, its negative effect can be compensated by tuning the supercharging system [4], [14]. Importance of such developments is confirmed by numerous publications devoted to this topic. At present such projects are implemented by Bowman Power LTD, Magnetti Marelli, Thin Gap, VAG, Porsche AG BMW, Volvo , Toyota , Honda R&D, Mitsubishi Heavy Industries, John Deere, Cummins (US), Wärtsilä (FI), and other companies. The performed research demonstrated that exhaust gas energy recovery made it possible to increase electric power of engines/generators by up to 12,5%, to decrease fuel consumption in the range from 3 to 7% depending on operation modes [15].

B. Algorithm

Let us consider turbogenerator design as exemplified by experimental unit described in [16]. The turbogenerator design contains the turbine unit comprised of turbine volute and turbine wheel, its shaft acts as rotor shaft of high-speed electric machine, its stator is installed in the shell of turbogenerator. The front and rear covers of the turbogenerator shell are equipped with sleeve bearings with oil supply and cooling chamber. The turbogenerator concept provides application of cooling and lubrication system of the main diesel engine, which significantly simplifies the design and expands capabilities of application under tight configuration of power generating unit. Specifications of turbogenerator provide its use in internal combustion engines operating on various hydrocarbon fuel. Since output voltage depends on design and polarity of high-speed electric machine and turbine shaft rpm, then turbogenerator makes it possible to produce alternative current in wide range of voltages and frequencies. In order to use the produced electricity, the output of turbogenerator should be equipped with power electronic unit.

Depending on parameters of propulsion unit of diesel locomotive or hybrid freight truck, it is required to apply DC-DC converter in order to provide preset voltage by its increase or decrease, as well as inverter to use alternative current [17]. Advantages of turbogenerator, in comparison with other net recovery systems, are as follows: compact sizes, superior weight and dimensions, no necessity to modify significantly engine design.

III. RESULTS AND DISCUSSION

This article discusses economic efficiency of turbogenerator as exemplified by Russian cargo vehicles characterized by specifications summarized in Table I.

Table – I: Specifications of vehicles

Diesel locomotive series **TEP70, TEP70BS, TEP70U**	
Weigh, t	130
Normal rated power, kW (HP) with auxiliary equipment	2,942 (4,000)
Engine type	Turbocharged diesel 5D49
Engine displacement, l	221
Crankshaft RPM at rated power, min^{-1}	1,000
Specific fuel consumption, l/(kW*h) at rated power	0.208
KamAZ R6 (Hybrid)	
Weight, t	7.99
Engine	KamAZ R6 920.10-700
Engine type	Turbocharged diesel
Engine displacement, l	11.94
Rated power, kW (HP)	515 (700) at 2,200 RPM
Maximum torque, N*m	2,700
Specific fuel consumption, l/(kW*h)	0.192

Let us compare specifications of vehicle power generating units without and with turbogenerator under the following conditions:

- price of 1L of diesel fuel: USD 0.71 (Russia, August, 2019);

- turbogenerator saves up to 5% of fuel with increase in power by 10%;

- increase in engine cost would amount to about USD 225 per each 1 kW of recovered power (based on average statistic data on electric machines and power electronics);

- recovered energy is used for vehicle driving.

Comparisons of specifications of vehicle power generating unit of TEP70BS diesel locomotive and KamAZ R6 920 freight truck with and without turbogenerator are summarized in Table II.

Table – II: Comparison of specifications of vehicle power generating units

Specification	TEP70BS	TEP70BS + turbogenerator	KamAZ R6 920	KamAZ R6 920 + turbogenerator
Average daily run, km	1,042		600	
Average daily speed, km/h	58		75	
Cost increase of power generating unit after installation of turbogenerator, USD	-	66,195	-	11,587
Fuel consumption, t/day t/month t/year	13.8 414 5,037	13.11 393.3 4,785.15	0.198 5.94 72.27	0.188 5.64 68.62
Fuel saving, t/day	- -	0.69 20.7	- -	0.01 0.3
t/month t/year	-	251.85	-	3.65
Yearly fuel saving, USD	-	17,881	-	2,591
Payback period, years		3.70		4.47

Operation lifetimes of diesel locomotives and freight trucks in Russia are 20 and 15 years, respectively, and it means that with application of exhaust gas recovery system based on turbogenerator after completion of payback period of turbogenerator, it is possible to save significant amount of fuel, which would exert positive influence not only on transportation costs but also on decrease in harmful environmental impact of spent gases.

IV. CONCLUSION

As demonstrated by the performed analysis, application of turbogenerator in engine of diesel locomotive or hybrid freight truck is economically reasonable solution stipulated by numerous positive engineering and economic reasons. Positive features of implementation of turbogenerators for cargo vehicles are as follows:

- decrease in fuel consumption from 5 to 7%;
- decrease in load on main engine: increase in its operation lifetime;
- relatively low prime production cost;
- improved competitiveness of vehicles and reduced cargo transportation costs for consumers;
- no competitiveness among foreign manufacturers in this field;
- moderate payback period for consumers: 3.7 years for diesel locomotive and 4.47 years for freight truck, and then only fuel savings would provide decrease in expenses by USD 17.7 thousand and 2.5 thousand per year, respectively;
- compact sizes of turbogenerator enable its installation even in high-density configuration of engine compartment;
- few engineering modifications of vehicle power generating unit;
- minimum modifications in design of propulsion unit;
- high potentials regarding improvement of turbogenerator specifications and decreased price due to batch production;
- possibility to apply module units of multiple power, both simultaneously and separately;
- wide scale potential market in Russia with possibility to access international manufacturers;
- increased number of employee population and tax payments due to development of new facilities in high-tech industries.

In its turn, the negative features of the considered technology concerning improvement of energy efficiency and environmental performances of cargo vehicles are as follows:

- more complicated design due to existence of additional mechanical units and electronic devices;
- necessity to train operators to maintain the new hardware;

- possible modifications of requirements to process fluids or their filtration.

ACKNOWLEDGMENT

This work was supported by the Ministry of Science and Higher Education of the Russian Federation, agreement No. 14.574.21.0154 of September 26, 2017. Unique project identifier: RFMEFI57417X0154.

REFERENCES

1. A. Ya. Isakov, "Ekologicheskaya bezopasnost' transportnykh sredstv [Environmental safety of vehicles]", *Polytematic online scientific magazine of KubGAU*, vol. 23(7), 2006, pp. 291-302.
2. K. E. Karpukhin, A. S. Terenchenko, A. F. Kolbasov, and V. N. Kondrashov. (2019, August). The Use Of Microturbines as an Energy Converter For Motor Transport. *International Journal* of *Innovative Technology and Exploring Engineering (IJITEE).* Vol. 89(10), pp. 2700-2703. Available: https://www.ijitee.org/wp-content/uploads/papers/v8i10/J94510881019.pdf
3. A. P. Tatarnikov, F. A. Shustrov, L. Y. Lezhnev, D. A. Petrichenko, and I. A. Papkin, "Combined supercharging systems and down-sizing as the modern trends in the development of vehicle engines", *International Journal of Applied Engineering Research*, vol. 11(22), 2016, pp. 10975-10979.
4. N. A. Khripach, B. A. Papkin, V. S. Korotkov, D. A. Ivanov, and A. S. Nekrasov, "Trends in the development of combined supercharging systems for the internal combustion engine", *International Journal of Applied Engineering Research*, vol. 11(22), 2016, pp. 10988-10993.
5. N. A. Khripach, B. A. Papkin, L. Y. Lezhnev, A. P. Tatarnikov, and V. A. Neverov, "Comparison of reciprocating engine boosting systems", *International Journal of Mechanical Engineering and Technology*, vol. 9(5), 2018, pp. 974-984.
6. D. A. Petrichenko, V. S. Korotkov, R. V. Stukolkin, V. A. Neverov, and I. A. Papkin, "Approaches to improvement of turbochargers for automotive engines", *International Journal of Mechanical Engineering and Technology*, vol. 9(6), 2018, pp. 999-1008.
7. N. A. Khripach, V. A. Neverov, B. A. Papkin, F. A. Shustrov, and A. P. Tatarnikov, "Analysis of the influence of modern combined super charging systems on the performance characteristics of internal combustion engines", *Pollution Research*, vol. 36(3), 2017, pp. 657-666.
8. N. A. Khripach, L. Y. Lezhnev, D. A. Ivanov, F. A. Shustrov, and A. P. Tatarnikov, "Design of a thermoacoustic module of a vehicle engine", *International Journal of Mechanical Engineering and Technology*, vol. 9(4), 2018, pp. 1036-1046.
9. N. A. Khripach, L. Y. Lezhnev, V. A. Neverov, D. A. Ivanov, and B. A. Papkin, "Comparative analysis of EG noise suppression systems", *International Journal of Civil Engineering and Technology*, vol. 8(10), 2017, pp. 1536-1553.
10. R. Yunusova. (2019). *V Rossii chislitsya okolo 52 mln edinits avtotransporta [About 52 million vehicles are listed in Russia].* Analiticheskoe agentstvo Avtostat. Available: https://www.autostat.ru/news/37917/
11. V. Chekhuta. (2013, October). Gibridnye gruzoviki: modeli, konstruktsii, perspektivy [Hybrid lorries: models, designs, challenges]. *Zhurnal AVTOTRAK - vsyo o kommercheskom transporte [Autotrack Magazine. All about commercial transport].* Available: http://www.autotruck-press.ru/articles/4457/
12. M. Bibichev. (2014, May). Tyagach perekhodnogo perioda. KAMAZ-5490 [Tractive vehicle of transition period. KamAZ-5490]. *Rossiiskii avtomobil'nyi portal 5koleso.* Available: https://5koleso.ru/content/tyagach-perehodnogo-perioda-kamaz-5490
13. Analiz rynka elektrovozov i teplovozov v Rossii v 2014-2018 gg., prognoz na 2019-2023 gg.[Market analysis of electric and diesel locomotives in Russia in 2014-2018: forecast for 2019-2023]. (2019, May). *Magazin issledovanii [Shop of research].* Available: https://marketing.rbc.ru/research/28142/
14. L. Y. Lezhnev, F. A. Shustrov, V. A. Neverov, and V. S. Korotkov, "Technical and economic evaluation of turbogenerators in small power plants", *International Journal of Innovative Technology and Exploring Engineering*, vol. 8 (8), 2019, pp. 2781-2785.
15. N. A. Khripach, L. Yu. Lezhnev, A. P. Tatarnikov, R. V. Stukolkin, and A. A. Skvortsov, "Turbo-generators in energy recovery systems", *International Journal of Mechanical Engineering and Technology*, vol. 9(6), 2018, pp. 1009-1018.
16. N. A. Khripach, D. A. Ivanov, A. P. Tatarnikov, and B. A. Papkin, "Turbogenerator: Designing and layout development", *International Journal of Mechanical and Production Engineering Research and Development*, vol. 9 (3), 2019, pp. 1625-1634.
17. V. G. Chirkin, N. A. Khripach, F. A. Shustrov, and A. P. Tatarnikov, "Review on DC-DC power converter topologies and control technics for hybrid storage systems", *International Journal of Mechanical Engineering and Technology*, vol. 9(5), 2018, pp. 985-992.