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CURRENT STATE AND DEVELOPMENT TRENDS IN THE FIELD OF LARGE DIESEL AND GAS ENGINES

Dobrivoje Ninković [1]

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RESEARCH ARTICLE

ABSTRACT: Large Diesel and gas engines with power higher than approximately 1 MW play a major role in the sea and land transport of people and goods, but also in the production of electrical energy in remote areas, for peak load balancing, and backup systems. While their total installed power and fuel consumption are vastly smaller than with their road transport counterparts, the vehicles they propel (ships and trains) represent the most efficient freight transport modes in existence. It is thus their importance for the world economy that has been driving their development, resulting in these engines belonging to the group of the most efficient thermal machines available to the mankind.

Presented in the paper is a survey of the current development state of the large Diesel and gas engines in terms of their thermodynamic performance, emission levels and the means for achieving them, and fuels used. Due to its indispensability for achieving the high performance of these engines, turbocharging is given a particular treatment in the paper.

Based on the study of the contemporary literature, an attempt is made to identify main development trends in this area. With regard to the latter, special attention is devoted to the so-called dual-fuel engines (Diesel and gas), which appear to have enjoyed a rapid development in the last decade.

KEY WORDS: large engines, diesel engines, gas engines, dual-fuel engines

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TEKUĆE STANJE I TRENDOVI RAZVOJA U OBLASTI VELIKIH DIZEL I GASNIH MOTORA

REZIME: Veliki dizel i gasni motori sa snagom većom od oko 1MW, imaju glavnu ulogu u pomorskom i kopnenom transportu ljudi i robe, ali i u proizvodnji električne energije u udaljenim područjima, za prihvatanje vršnog opterećenja i rezervne sisteme. Dok su njihova ukupna instalisana snaga i potrošnja goriva znatno niže nego kod motora u drumskom saobraćaju, vozila koja oni pokreću (brodovi i vozovi) predstavljaju najefikasnije vidove transporta tereta koji postoje. Zbog toga je njihov značaj za svetsku ekonomiju pokretač njihovog razvoja, što je dovelo do toga da ovi motori pripadaju grupi najefikasnijih toplotnih mašina dostupnih čovečanstvu.

U radu je prikazan pregled trenutnog stanja razvoja velikih dizel i gasnih motora sa stanovišta njihovih termodinamičkih performansi, nivoa emisije i načina za njihovo postizanje i goriva koja koriste. Zbog zahteva za postizanje visokih performansi ovih motora, posebna pažnja, u ovom radu, je posvećena turbo punjenju. Na osnovu proučavanja savremene literature učinjen je pokušaj da se identifikuju glavni trendovi razvoja u ovoj oblasti. Stoga, posebna pažnja je posvećena tzv. dvogorvim motorima (dizel i gas) za koje se čini da se u poslednjoj deceniji doživeli nagli razvoj.

KLJUČNE REČI: veliki motori, dizel motori, gasni motori, dvogorivi motori

CURRENT STATE AND DEVELOPMENT TRENDS IN THE FIELD OF LARGE DIESEL AND GAS ENGINES

Dobrivoje Ninković

1. INTRODUCTION

The year 2017 marked the 125th anniversary of the Rudolf Diesel's patent on the theory and the realisation method for combustion engines (in original: "Arbeitsverfahren und Ausführungsart für Verbrennungskraftmaschinen"), a patent formulated rather broadly, but which in essence dealt with an engine with constant temperature and slow combustion. The thermodynamic goals that Diesel set for his engine concept in 1892 were bold, but at the same time held a powerful prophecy for the future: maximum cylinder pressure of 253 bar and an efficiency of 58%; and that at the time when the dominating prime mover – the steam engine – ran with an efficiency of mere 7%.

The patent brought neither a fortune nor a personal happiness to his inventor, but it can be seen as the starting point for the rise of an engine branch without which the modern large-scale goods and passenger transport would have been unthinkable, namely the large engine division. It definitely took time for this engine branch to set foot and gain momentum, for it wasn't until 1912 that a four-stroke Diesel engine was used as the main propulsion set on a high-sea ship, the MV Selandia [1]. However, it was not a sign of change in the sea transport, for in the Second World War two thirds of the shipping was still driven by steam, and there were only two capital warships powered exclusively by Diesel engines. The situation started to change with the first application of the turbocharging to a two-stroke Diesel engine in 1946 [2], partly due to the "downsizing" of this engine kind brought about by the turbocharging, for turbocharged four-stroke engines were in use on ships since 1927.

It is now a recognized fact that shipping is the most efficient form of bulk transport, without which the globalization of the world trade would hardly have been possible. Given that the carrying capacity of modern container ships already exceeds 21000 TEU (Twenty-foot Equivalent Units) containers, and that they are almost invariably propelled by a single low-speed two-stroke engine (75570 kW in the case of OOCL Hong Kong, currently the world's largest container ship), the importance of the large engines can hardly be overstated.

The breakthrough in rail transport came about in 1939 with the introduction of the EMD FT, the two-stroke Diesel-electric locomotive in the U.S.A. [3]. The Second World War slowed the proliferation of the Diesel engine in this transport sector too, because it was forbidden to build Diesel engines in the war-time U.S.A. on account of the steam engine being much better known and requiring less precious materials in the production. Diesel engines have also been widely used to generate electricity, an example of which is the Diesel locomotive whereby the engine is used to generate electricity to be supplied to the electric motors driving the wheels. On ships, Diesel generators are used to supply electricity for lighting, ventilation, powering the ballast water pumps for balancing the ship, but also for auxiliary propellers, i.e. thrusters, used for enhancing the ship's manoeuvrability, especially in ports.

Another important application field of large engines is the stationary electricity generation, either as the so-called "island solutions" in areas without connection to an electric grid system, or for supporting a national grid system at meeting the peak or a sudden load demand. A typical power plant of this kind may consist of one to twenty 10 to 20 megawatt units ready to start at short notice, which is of an ever increasing value in connection with the often unpredictable availability of the renewable electrical energy sources, such as e.g.

the wind turbines [13]. Lest the impression be given here that the Diesel engines are the only large engines in existence, the gas-burning engines actually predate the Diesel ones by some 30 years, as gas was available for lighting, and thus the so-called atmospheric gas engines appeared. However these engines were very inefficient and the development impetus for gas engines came about with the four-stroke patent of Otto in 1876.

Large gas engines experienced an ever accelerating development rate in the last 20 to 30 years, constituting nowadays a mature segment of the large engine family. At powers of up to 50 MW, low-speed, two-stroke gas engines are more efficient than the corresponding gas turbines; and their small environmental impact makes them also attractive for being used as prime movers in the transportation as well, competing ever more with the four- and two-stroke Diesel engines on ships. As a matter of fact, the former clearly-cut difference between the gas and Diesel engines has been progressively blurring in the past decade or so due to the introduction of the dual-fuel engines that are capable of burning both fuels, switching between them according to the situation at hand.

Given that the slow-running two-stroke Diesel engines are at least equal if not better in terms of the fuel efficiency than the gas turbine installations, being thus the most efficient thermal machines known to man, and the importance of the large engines in general to the large-scale transportation of goods and people, it is of interest to review their current state and development trends, borrowing thus the motto "Quo Vadis Large Engines" from a recent Guest Commentary in MTZ Industrial [4].

2. MAIN ENGINE TECHNOLOGY DRIVERS

The engine technology has in the past been driven by the need to continuously fulfill the standard criteria of the general product development, namely:

- Efficiency, i.e. the operating costs
- Price, i.e. the production price at the manufacturer's side, and the purchase price at the buyer's side
- Reliability and safety
- Ease of maintenance (also a part of the operating costs).

The state and its agencies may have intervened insofar as to define regulations concerning the reliability and safety of the products, which has traditionally been the concern of the insurance business as well, leaving the rest to the negotiations between the manufacturers and buyers.

The situation changed sharply as the concern arose for the environment pollution and its consequences upon the human and animal health, which in the case of large ship engines may be dated to the year 1997 as the IMO (International Maritime Organization) published the MARPOL (Maritime Pollution) Annex VI [5]. This agreement was intended to come into effects on 1.1.2000, subject to being ratified by enough countries to reach 50% of the world ship tonnage. There were several previous declarations to the subject of the environment protection, but it was the first time that concrete emission values were to be applied along with the measures and the timetable for their implementation and enforcement. A process was thus set up that would become a major development driver in the engine business for the decades to come, as the regulations were to be updated, i.e. become ever stricter, on a regular basis [18].

The evolution of the IMO limits on the nitric oxides (NOx) emissions from large engines is presented in Figure 1 below [6]. It is valid for marine Diesel engines with power larger than

130 kW, but not for vessels operating in national waters, where local legislation applies. It is seen that the limits were lowered in stages (so-called Tiers), first mildly, and then drastically in the so-called Emission Control Areas (ECA). These are to be defined by the individual countries. It is also apprent that the slow-running engines (< 250 rpm) were allowed higher NOx values in the beginning, but the Tier III practically eliminated the difference between the two- and four-stroke machines.

The sulphur limits were also scheduled to be reduced with time at the global and ECA levels, but since the SOx emissions are primarily determined by the sulphur content in the fuel, they have repercussions upon the engine only insofar as regards the exhaust after-treatment. The soot (black carbon) and particle emissions are currently not regulated, and it is apparently not likely that the discussions within the IMO are to be soon concluded.

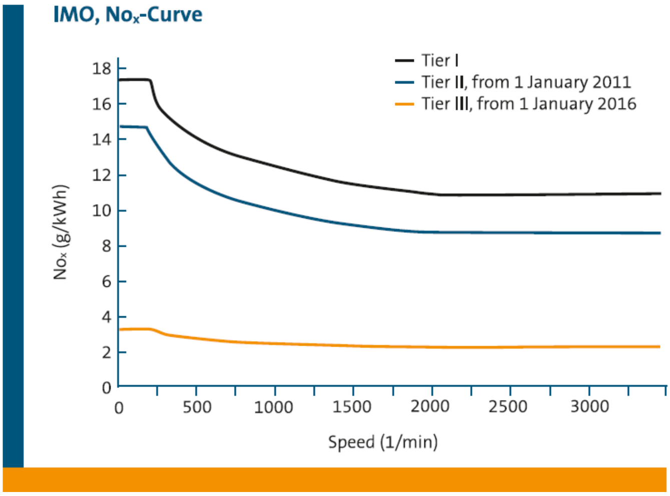


Figure 1. Evolution of the No_x legislation for large maritime engines

The emission limits for rail engines came about at approximately the same time, in the form of the EU Directive 97/68/EC, which was adopted by the Int. Union of Railways (UIC) as the Code 624V, shown in Figure 2 below. The former was superseded in 2016 by the all-encompassing NRMM (Non-Road Mobile Machinery) legislation (EU 2016/1628), which covers practically everything from the small agricultural machinery to the inland waterway vessels and electricity generating sets [7]. The relevant emission limits for the rail transport are shown in Figure 3 below.

Stage	Power, Speed	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]	Date
UIC II	$P_n \leq 560$ kW	6.0	0.6	2.5	0.25	1 Jan 2003
	$P_n > 560$ kW, $n_n > 1000$ rpm	9.5	0.8	3.0	0.25	1 Jan 2003
	$P_n > 560$ kW, $n_n \leq 1000$ rpm	9.9	0.8	3.0	0.25	1 Jan 2003

Figure 2. The UIC Code 624V emission legislation for railway propulsion engines

Similar legislation for the rail transport exists in other countries, with the U.S.A. NOx limits of 1.74 g/kWh for their Tier 4 (2015+) locomotive engines being more stringent than the Stage V (2021+) EU limits of 4 g/kWh [6].

The above mentioned exhaust gas limits must be met without sacrificing the fuel efficiency. However, the latter determines the CO2 emissions; and as a Greenhouse Gas (GHG), CO2 is also the subject of regulatory measures. Although the global shipping is currently responsible for only 2.5% of the worldwide CO2 emissions [9], IMO has initiated a program for reducing the total annual GHG emissions by 50% relative to the 2008 level, i.e. the CO2 emissions by 40% by the year 2030. To this end, IMO has introduced mandatory technical (EEDI) and operational (SEEMP) measures for the energy efficiency of ships [10].

The term EEDI (Energy Efficiency Design Index) is a comprehensive efficiency parameter that takes into account not only the main engine efficiency, but also all other GHG emissions, the ship's capacity, the so-called „hotel load“ (crew facilities), and speed. Referring to Figure 4 below, there is a reference EEDI line for each ship commissioned after January 1st of 2013 as a function of its DWT (Deadweight Tonnage), and a set of required lines for the new or retrofitted ship generations as a parameter, reducing by 10% every five years [9].

Locomotive propulsion engines

Stage	Power Cylinder displ.	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]	PN [#/kWh]	Date[A]
		HC + NO_x [g/kWh]					
III A	$130 \le P_n \le 560$ kW	4.0		3.5	0.2	–	2007
III A	$P_n > 560$ kW	6.0	0.5	3.5	0.2	–	2009
III A	$P_n > 2000$ kW, $V_{h,z} > 5$ L	7.4	0.4	3.5	0.2	–	2009
III B	$P_n > 130$ kW	4.0		3.5	0.025	–	2012
V	$P_n > 0$ kW	4.00[B]		3.50	0.025	–	2021

[A] Date for placing on the market of engines, type approval one year earlier.
[B] A = 6.00 for gas engines.

Railcar propulsion engines

Stage	Power	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]	PN [#/kWh]	Date[A]
		HC + NO_x [g/kWh]					
III A	$P_n > 130$ kW	4.0		3.5	0.20	–	2006
III B	$P_n > 130$ kW	2.0	0.19	3.5	0.025	–	2012
V	$P_n > 0$ kW	2.00	0.19[A]	3.50	0.015	$1*10^{12}$	2021

[A] Date for placing on the market of engines, type approval one year earlier.
[B] A = 6.00 for gas engines.

Figure 3. The EU 2016/1628 emission legislation for railway propulsion engines

Ship owners can improve the respective EEDI figures of their ships by various measures, such as making changes to the engine (installing better injectors, turbochargers, etc.), and by optimizing the entire energy flow of the vessel. Engine manufacturers are thus stimulated not only to improve their products, but also to offer various devices for enhancing the performance of the existing engines in service.

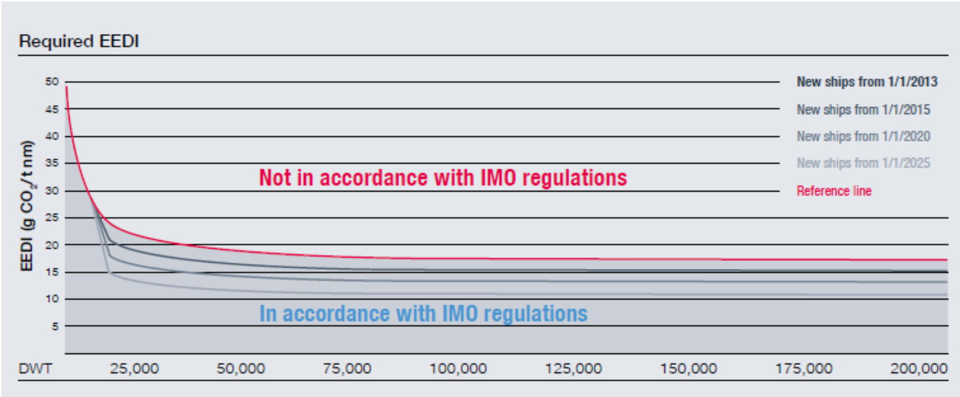


Figure 4. The required IMO EEDI lines for the existing and future ships [8]

As regards meeting the above goals set by the respective legislation bodies, Schlemmer-Kelling [5] writes that the potential for increasing the efficiency at high engine loads by improving the combustion process, the gas exchange, and the mechanical efficiency has already been exhausted. The only remaining measures would be increasing the firing pressure, and opting for a two-stage turbocharging with an intercooler. In his opinion, it is the part-load where larger potential for improvement exists in terms of better air supply to the cylinders, and optimized fuel injection.

It is at this place necessary to mention one technology that has been and remains instrumental to achieving the improvements required for meeting the exhaust legislation, namely the supercharging, which in a vast majority of cases is realized by means of turbochargers. There is now hardly a large engine without turbocharging, and new theoretical IC cycle variants such as Miller and Atkinson would have been impossible to realize without this technology. It has been developing in parallel with the engines, exchanging the development incentives in both directions. This is also true of the newest T/C products, namely the two-stage turbochargers that have been offered as mature products by all major T/C manufacturers in the last years, e.g. [11][12]. The fact that the GHG emissions from many energy sectors in Europe have been falling, and those from transport have increased over the last decades, and are expected to increase significantly to 2050 [14], has become an additional technology driver in the large engine sector. The GHG emissions of fuels with a smaller carbon content than the standard marine fuel oil (MFO) and the heavy fuel oil (HFO), such as .e.g. the Liquid Natural Gas (LNG), have a favourable impact on the emissions [15], and the use of LNG is thus expected to rise [16], but presupposes the availability of the corresponding engines [17].

3. SLOW-RUNNING TWO-STROKE ENGINES

3.1 Current development state

The two-stroke, low-speed large engine industry has undergone a concentration process, with the result that there are now only two major companies developing but not necessarily manufacturing the largest engines, these being MAN Energy Solutions (formerly MAN Diesel & Turbo) of Augsburg, Germany, and a company now called WinGD (Winterthur Gas & Diesel), which started in 2015 as a joint venture of Wärtsilä of Finland with the China State Shipbuilding Corporation (CSSC), but is from 2016 owned solely by CSSC.

The business model of both companies consists of developing state-of-the-art Diesel engines, which are then built in license almost exclusively in the Far East. MAN also manufactures turbochargers, whereas WinGD do not, relying mostly on ABB Turbo Systems as the turbocharger supplier. The most powerful engines of both companies are in the same range (Wärtsilä: 80 MW, MAN: 87 MW), with Wärtsilä having the largest one in use with the power of 80080 kW on board the container ship Emma Maersk.

Kobe Diesel, having recently acquired the large engine program of Mitsubishi Heavy Industries (MHI), is the third company developing and manufacturing this class of engines (about 2% of the world market), their range currently extending up to about 35 MW units.

Before the financial crisis of 2008, the container ships were built for speed, and it was expected that the future ship classes with the carrying capacity of the order of 20000 TEU would need main propulsion power of over 100 MW. However, this trend has not materialized because the shipping companies realized that significant fuel savings are possible by reducing the cruising speed somewhat. For example, reducing the ship speed from 27 to 22 knots, i.e. by 19%, lowers the nominal engine power to 42%, saving thus 58% of the hourly fuel consumption [19]. So now the 21000 TEU OOCL Hong Kong with the main propulsion power of 75 MW has a smaller engine than the 16000 TEU Emma Maersk.

Main characteristics of modern two-stroke, main propulsion ship Diesel engines are:

- Long-stroke crosshead design
- Cylinder diameter of up to about 100 cm, stroke-to-bore ratio about 4 and higher (in newer engines)
- Hydraulically activated exhaust valve in the cylinder cover, electronic valve control
- Single-stage turbocharging, mechanical blower for the low power regime
- Electronically controlled fuel injection, common rail (MAN and WinGD), mechanical (MHI)
- Up to three injection nozzles per cylinder in order to achieve fuel injection flexibility
- HFO and MFO as the main fuel types, switchable on demand.

Three general technology trends are discernible in the low-speed two-stroke large engine segment:

- Comprehensive engine optimization aimed at improving the fuel efficiency, reliability, maintainability, etc. achieving thus low life-cycle costs
- Changes with regard to meeting the emission legislation, esp. the current Tier III norm
- System optimization (ship, engine, propulsion, operating procedures) for improving the EEDI figure.

The above trends are not isolated from each other – they rather intersect and interact in the attempt to meet the changed economic criteria of the customers, namely the Total Cost of

Ownership (TCO) that now dominates the decision making process instead of the previously most important criterion of the First Cost, i.e. the purchase price.

Discussing the numerous measures and solutions that have been studied and realized in order to arrive at the current optimization level of this engine class is beyond the scope and limits of this paper. Therefore, only a short list will be given of the most important improvements and optimization areas [21], [22], [23], [24], [25]:

- Fuel injection: electronic control, common-rail in different variants, pumps and injectors
- Exhaust valve electronic control
- Auto-tuning in the engine control
- Mechanical improvements of the engine structure
- Minimization of the mechanical (friction) losses in the critical areas, e.g. in the cylinder ring packing and the crosshead guide shoe bearing
- Cylinder lubrication system
- Cylinder cooling
- Turbocharging, e.g. variable turbine area, turbocharger cut-out at low loads, etc.

As an example, shown in Figure 5 below is a diagram showing a possible fuel oil cost savings for a 1 g/kWh reduction of the lubrication oil consumption with optimized piston rings [25].

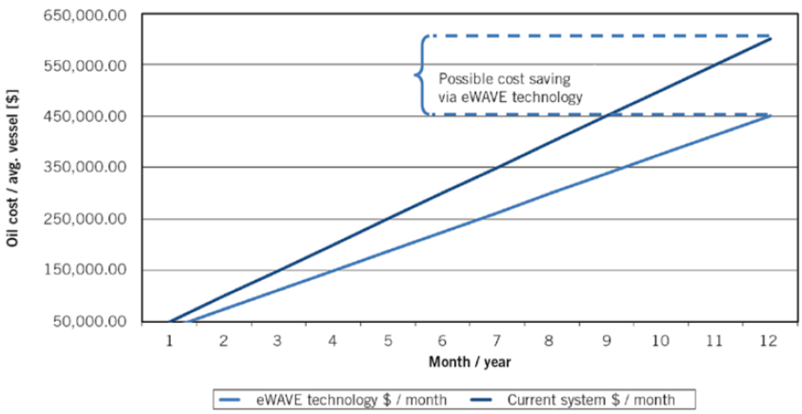


Figure 5. Possible savings by reducing the lubrication oil consumption by 1 g/kWh [25]

In looking at the optimization possibilities in the entire ship propulsion system, one of the obvious elements is the ship's propeller, and its feature of increasing the efficiency with the diameter. Using larger propellers necessitates lower engine rotation speeds, and in order to keep the engine power at the level required by the ship, the stroke-to-bore (S/B) ratio must be increased. This was the approach that led MAN to develop the G-Type engine, with S/B ratio of up to five [20]. According to MAN, CO2 reductions of up to 7% are possible as a part of the propulsion package. Referring to Figure 6 below, overall efficiency increase of 4-5% should be possible with the new engine and a larger propeller.

With the introduction of the RT-flex mid-size engines (48 to 68 cm bore) in the mid-nineties, Wärtsilä also increased the S/B ratio to over 4.0, and this trend continued with the current Generation X-engines. The latter engines have an S/B ratio between 4.1 and 4.5, with the largest model W-X92 (92 cm bore) still at 3.8 for the lack of manufacturing capacity at the crankshaft factory [21]. The authors point out the compromises that need to be made when realizing the long-stroke engines, both from the standpoints of the manufacturing, and of the engine room limitations on the ship.

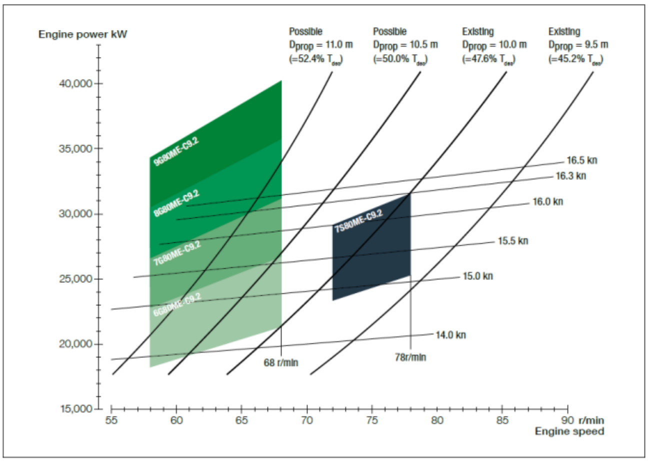


Figure 6. Efficiency gain by using a larger propeller with a G-Type engine [20]

As regards meeting the emission legislation, particularly the NOx pollution, already at the introduction of the Tier II norm the engine designers were confronted with the so-called "Diesel dilemma". This refers to the fact that there is no simple way towards simultaneously lowering the fuel consumption and reducing the emissions, for the mechanisms of their generation within the cylinder are different and lead in part to opposite effects. Referring to Figure 7 below, reducing the NOx emissions is accompanied by a fuel consumption increase, which MAN in 2010 quantified to 6 g/kWh for their mechanically controlled engines, and 4 g/kWh for the electronically controlled ones [26].

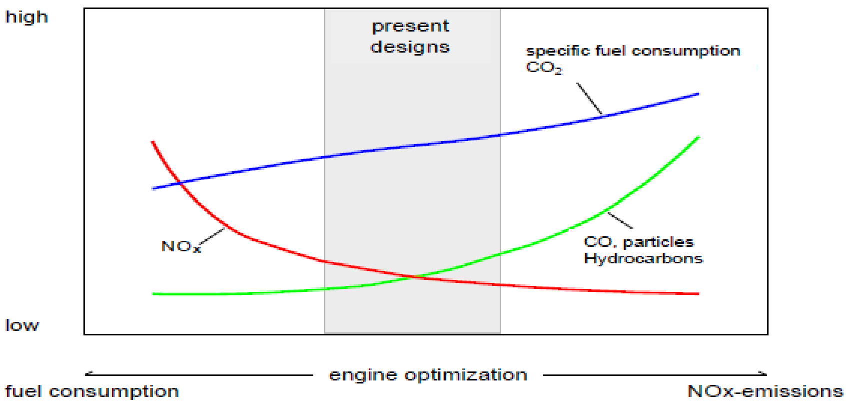


Figure 7. The "Diesel dilemma" [18]

MAN subsequently reduced the fuel consumption penalty for their Tier II engines to 1-2 g/kWh by a combination of measures [26]:

- increased scavenging air pressure
- reduced compression ratio (two-stroke Miller timing)
- increased maximum combustion pressure
- adjustments of the compression volume, and other engine design changes.

Wärtsilä introduced a new generation of two-stroke, Tier II conformable Diesel engines in 2011 [22]. Beside the already quoted optimization measures, the new RT-flex engines featured full electronic control of the exhaust valves and the common-rail injection. As mentioned above, these engines are now offered by WinGD.

Compliance with the Tier II limits adds one more parameter to the procedure for matching the engine speed and power with the nominal operating point of the vessel's propeller. This means that there are limits to the lowest feasible BMEP (Brake Mean Eff. Pressure) level at lower engine ratings in the engine operation map, calling thus for stronger internal NOx reduction measures, which in turn may have adverse effects on the BSFC (Brake Specific Fuel Consumption). These measures include the reduction of the scavenging air pressure, use of extended "Miller timing" (late exhaust valve closure in conjunction with increased scavenge pressure), and reduction of the peak cylinder pressure – the ultimate measure because of its adverse effects on BSFC. The availability of electronic controls on the engine greatly facilitates the application of these measures to the engine [27].

Today, all commercially available low-speed two-stroke engines comply with the IMO Tier II legislation without any additional measures to the ones mentioned previously. Reducing the NOx emissions by additional 75% for compliance with the Tier III values stipulated for the ECA requires much more complex technologies [27], most of which are accompanied by considerable financial expenditures. Since the HFO remains the principal fuel in this field [5] and its high sulphur content will be tolerated only until 2020 (<5000 ppm in non-ECA afterwards), and that because of the high capital costs the oil refineries are unlikely to modernize their HFO plants for lower sulphur content, it is the engine manufacturers who will have to solve the SOx emission problem.

Several technologies for meeting the Tier III criteria have been already investigated and experimentally tested, and some of them have been also commercially available for a number of years, e.g. [28]:

- Selective Catalytic Reactor (SCR) with urea injection for reducing the NOx content; injection of ammonia gas (NH3) has been introduced as an alternative recently
- Exhaust gas scrubbing and/or washing in order to reduce the SOx content
- Dual-fuel engines (HFO at high sea, gas in the ECA)
- EGR (Exhaust Gas Recirculation).

Starting with the SCR technology, there has been experience with it on the low-speed two-stroke engines previous to the establishment of the IMO Tier II norm, but it was limited to stationary power plants, e.g. [28]. In this particular case, the engine manufacturer (MAN) quotes both the power plants equipped originally with the exhaust gas treatment, and the retrofitted ones. Given the power range of the plants mentioned (40 to 50 MW), the SCR and the auxiliary equipment may be quite large. While in these cases there was enough space to accommodate whatever equipment was necessary, an application of this technology on ships is confronted with a number of restricting factors. Retrofitting an existing ship engine must take into account factors like tight space in the engine room, ship balance, engine room deformation with various cargo arrangements, having enough space for routine engine maintenance, possibilities for a relocation of the existing auxiliary components of the engine, etc. [29].

Referring to Figure 8 below left, the SCR from the reference above is seen at the RHS of the engine. While this installation is not a true retrofit (the system was previously tested on the test-bed) and the engine room was redesigned to accept thus modified engine, it conveys the idea of the space requirements. The RHS picture shows a different SCR arrangement on an engine of comparable size to the previous one [30].

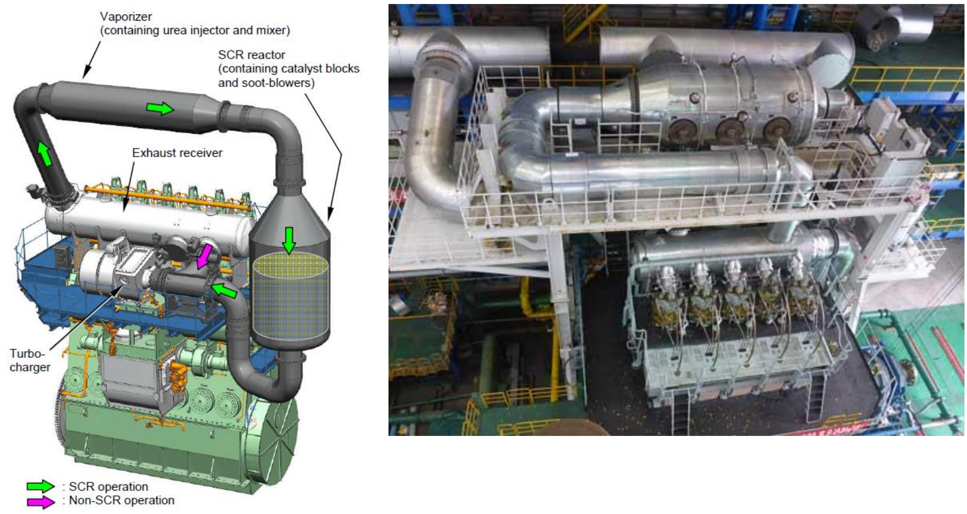


Figure 8. The SCR systems on two similar, middle-power two-stroke engines [29],[30]

Being installed between the exhaust receiver and the T/C turbine inlet, the SCR solutions shown above operate at high exhaust pressure and temperature. However, in both cases there is a single turbocharger on the engine, which greatly facilitates adding the SCR, but limits the solution to relatively low power engines. Large engines have typically several turbochargers, typically one for each three to four cylinders, and it is questionable whether this concept is applicable to such engines without major modifications. An SCR system after the turbochargers, i.e. at the funnel inlet is a more attractive solution for the high-power engines, and one such system was recently developed and commercially produced [31].

Dual-fuel engines have experienced very intensive development in the last years on the account of being capable of full Tier III compliance without the need for the exhaust after-treatment measures. The approach consists of using the HFO on the high sea, and gas (typically LNG) in the ECA. The two fuels differ significantly, but the engine remains essentially a Diesel, with modifications for the gas combustion. Two concepts have been established, the low-pressure one by Wärtsilä [32] and the gas injection (GI) of MAN [33], recently extended to the liquid gas injection (LGI), methanol, and ethane gas, i.e. practically to all gas fuels [34]. A comparison of the two concepts is presented in [37].

Referring to Figure 9 below, shown at the left is the low-pressure dual-fuel engine concept of Wärtsilä in the gas fuel mode. The gas is injected at a low pressure (about 16 bar) in the middle of the compression stroke. The compressed air-gas mixture is ignited at the end of the compression stroke by injecting the pilot fuel oil (MDO) into the prechambers in the cylinder cover. The mixture has a high air excess ratio, creating thus the conditions for a lean combustion. However, since the air-gas mixture is compressed to a high pressure, there may be a tendency towards knocking combustion under certain conditions, so the engine must be monitored by the control system. In addition, the compressioin ratio of the engine is determined by the gas fuel operation, which means that the engine is derated in the Diesel fuel mode. The MAN dual-fuel engine is based on high pressure gas injection directly into the cylinder, and subsequent ignition of the mixture by a pilot fuel flame. The combustion process is the same as in the same engine operating with Diesel fuel injection, such that there is no knock limit, as well as no limit on the compression rate and BMEP. The engine thus achieves the same thermal efficiency as when operating with HFO or MDO. The fuel gas is supplied to the engine at a pressure between 200 and 315 bar [33]; the pressure is dependent upon the engine load. If the gas is available in the gaseous state, it is supplied by a suitable compressor, whereas LNG must be supplied by a cryogenic pump and a vaporiser (LNG is kept at -162 °C in the tank). Since the gas fuel is potentially explosive if it leaks and mixes with the surrounding air, proper high-pressure sealing of the gas system must be guaranteed at all times.

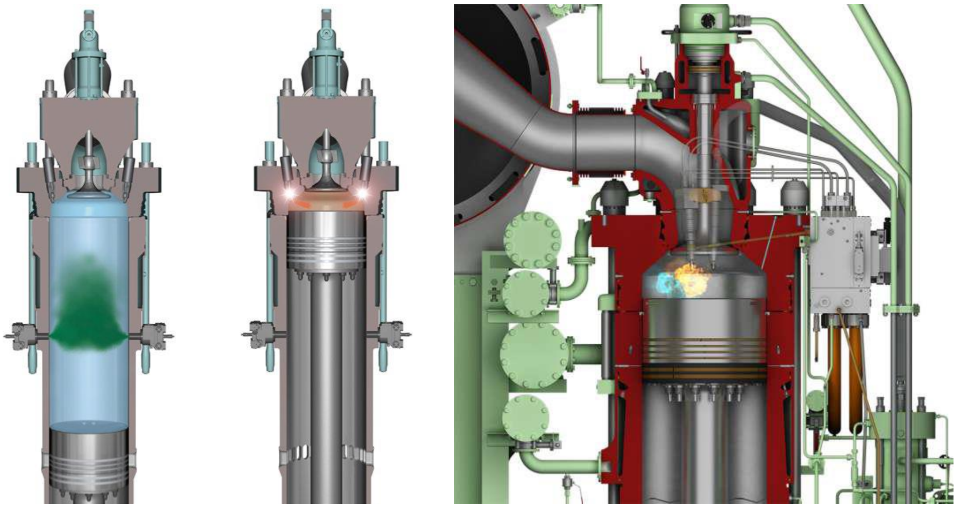


Figure 9. The Wärtsilä [32] and MAN [33]dual-fuel engine concepts

If a dual-fuel engine is for any reason not an attractive option for the ship owner, the Tier III limits can be met by burning MDO and employing the SCR and/or EGR for the exhaust gas treatment. The latter is only possible with very low sulphur content in the fuel oil, for sulphur is responsible for the major part of the PM (Particulate Matter) in the exhaust gas; alternatively, a SOx scrubber/washer can be used.

EGR solutions have been tested by MAN and their licensees, and found to meet the Tier III criteria. In comparison with the SCR, the necessary installation space is obviously much smaller (Figure 10), but the air supply to the engine, i.e. the turbocharging solution, must be redesigned [35], and a number of other non-trivial conditions met [36].

Figure 10. The MAN EGR concept (left) vs. the SCR solution for the same engine (right) [36]

3.2 Future R & D directions

According to the German engine consulting firm FEV, for price reasons the HFO remains the fuel of choice in the next decade, and this prediction has repercussions on the future research activities in the low-speed two-stroke engine field. While LNG is a very attractive fuel on an LNG tanker, using it as main fuel on an e.g. container ship is hardly a practicable idea, for LNG must be kept at -162 °C in the fuel tank and the inevitable boil-off must be continuously recompressed, which requires a special compressor. Therefore, there will be a legislation-driven need for attractive exhaust gas after-treatment solutions [5].

The other factor influencing the future research is expected to be the change to the TCO concept at the customer's side, which means that the engine is only a part of the much larger picture. However, since the TCO approach tends towards lower ship speeds, it leads sometimes to surprising results. Referring to Figure 11 below, a TCO-based optimal ship speed for a 1000 TEU container feeder would be 14 knots (prices as of 2015), roughly the value achieved by the sailing ships of the 19th century [37]. Because of the thus prolonged transport times, the ship operator will all the more be interested in having maximum efficiency of the entire business unit, including the engine.

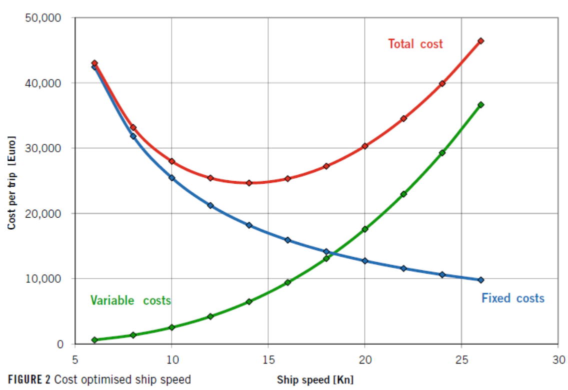


Figure 11. TCO-based optimal ship speed for a 1000 TEU container feeder [37]

The future development directions, as predicted by the FEV [5], are shown in Figure 12 below. Some of the solutions that should be important in the next decade are already available, such as common-rail injection, and the two-stage turbocharging [39]. The latter was tested a decade ago on an engine test bed and found unattractive, but should now become interesting on account of offering a possible 2 to 7 g/kWh reduction of the fuel combustion.

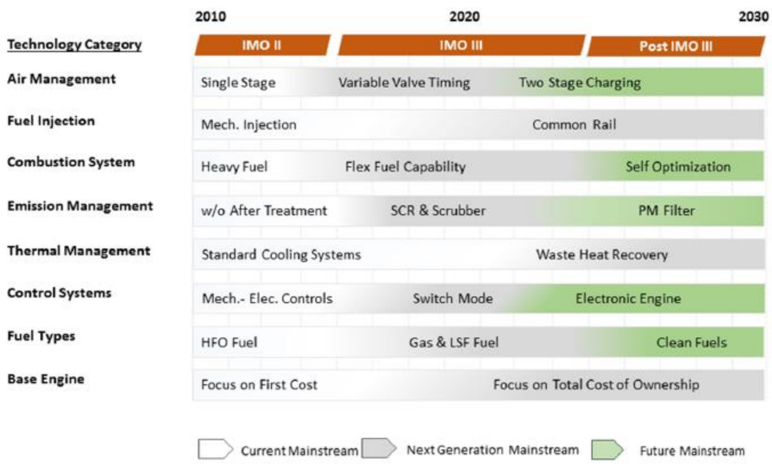


Figure 12. FEV road map for the necessary R & D activities in the two-stroke low-speed sector [5]

The above road map does not include a recent addition to the turbocharging technology that holds a considerable potential for a BSFC reduction in the slow-steaming ship mode, especially at the low end of the engine load (below 40%). It is based on adding an electric motor/generator (M/G) to the turbocharger, and in the solution of Mitsubishi [58] the electrical machine is an intrinsic part of the latter, sharing its shaft. Referring to Fig 13 (left) below, the M/G is located at the compressor inlet, in the middle of the filter/silencer. At high engine loads, the excess turbocharger power is used to drive the generator, reducing thus the demand on the main electricity generator; in a case reported in the paper, the generator consumed about 13% of the T/C turbine power [58].

At low engine loads, when the T/C turbine does not become enough energy in order to supply enough scavenging air to the engine, it is customary to use an electrically driven blower for this purpose. However, the electrical machine within the T/C can also be used in the motor mode, providing thus additional energy to the compressor, possibly obviating the need for the auxiliary blower. In the case reported in [59], generating the scavenging pressure by this method consumed 30% less electricity as compared to the auxiliary blower, reducing simultaneously the total fuel consumption by 1.3 to 6.7%, depending on the main engine operating point [58]. Obviously, this approach has a solid potential for the future, but the motor/generator price is currently rather high.

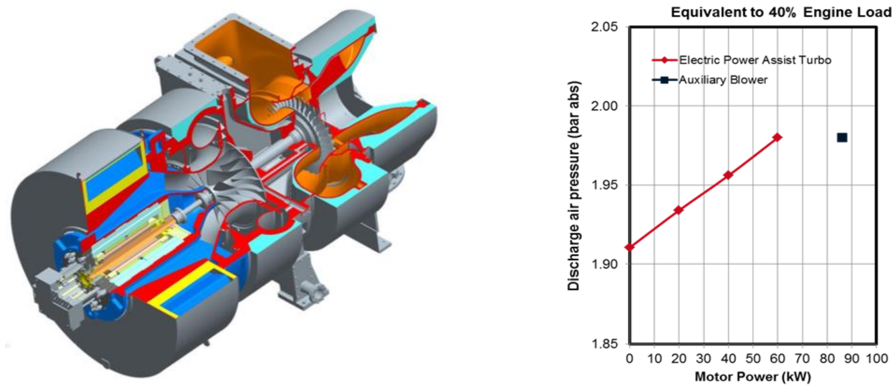


Figure 13. The “Electric-Assist” T/C of Mitsubishi [58], and the available scavenging pressure [59]

Regarding the EEDI as a technology driver, an interesting combination of the low-pressure EGR and the OCR (Organic Rankine Cycle) as a possibility for low-temperature waste heat recovery has recently been reported in the literature [60]. As a matter of fact, not only the EGR system can be used as the OCR heat source, but practically any low-temperature energy source can be harnessed for this purpose. Savings of the order of 6 to 7% can be expected from this heat recovery method.

4. FOUR-STROKE LARGE ENGINES

Traditionally, engines in this group are differentiated according to their speed (medium and high speed) and the fuel they burn (Diesel or gas). While the speed criterion is still valid (<1000 rpm: medium speed), the fuel criterion is not sharp anymore, for the proportion of dual-fuel engines appears to be rising in this segment too [40], [41].

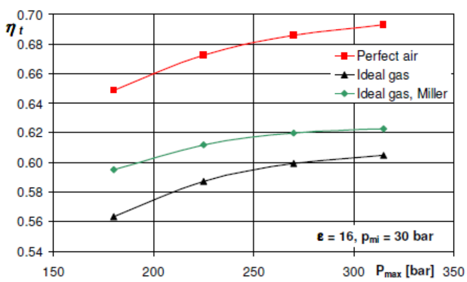
With the exception of the air and road transports, large four-stroke engines are encountered on ships, boats, and submarines (main propulsion, auxiliaries), in the rail transport (locomotives and railcars), in the stationary power plants (electricity generation), on the oil drilling platforms, and in nonroad mobile machinery (excavators, etc.).

4.1 Current development state

The developments in this engine class have also been influenced by the exhaust gas legislation, especially in the maritime sector, but also by fuel price fluctuations and customer requirements. For example, a TCO projection for a 10 MW DF ship engine calculated in 2014 would give a three-year ROI (Return on Investment) for the gas operation, but due to the falling HFO prices, the same calculation made in 2016 would have incurred heavy losses [42]. This is where the flexibility of the DF engines could play a prominent role, provided that the vessel has provisions for storing both fuel types. Practically all modern ships with the four-stroke main propulsion are equipped with DF engines. Modern four-stroke engine portfolios are optimized to satisfy not only the exhaust gas norms, but also the ever-present striving towards maximum efficiency across the entire load range, low manufacturing costs, high reliability, and low maintenance costs. Treating an engine in the development process as a part of the entire object (ship, power plant, etc) requires solutions facilitating the system integration, both at the engine level itself, and at its „working place“.

Turbocharging has apparently played a decisive role in bringing about both increased efficiencies and lowered emissions of polluting gases. The effects of higher charging pressure have been known for more than twenty years, but the impetus for developing such solutions came from the emission legislation, e.g. [43]. At the 2007 CIMAC Conference, Wärtsilä presented the first test-bed results for their Type 20 engine turbocharged with an ABB two-stage T/C delivering the air at a pressure ratio of 9.1, which enabled the use of the Miller timing [44]. Valuable results were obtained as regards the NOx reduction, and further research and development activities indicated. Theoretical studies of the Miller cycle indicate that the maximum cylinder pressure must not be increased in comparison with the Diesel cycle in order to obtain an efficiency gain [43]. Referring to Figure 14 below left, it is seen that the efficiency gain increases with the reduction in the maximum cylinder pressure, such that e.g. p_{max} of 190 bar with the Miller process results in the same efficiency as with the Diesel p_{max} of 270 bar, lowering the NOx generation at the same time. In making these calculations, it is important to use the ideal gas hypothesis (temperature-dependent specific heats), because the perfect gas hypothesis leads to incorrect results [43].

In order to achieve the above results, a large pressure drop over the engine is needed, calling thus for a turbocharging efficiency of about 70%, which in turn means a T/C compressor ratio of the order of ten (Figure 14, right). Such pressure ratios are impossible to realize with a single stage compressor if a useful performance map is to be simultaneously obtained, hence the reason for a two-stage compression. Together with the intercooling, which renders the overall compression process approximately isothermal, i.e. energy-efficient, favourable conditions are created for the realisation of the Miller process.



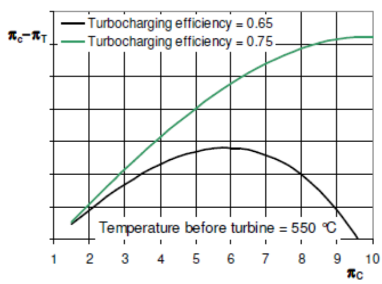


Figure 14. Theoretical Miller and Diesel efficiencies (left) and the required turbocharging efficiency (right) [43]

In 2015, Wärtsilä announced its “31” medium speed, four-stroke engine with the world’s highest efficiency in its class (BSFC of 165 g/kWh with MDO), available in the Diesel, dual-fuel, and spark-ignited gas versions [45]. In the current Product Specification sheet (2017), the BSFC is quoted at 170 g/kWh for somewhat heavier distillates with the sulphur content of up to 2% [46]. An SCR is needed for compliance with the Tier III when operating with these fuel oils. In order to secure acceptable performance at part loads, the inlet valve drive has variable closure timing. The turbocharging technology has also made advances since the introduction of the first two-stage models. For example, the second generation of the two-stage turbochargers of ABB Turbo Systems (Baden, Switzerland) has a potential for achieving the equivalent turbocharging efficiency of up to 80% at overall pressure ratios of 12 [47], giving the engine designer possibilities for further performance improvements (Figure 15, left).

Looking at the low-pressure stage turbine efficiency of almost 90% (Figure 15, right, one has a feeling of the physical limits being about to be reached (turbine efficiency of over 90% has been attained on the test stand). Generally, the benefit of the two-stage turbocharging is a BSFC reduction of 3 to 5%, depending on the application [49].

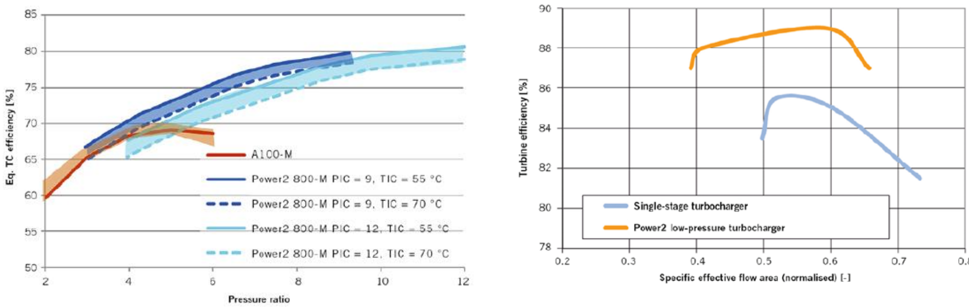


Figure 15. Turbocharging efficiency (left) and low-pressure turbine efficiency of the ABB two-stage T/C [47]

However, designing a two-stage turbocharged engine solution requires solving a number of problems in connection with the mounting of the T/C onto the engine, dealing with the noise and the changed vibration patterns and levels, securing serviceability of the entire system, etc. For example, going from a single-stage to a two-stage T/C increases the mass to be held by the engine by 1.5 to 1.7 times, making a new structural analysis of the entire assembly necessary [48]. Fundamental research is sometimes necessary in order to achieve the engine performance goals under the new conditions; and the literature abounds with papers on the subject of combustion, heat transfer, and gas flow optimization through the valves, e.g. [40].

Thermodynamically efficiency of the large four-stroke engines appears to have been rising at a rate of 0.25% per year (Figure 16, left) for the Diesel and 0.3% for the gas fuel (Figure 16, right) in the last two decades (note that the ordinate in the LHS plot was in the original paper incorrectly labelled, and has been corrected by the present author in the image below). Both trends appear to have continued to the present with the already mentioned Wärtsilä 31 engine (the efficiency figure has not been published, but with the BSFC of 165 g/kWh it is likely to be about 50%), and the newest Jenbacher J920 gas engine genset with an electrical efficiency in excess of 50% has the engine efficiency of more than 51% [52].

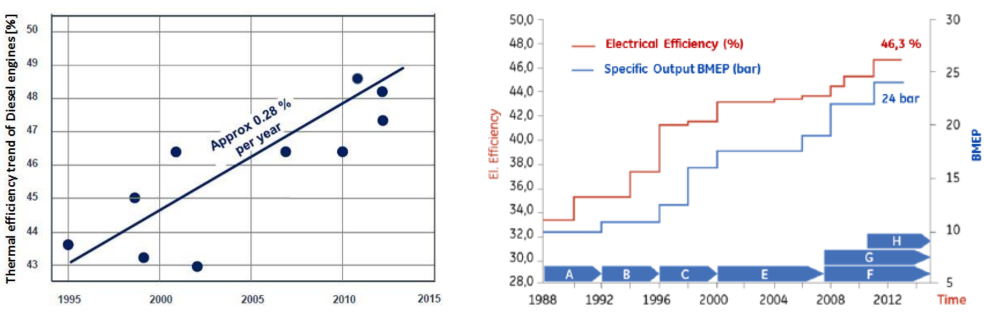


Figure 16. Diesel (left) and gas engine (right) efficiency trends in the past decades, [50], [51] resp

The performance figures of the new J920 gas engine came about through a comprehensive system-based analysis optimization of the already efficient first version of the engine (electrical efficiency of 48.7%, [53]). Referring to the comparison of the respective contributions of the fundamental thermodynamically and mechanical processes in the first and second engine versions, presented in Figure 17 below, it is seen that the performance improvement came about through reductions of the losses due to incomplete combustion, gas exchange, and friction [52].

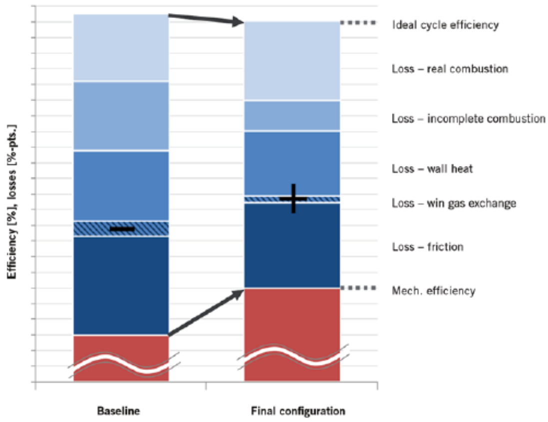


Figure 17. Reduction of losses in the Jenbacher J920 gas engine design process [52]

Summarizing, modern four-stroke large engines are capable of meeting the current exhaust legislation while keeping or improving the engine efficiency, and hold promise for the future. The current development state has been attained by intensive R & D efforts which, given the importance and the omnipresence of these engines, are going to continue.

Nowadays, the four-stroke engine family is characterised by a combination of features, such as:

- Two-stage turbocharging, making the Miller and/or Atkinson cycles possible
- Flexibility with regard to the fuel to use
- Compliance with the IMO Tier III and other equivalent exhaust legislation norms without external exhaust gas treatment when burning gas fuel
- Availability of a combination of intra-engine, e.g. EGR, and external measures for compliance with the norms in the case of liquid fuel oils
- Variable valve timing
- Improvements in the fuel supply to the cylinders (common-rail injection, optimized gas supply)
- Comprehensive electronic control of the entire engine, capable of securing optimal results in the entire operation map; and individual cylinder control has already been reported upon
- Prolonged maintenance intervals of the order of a year's continuous service
- Modular design, facilitating quick repairs but also supporting future upgrades and retrofits.

It is the opinion of the author that the above represents a solid basis for, as formulated in [54], a "future-proof" engine.

4.2 Future R & D directions

It is to be expected that current fine-tuning efforts will be continued and extended, especially as regards the part-load operation. For example, contemporary DF engines must revert to Diesel operation when the load drops below 50% either because of instable operation or the increased emissions. It appears that this problem can be alleviated by selectively switching individual cylinders off [56].

Transient operation is known to give rise to smoke emission (limited by some countries in the ECA), and it has been shown that a better control of the turbocharging can eliminate this problem [55]. Individual cylinder pressure sensors are regularly used in low-speed two-stroke engines, and the trend is expected to carry over to the four-stroke segment. For example, Caterpillar have developed an in-cylinder pressure module (ICPM) that not only measures the maximum pressure, but also evaluates several combustion-relevant parameters, enabling thus the balancing of cylinders in operation [41]. Such efforts then almost inevitably lead to a closed-loop cylinder control, which would be instrumental in further reducing the engine emissions. The Mitsubishi hybrid turbocharger mentioned above within the low-speed two-stroke context has also a fuel saving potential in the four-stroke segment. Tested on a rather small engine (660 kW), it demonstrated a net fuel oil consumption reduction of between 1.9 and 2.8% [58]. It is therefore clear that further R & D efforts are to be expected with this approach, reducing the price being one of the targets. Variable valve timing remains essential for achieving high efficiency and low emissions under varying operating conditions, but it cannot solve the derating problem in low-pressure dual-fuel engines. Essentially, a straightforward solution would be an engine with a variable compression ratio, which has been known in general for a long time. A conference with this topic was held in 2017 [57], showing the current activities at several institutions. One of the concepts is based on an eccentric bushing, integrated in the upper connecting rod eye, which can change the effective connecting rod length in two fixed positions [42]. The VCR idea and theoretical BSFC reduction obtainable with this technology (up to 10 g/kWh with Diesel engines, and up to 8 g/kWh for the gas ones) are shown in Figure 18 below. Intensification of the research is to be expected in this domain.

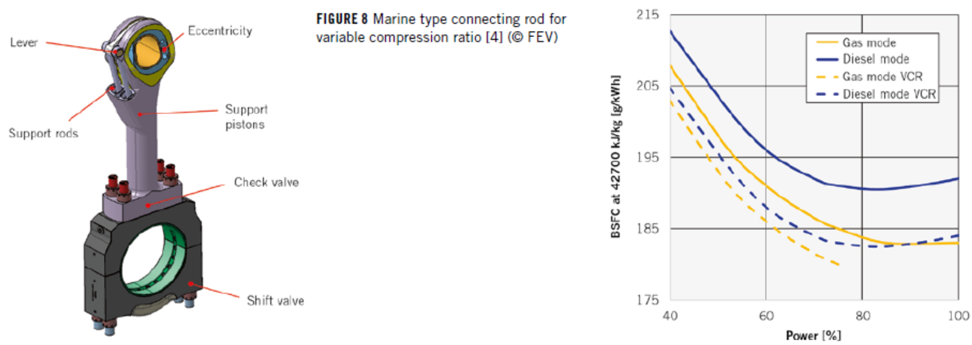


Figure 18. The FEV variable compression ratio proposition and the expected effects [57]

5. CONCLUSIONS

The legislation limiting the emission of hazardous gases has led to unprecedented R & D efforts in the field of large engines, aimed at meeting the emission limits. But it is also their importance for the world economy that has been driving their development, resulting in these engines belonging to the group of the most efficient thermal machines available to the mankind. Due to the work done in the last two decades, all engines offered in the market today comply with the exhaust gas regulations; while in many cases there has also been a considerable progress in improving their efficiency even further.

In the low-speed, two-stroke engine field, compliance with the legislation was brought about mostly by external measures, such as after-treatment of the exhaust gas, and switching to a different fuel in the ECA's. The latter led to the introduction of the dual-fuel engines and their further development into multi-fuel engines. System integration plays a key role in reducing the GHG emissions, in that not only the engine efficiency is of importance, but rather the efficiency of the entire object containing the engine (ship, power plant). For example, this led to the change in the stroke/bore ratio of the ship's main propulsion engine from about 3.5 to up to five in order to enable using large, i.e. more efficient, propellers.

In the case of the four-stroke engines, one technology has played a major role in making possible intra-engine NOx reduction, and this is the turbocharging. Having been known for a long time for making out 10% of the engine price, but bringing about 75% of its power, in its new, two-stage version it provided the high charging pressure required for employing the Miller/Atkinson cycle. Alone or combined with other measures, such as variable valve timing, EGR, SCR, urea or ammonia injection etc. two-stage turbocharging secures full compliance of the current four-stroke engines with the exhaust gas legislation.

Two-stage turbocharging has also led to these engines attaining thermal efficiency of almost 50% with a potential for further increases, especially with gas engines. However, obtaining high efficiency over a broad range of operating conditions, and/or with different fuels, will require further measures and new concepts. One such solution that has been known for a long time, but for cost reasons never utilized in commercial engines, may be the variable compression ratio (VCR). The general trend towards digitalization has been slowly taking grasp of the large engine area. In addition to the local computer control of the engines themselves, which has already become indispensable, optimization of the vehicles (ships, locomotives) and plants (electricity generation) containing large engines, seen as integrated systems is becoming possible. Large amounts of data are already being transferred from ships en route to their control centers, making applications such as e.g. remote monitoring and on-line optimization possible. Summarizing, it can be stated that large Diesel and gas engines will continue to provide the global mass transport with a reliable propulsion power that complies with the environment protection legislation while simultaneously offering ever increasing efficiency and fuel flexibility.

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IMPACT OF INTRODUCTION OF LOW EMISSION ZONES IN THE CITY OF ZAGREB

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RESEARCH ARTICLE

ABSTRACT: Despite significant improvements in vehicle technology in recent years, vehicle emissions remain a major influencing factor on air quality. Although air quality in the City of Zagreb is still relatively acceptable, official standards, i.e. limiting values are under threat. More than ever, policymakers are actively exploring options for new vehicle emission control and local fleet management policies, as well as the new monitoring technologies to support these activities. The goal of the research was to assess the influence of the introduction of Low Emission Zone on the total emission from the road traffic in the City of Zagreb. To make a model of emissions from road traffic, emissions on selected roads in the City of Zagreb using measured traffic activity data and adequate vehicle fleet characteristics description are calculated. Traffic activity data were obtained from traffic study of the City of Zagreb, while vehicle fleet characteristics are extracted from the database maintained by Center for Vehicles of Croatia and the Ministry of the Interior of the Republic of Croatia. The database contains all the data collected during the homologation process of the vehicles registered in Croatia as well as the data collected during the vehicle periodical technical inspection.

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It is important to note that the database contains exact data on the date, time and site of periodical technical inspection. Fleet data for vehicles registered in Zagreb was compared with the fleet data for the entire Republic of Croatia. The comparison shows the sensitivity regarding the fleet characteristics and that it is possible to improve air quality with simple regulation, i.e. introduction of the Low Emission Zone.

KEY WORDS: vehicle emissions, air quality, low emission zone, road traffic, vehicle fleet

UTICAJ UVOĐENJA ZONA NISKIH EMISIJA U GRADU ZAGREBU

REZIME: Uprkos značajnim poboljšanjima tehnologije vozila u poslednjih nekoliko godina, emisija vozila ostaje glavni faktor koji utiče na kvalitet vazduha. Iako je kvalitet vazduha u gradu Zagrebu još uvek relativno prihvatljiv, službeni standardi, tj. granične vrednosti su kritične. Više nego ikada, zakonodavci aktivno istražuju opcije za novu kontrolu emisije vozila i lokalnu regulativu kontrole voznog parka, kao i nove tehnologije za praćenje koje podržavaju ove aktivnosti.

Cilj istraživanja je bio da se oceni uticaj uvođenja zone niske emisije na ukupnu emisiju saobraćaja u gradu Zagrebu. Da bi se formirao model emisije od drumskog saobraćaja, merena je emisija od saobraćaja na odabranim saobraćajnicama i proračun je izvršen na osnovu karakteristika voznog parka. Podaci o prometnoj aktivnosti dobijeni su iz predmetne studije grada Zagreba, dok su karakteristike voznog parka izdvojene iz baze podataka koju vodi Centar za vozila Hrvatske i Ministarstvo unutrašnjih poslova Republike Hrvatske. Baza podataka sadrži sve podatke sakupljene tokom procesa homologacije vozila registvonavih u Hrvatskoj, kao i podatke prikupljene tokom periodičnog tehničkog pregleda vozila. Važno je napomenuti da baza podataka sadrži tačne podatke o datumu, vremenu i mestu periodičnog tehničkog pregleda. Podaci o voznom parku vozila registrovanih u Zagrebu su upoređeni sa podacima voznog parka cele Hrvatske. Poređenje pokazuje osetljivost u pogledu karakteristika voznog parka i da je moguće poboljšati kvalitet vazduha jednostavnom regulacijom, tj. uvođenjem zone niske emisije.

KLJUČNE REČI: emisija vozila, kvalitet vazduha, zona niske emisije, drumski saobraćaj, vozni park

IMPACT OF INTRODUCTION OF LOW EMISSION ZONES IN THE CITY OF ZAGREB

Goran Pejić, Marko Bunjevac, Matija Pečet, Zoran Lulić

1. INTRODUCTION

According to the European Environment Agency (EEA), around 30% of total carbon dioxide emissions comes from traffic-related activities [1]. Air pollution represents a significant problem for environment and human health and traffic-related activities are major contributing factor. Harmful emissions (tailpipe gases and particulate matter) which occur after fuel combustion in vehicles internal combustion engines cause respiratory, cardiovascular and neurological diseases [2]. Beside the air pollution, studies have shown that traffic-related pollution is the reason for the increase in global mean surface temperatures. For example, simulations performed in [3] suggest that German transport emissions induce an increase in the global mean surface temperature of the order of 10 mK during the 21st century. With the goal of reducing air pollution, the European Parliament and Council have adopted Directive 2008/50/EC on ambient air quality and cleaner air for Europe. The Directive 2008/50/EC state that the public has a right to demand from local authorities to provide a quality environment for life, meaning that authorities should ensure that the air pollution is within permissible limits, which are set within the Directive [4].

Main products of combustion within internal combustion engine can be split into two distinctive groups, those which are harmful to human health and those who are not. Carbon dioxide (CO_2) and water vapour (H_2O) are not harmful to human health, but are closely related to the Greenhouse Gasses and global warming, while carbon oxide (CO), nitrogen oxides (NO_x) and particulate matter (PM) are. Today, major attention is given to the reduction of GHG and minimisation of those which are harmful, especially nitrogen oxides and particular matter. Emission of nitrogen oxides (NO_x) occurs in an engine cylinder by oxidation of atmospheric nitrogen typically at temperatures higher than 1,800 K [5]. They can further be divided into nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Nitrogen monoxide converts to nitrogen dioxide in the atmosphere which can later form acid rain. Furthermore, nitrogen oxide can contribute to forming low-level ozone which is also harmful to human health. Alongside with harmful influence on the environment, nitrogen oxides have a negative influence on human health, causing eye and lung irritation, fatigue and nausea. With long-term exposure, there is an increased chance of asthma occurrence and permanent lung and nervous system damage, and may even cause genetic disorders. Nitrogen oxides, like the carbon oxide (CO), can also prevent the normal flow of oxygen throughout the human blood system. Particulate matter (PM) mostly consists of soot. According to its average diameter, it is divided into PM_{10} and $PM_{2.5}$. PM_{10} represents particles whose medium diameter is smaller than 10 micrometres, and $PM_{2.5}$ represent particles with a medium diameter smaller than 2.5 micrometres. Such fine particles are severely hazardous to human health because they can infiltrate human respiratory and cardiovascular system [6]. It is proven that particulate matter increases mortality by causing chronic obstructive pulmonary disease (COPD), ischemic heart disease and lung cancer [7].

1.1 Low Emission Zone (LEZ)

In its wider meaning, Low Emission Zones (LEZ) represent areas in which traffic is regulated according to vehicle category or emission standard. Restriction implies fully banning certain vehicles or charging their entrance into the zone. LEZ can include from a few main roads up to wide city areas. They are implemented in the areas where air pollution represents a significant threat to human health. Since the grates threat is from particulate matter and nitrogen oxides which are common for diesel-powered vehicles, LEZ often has stricter regulations for those types of vehicles. Studies have shown that heavy duty vehicles (HDV) which commonly run on diesel fuel have up to 30 times greater emission of PM2.5 and up to 26 times greater emission of nitrogen oxides (NOX) than light-duty vehicles (LDV) [8]. Therefore, those kinds of vehicles are often not allowed to enter LEZ, or their entrance is regulated in some way.

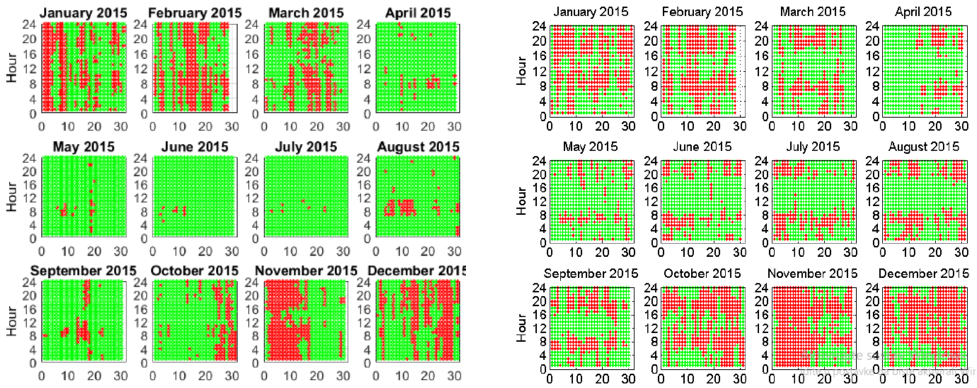
World Health Organization (WHO) states that air pollution is responsible for the premature death of nearly 310,000 people in Europe which is more than deaths involved in traffic accidents. Besides air pollution having an adverse impact on human health, it consequently causes great financial losses. Cost of treatment for people with air pollution-related diseases is estimated somewhere between 427 and 790 billion EUR annually [9].

As mentioned earlier, a great number of LEZs ban or regulate the entrance of heavy-duty vehicles with great emissions, while some even ban or regulate the entrance of coaches, passenger vehicles and motorcycles. Most of LEZs are active throughout the entire year, while other are active only occasionally, e.g. in the rush hour, in winter or in summer. Currently, there are 258 Low Emission Zone in 23 European countries with over 230 major access regulations and 14 charging schemes [9].

1.2 Air Quality in the City of Zagreb

In Zagreb, capital of the Republic of Croatia, there are six stations for continuous measurement and monitoring of air quality. Locations of the station can be seen in Figure 2. The measuring station Zagreb 1 is very interesting because it is located near to the crossing of Vukovarska and Miramarska Street which represents crossing with one of the densest traffic in the city because it is located near the centre of the city.

By using the developed application, the data from all measurements stations in Zagreb have been collected and analysed from January 1st 2015 to December 31st 2015. The greatest attention was given to the following pollutants: nitrogen oxides (NOx) and particulate matter (PM). A limit value for PM2.5 according to Air Quality Standards is 25 μg/m3, while the PM10 is defined with the limit value of 50 μg/m3, and the permitted exceedances each year is 35 times.



Green dots represent values below the limit, red dots represent values over the limit.

Figure 1. Hourly exceedances (shown as red dots) of PM in measuring station Zagreb 1 (left) and exceedances of NOX in measuring station Zagreb 3 (right) during 2015 [10]

As graphically represented in Figure 1, analysis has shown that the limit for PM10 is exceeded more than 35 times, but it is also evident that pollutant concentrations of PM are lower in those months when Zagreb's inhabitants are using their vacations [10].

2. METHOD

It is well known that for calculation of vehicle emissions it is necessary to know vehicle emission factors and vehicle activity. For the purpose of emission calculation in this study, the emission factor implemented in the COPERT: Street Level were used, and they can be seen in the Figures 6, 7, 8 and 9. Vehicle activity was recorded on multiple sites throughout the City of Zagreb as shown in Figure 2.

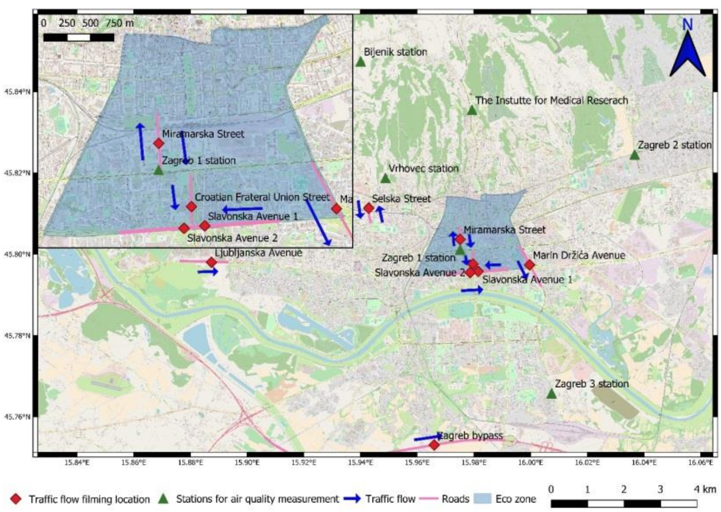


Figure 2. Main steps in ELV recycling process, according to EC Directive 2005/64/EC

2.1 Traffic Flow

Traffic flow is a simultaneous movement of a number of vehicles on a certain road segment in some ordered way. To describe traffic flow, it is necessary to define the basic traffic flow parameters. For the determination of these parameters, traffic was recorded using a GoPro Hero camera which has the ability to capture 50 frames per second at 2704x1520p (2.7k) resolution. Purpose of this camera was to accurately determine the exact moment when a vehicle passing across the detection line, as it is shown in Figure 3. Traffic flow recording locations are marked with red squares in Figure 2.

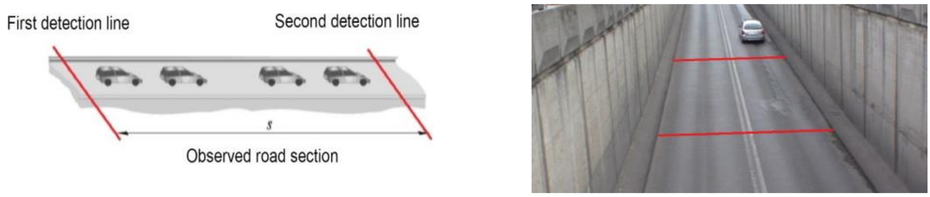


Figure 1. Example of observed road segment with detection lines (left - scheme, right - real situation) [11]

Basic traffic flow parameters are:

- Traffic flow –number of vehicles passing through the observed cross-section of the road in the unit of time, q_{veh} [veh/h];
- Traffic flow density – number of vehicles in the observed traffic lane per length unit, g [veh/km];
- Traffic flow speed – median value of speed from all vehicles involved in the traffic flow, v_{tf} [km/h];
- Vehicle passing interval – time between the passing of two consecutive vehicles through the observed cross-section on the road, t_h [s].

$$\Delta t_{h,x} = \frac{f_{L2} - f_{L1}}{50} \tag{1}$$

Where:

$\Delta t_{h,x}$ - vehicle x passing time, s

f_{L1} - frame number of front axle passing over the first detection line

f_{L2} - frame number of front axle passing over the second detection line.

After calculation of vehicle passing time, it was possible to determine vehicle speed according to equation 2.

$$v_x = \frac{\Delta s}{\Delta t_{h,x}} \tag{2}$$

Where:

v_x - vehicle x speed, m/s

$\Delta t_{h,x}$ - vehicle x passing time, s

Δs - distance between detection lines (17 m).

Traffic flows were recorded in February and March 2017 at eight locations on working days. Most of the city roads have similar peak hour interval as shown in Figure 4, so data was analysed for the period from 16:15 to 17:15. Figure 4 shows hourly traffic flow during the whole week at the intersection of Ljubljanska Avenue and Puljska Street and afternoon peak hour can be clearly seen.

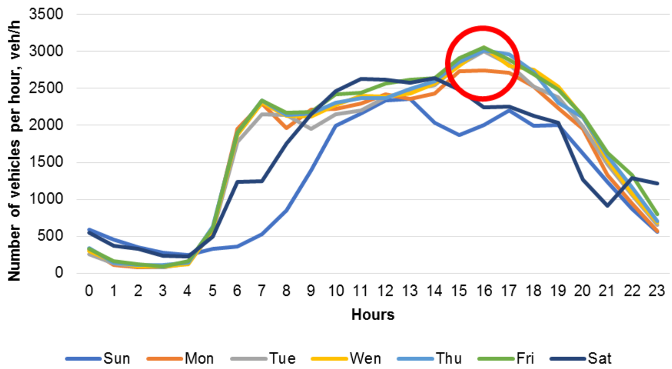


Figure 2. Example of weekly traffic flow

As it is earlier stated, for emission calculation it is important to define the traffic flow speed. After calculating the speed for all vehicles, the median value was used. The median value represents value separating higher and lower half of all calculated speeds. The median value is used instead of the arithmetic mean value because it is less sensitive to extreme value oscillations. Figure 5 shows an example of the median value of speed at Slavonska Avenue 1.

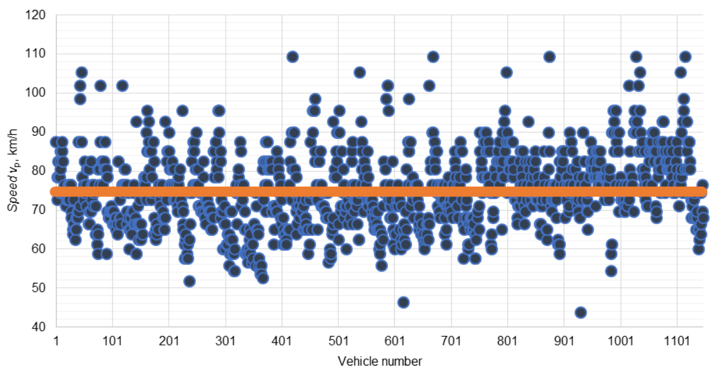


Figure 3. Example of the median value of speed at Slavonska Avenue 1

2.2 Vehicle fleet

For the purpose of calculating emission of harmful substances, it is necessary to determine vehicle fleet on the observed roads. One of the ways would be to record every vehicle registration plate and verify vehicle characteristics through the database of the Ministry of Interior, which is very slow and time-consuming process. For that type of vehicle fleet recognition, it would be better to use the specialised camera for number plate's recognition.

Other way, used for the purpose of this research, is to use predefined vehicle fleet composed of all the vehicles that had an active periodic technical inspection (PTI) in the City of Zagreb on the date of January 1st 2018. This way vehicle fleet definition was much easier and quicker, while still precise enough for the calculation of roadside emission. By using this method, the majority of the vehicles registered in the City of Zagreb that are not used in the city are left out and vice versa. Fleet is structured from all the vehicles from M1 and N1 category as they represent more than 90% of all vehicles entering the city. In addition, all the vehicles of M1 and N1 category which use compressed natural gas (CNG) or liquefied petroleum gas (LPG) are not included in the fleet mostly because they represent a small fraction, but also because it was not possible to precisely define their emission factor.

Table 1. Number of vehicles that had an active periodic technical inspection (PTI) in the City of Zagreb on the date of January 1st 2018 according to the emission standard

Category	Fuel type	EURO 0&1	EURO 2	EURO 3	EURO 4	EURO 5	EURO 6
M1	PETROL	9,390	25,856	28,840	44,518	20,730	13,872
	CNG (total)	13					
	DIESEL	6,526	12,293	34010	44,680	43,445	28,316
	LPG (total)	11,908					
M1 (total)	/	27,897	38,149	62850	89,198	64,175	42,188
N1	PETROL	41	57	128	171	239	120
	CNG (total)	32					
	DIESEL	778	1,716	3,895	6,716	8,893	2,939
	LPG (total)	224					
N1 (total)	/	1,115	1,773	4,023	6,887	9,132	3,059

As it is shown in Table 1, there are 324,457 vehicles of M1 category in everyday traffic across the City of Zagreb. It can be clearly seen that diesel vehicles are most represented type with 52.17%, gasoline vehicles are following with 44.14%, vehicles powered by LPG are present with 3.67% while CNG vehicle holds a neglect able share of the M1 fleet.

Following the M1 category, there is N1 category with 25,989 vehicles operating across the City of Zagreb. Again, diesel vehicles are the most represented type with 95.95% followed by gasoline vehicles with only 2.91%. Vehicles of N1 category powered by liquefied petroleum gas and compressed natural gas hold 1.14% combined. Overall, it can be assumed that there are around 350,446 vehicles involved in everyday traffic across the City of Zagreb. Average vehicle age of these vehicles is over 10 years. Disregarding vehicle powered by LPG and CNG and looking by emission standard it can be seen that Euro 0, Euro 1 and Euro 2 represent high 16.75% and if we add up Euro 3 vehicles, number crosses over one-third of entire vehicle fleet with 36.52%, which is extremely high.

2.3 Emission Calculation

After traffic flow calculation and vehicle fleet description, the last step in emission calculation is the definition of emission factors. Emission factors need to be from reliable source, e.g. internal combustion engine manufacturer, environmental agency etc. Emission factors used for this research are compiled from emission factors from COPERT: Street Level, a commercial software package used for calculation of emission on street level [12]. Emission factor represents a functional link between vehicle fleet characteristics, vehicle activity and emission. Emission factors of particulate matter and nitrogen oxides can be seen in Figure 6, 7, 8 and 9.

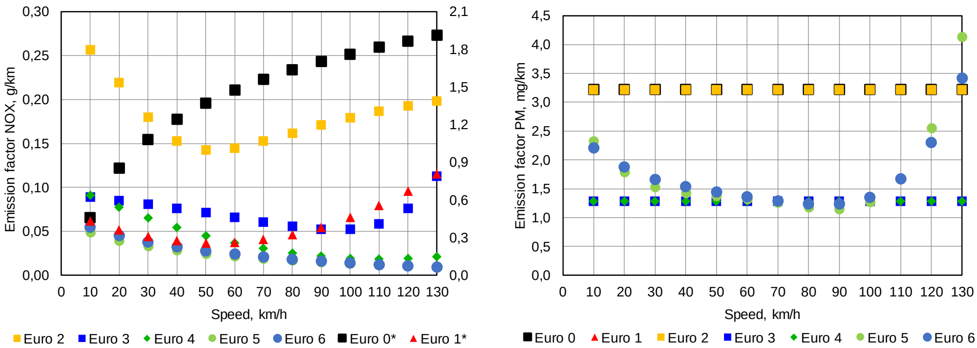


Figure 6. Emission factors for NOX (left) and PM (right) for M1 vehicle category (petrol) - * secondary axis

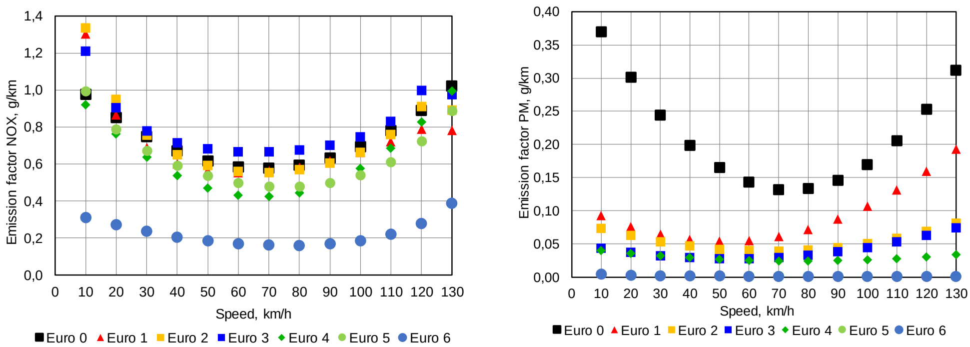


Figure 7. Emission factors for NOX (left) and PM (right) for M1 vehicle category (diesel)

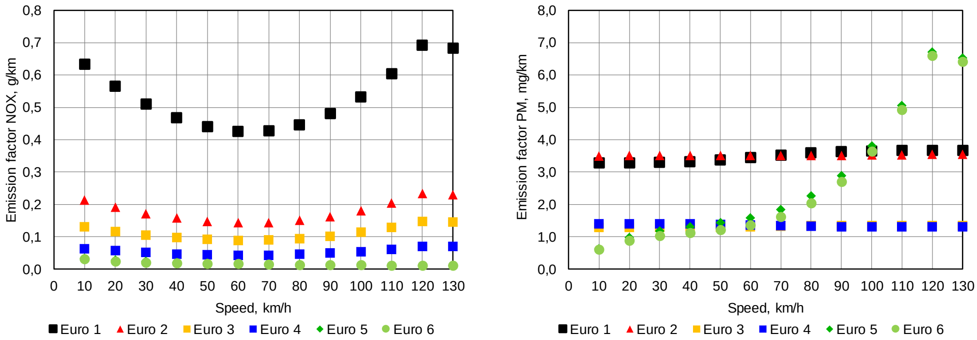


Figure 4. Emission factors for NO_X (left) and PM (right) for N1 vehicle category (petrol)

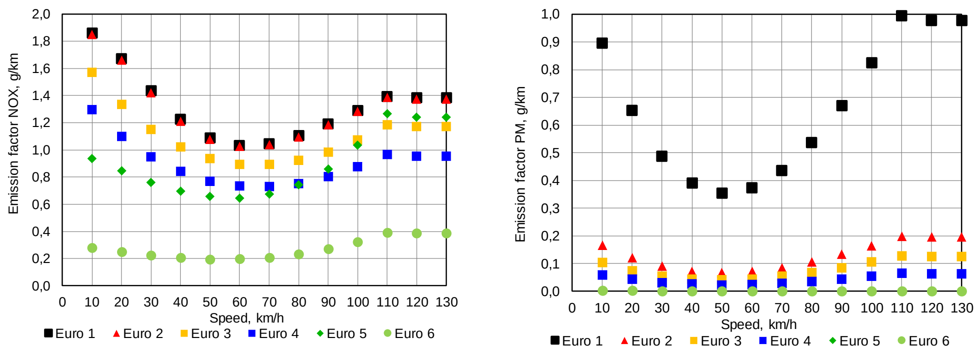


Figure 5. Emission factors for NO_X (left) and PM (right) for N1 vehicle category (diesel)

Vehicle activity is represented through vehicle fleet characteristics, traffic flow, length of a road segment and vehicle speed. The basic equation for calculation of roadside emission is:

Emission = Vehicle activity(speed, type, number, ...) x Emission factor (3)

By implementing this method, it is possible to calculate roadside emission from traffic in the specific time period on the observed road segment. In this research, the emission is calculated for eight observed road segments. For emission calculation, according to this method, it was necessary to define overall vehicle number and divide them according to fleet characteristics, add travelled distance and median speeds to all vehicles and allocate them their unique emission factor as shown in Equation 4.

$$E_p[g] = \sum_{FUEL} \sum_{EURO} \sum_{j=1}^{n} EF_p(EURO, v) \left[\frac{g}{km}\right] \text{x } s\ [km] \qquad (4)$$

Where:

E_p -Overall emission of a specific pollutant

FUEL -Fuel type (petrol or diesel)

EURO -Emission standard
N -Vehicle number
EF_p -Emission factor of specific pollutant as a function of emission standard and vehicle speed
p -Specific pollutant (NO_X or PM)
v -Vehicle speed
s -Travelled distance.

2.4 Scenarios

Before the development of different scenarios, the base case (Scenario 0) was calculated and analysed for before mentioned composition of the vehicle fleet. After the base case was established, several other scenarios were developed. Scenario 1 represents LEZ with the ban of all Euro 2 or lower emission standard vehicles with petrol engines and all Euro 3 or lower emission standard vehicles with diesel engines and the same goes for Scenario 2. The difference is that Scenario 1 represents a condition in which total traffic flow vehicle number is lowered for the share of banned vehicles which in return represents starting state of LEZ implementation. In other hand, Scenario 2 represents a state where the number of all vehicles banned by LEZ implementation is returned to the normal state by other vehicles which in return shows long-term effect.

Table 2. Vehicles permitted to enter LEZ by emission standard and category

Scenario	Fuel type	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6	Vehicle category	
									M1	N1
Scenario 1 & 2	Petrol	✗	✗	✗	✓	✓	✓	✓	✓	✓
	Diesel	✗	✗	✗	✗	✓	✓	✓	✓	✓
Scenario 3	Petrol	✓	✓	✓	✓	✓	✓	✓	✓	✗
	Diesel	✓	✓	✓	✓	✓	✓	✓	✓	✗

3. RESULTS

The busiest street during the peak hour with 2296 vehicles is Hrvatske Bratske Zajednice Street and is closely followed by Selska Street and Slavonska and Ljubljanska Avenue. Miramarska Street has least vehicle passages during the peak hour which is slightly under 1600 vehicles. On the other hand, Zagreb bypass has the fastest moving traffic with a median speed of 93 km/h, while the slowest traffic can be observed on Slavonska Avenue if a traffic jam occurs. If there is no traffic congestion, Miramarska Street traffic becomes the slowest moving with the median speed of 37 km/h and Slavonska Avenue traffic becomes one of the fastest with median speed over 70 km/h. Largest observed road section is Zagreb bypass with well over 4 kilometres, while the length of Ljubljanska Avenue observed road section is only 380 meters.

Table 3. Road measurement data and specific road emissions with possible reductions to the base scenario

Location	Traffic flow, veh/h	Vehicle speed, km/h	Observed road section, km	Harmful emission	Scenario 0 (Base case), g/km	Scenario 1		Scenario 2		Scenario 3	
						g/km	%	g/km	%	g/km	%
Slavonska Avenue (regular traffic)	2059	72	1.65	NO_X	552	296	46%	313	43%	518	6%
				PM	40	24	80%	8	79%	39	3%
Slavonska Avenue (traffic jam)	1616	15	1.65	NO_X	1536	527	66%	962	37%	779	49%
				PM	64	12	81%	35	46%	24	62%
Hrvatske bratske zajednice Street	2296	50	0.55	NO_X	740	429	42%	440	41%	622	16%
				PM	47	11	77%	11	77%	44	8%
Marin Držić Avenue	1721	57	1.17	NO_X	532	303	43%	312	41%	446	16%
				PM	35	8	78%	8	78%	32	7%
Ljubljanska Avenue	2166	78	0.38	NO_X	666	371	44%	379	43%	550	17%
				PM	47	11	78%	11	78%	42	11%
Selska Street	2123	40	0.52	NO_X	750	442	41%	456	39%	633	16%
				PM	46	12	75%	12	75%	44	4%
Miramarska Street	1596	37	0.58	NO_X	634	397	38%	417	34%	543	14%
				PM	36	9	76%	9	76%	34	5%
Zagreb bypass	1759	93	4.24	NO_X	596	335	44%	344	42%	489	18%
				PM	43	8	81%	8	80%	38	12%

Emission calculation for the base case (Scenario 0) shows that despite the small number of 1,616 vehicles per hour, congestion on Slavonska Avenue causes greatest specific emission of NOX (1,536 g/km) and PM (64 g/km). The reason behind that is a very small median traffic speed of just 15 km/h. According to the emission factor in Figures 6, 7, 8, 9 and 10 low vehicle speed can cause a significant increase in harmful emission. If only roads with regular traffic were observed, greatest specific emission of NOx would be on Selska Street with 750 g/km, while for particulate matter it would be on Ljubljanska Avenue and Hrvatske Bratske Zajednice Street with 47 g/km.

Scenario 1 shows large reduction in specific emission for all observed roads. Emission of NOX can be reduced in the range of 38% to 66% while particulate matter shows an even greater reduction in the range of 75% to 81%. For nitrogen oxides, the greatest reduction would be achieved during the congestion on Slavonska Avenue while on the other roads reduction would be around 40%. Once again, it is necessary to mention that this scenario shows a reduction that would occur right after Low Emission Zone implementation and mainly as a result of vehicle number reduction. After the introduction of LEZ, it takes time for vehicle number to increase to its regular value.

Scenario 2 shows specific emission values after banned vehicles are replaced with newer ones. It can be seen that after the vehicle fleet stabilisation reduction from 34% to 43% can be achieved for NOx and 46% to 80% for particulate matter. The minimum reduction is achieved on Miramarska Street because of a small number of vehicles, while the greatest reduction is on Slavonska and Ljubljanska Avenue. In the case of particulate matter, the majority of streets could achieve a reduction up to 80%, while congested Slavonska Avenue could achieve minimal but still significant reduction of 46%.

Scenario 3 in which ban of all N category vehicles is being simulated represents a solution for incensement of traffic speed. Vehicles of this category are often responsible for slowing down traffic. With this kind of restriction, it is possible to reduce NOx and particulate matter emission by less than 20%. A significant difference can be seen during traffic jam where 49% of NOx emission reduction is achieved and 62% particulate matter emission reduction. This fact shows how vehicles of this category contribute to roadside emission during the traffic jam. If some type of congestion regulation was implemented, it would have a two-sided effect. Firstly, it would greatly reduce emission and secondly it would increase traffic speed which in return would have an even further reduction in emissions.

Despite the highest number of vehicles on Hrvatske bratske zajednice Street does not stand out in specific emission nor in emission reduction. Reason for this lies in the traffic speed. Emission factor shows that traffic speed of around 60 km/h has the advantage of low emission of harmful substances. The same thing goes for Marin Držić Avenue where the lowest specific emission is achieved for both particulate matter (35 g/km) and nitrogen oxides (532 g/km) because of its median speed of 57 km/h.

4. DISCUSSION

The most of Low Emission Zones already introduced in cities of Europe have less restrictive emission standard than one proposed in this research. Reason for the proposal of such a high standard lies in the fact that every major LEZ was introduced 10+ years ago and have set higher goals for the future. Implementation of LEZ in Zagreb takes time, and by the time it would be introduced, LEZ with lower standards will have the same or stricter standards than those proposed in this research. For example, authorities in London have set a goal for Euro 4 petrol vehicles and Euro 6 diesel by 2020 which is a lot higher standard than proposed. Similarly, Brussels plans to introduce Euro 2 petrol and Euro 4 diesel by 2020 and Euro 3 petrol and Euro 6 diesel by 2025 [13]. Traffic was analysed on distinctive road segments across City of Zagreb for the purpose of traffic modelling [11]. As it is evident, each and every observed road segment is specific and different from others, but the result of emissions reduction are still very similar and intuitive. This states that overall percentage emission reduction does not lie within the road segment type or traffic flow but in its speed and vehicle fleet composition. Vehicle fleet composition and emission factors showed that traffic speed has significant influence in the specific emission of harmful substances. When talking about traffic speed, there are two relevant facts that need to be considered. Firstly, because of the large variety of traffic speeds over the observed road segments, it can be considered that same results could be applied on roads across proposed LEZ according to their own traffic speeds, meaning that the same results would be achieved over roads with traffic speed similar to those observed. Secondly, traffic congestion has the largest specific emissions, and the reason for this is low vehicle median speed, despite small overall vehicle number. To ensure reduction of congestions specific emission, it is necessary to increase medial vehicle speed towards optimum of approx. 60 km/h. This could be achieved with better traffic organisation during daily traffic peak hours or by some sort of congestion charge.

The biggest concern lies in particulate matter (PM), especially PM2.5 because the general rule says that the smaller the PM, the more dangerous it is to human health. Also, it is quite difficult to define minimum value at which particulate matter is harmless to human health, so this represents the reason why it should be closely monitored and kept at its minimum level. As it is shown earlier, depending on the type of the street, particulate matter can be reduced from 46% to 80%. Studies have found that there is a 7% increase in mortality with every 5 micrograms per cubic metre increase in the particulate matter [14]. Therefore a huge accomplishment could be achieved if some type of LEZ is implemented in the City of Zagreb. Although particulate matter represents the biggest concern in cities, by implementing Low Emission Zone nitrogen oxides would also be affected. As it is earlier shown, by implementing some kind of restriction it is possible to reduce nitrogen oxides in the range of 34% all the way up to 43%. Nitrogen oxides are a big concern not only to human health but the environment as well [15]. Many European cities struggle with the balance of congestion, 'liveability', air pollution, noise levels, accessibility, damage to historic buildings and other pressures of urban life. As shown earlier, many cities have levels of pollution that adversely affect health. Also, congested, polluted, noisy cities are not attractive for businesses, residents or tourists. Congestion also has a significant impact on the economy, costing nearly €100 billion, or 1% of the EU's GDP [16]. The different types of traffic regulation zones can reduce traffic and congestion in a city, and ensure that those that need to travel with a vehicle can travel rather than sit in a traffic jam. In addition, noise contributes to at least 10,000 cases of premature mortality each year and almost 90% of the health impact caused by noise exposure is associated with road traffic noise [17]. According to the data gathered by Center for Vehicles of Croatia, average M1 category vehicle age stands at 12.95 years while for N1 category is slightly lower at 11.09 years. Older vehicles increase safety concerns in traffic. Research done by the Center for Vehicle of Croatia show that vehicle age has a high influence on vehicles technical validity and roadworthiness. By implementing the Low Emission Zone, it would help to reduce the high age of the fleet and ensure better traffic safety.

5. CONCLUSIONS

Conducted research has shown that the City of Zagreb deals with the problem of high emission of harmful substances derived from traffic. In order to deal with this problem, it is necessary to implement some sort of a Low Emission Zone which primary purpose would be to ensure greater air quality and cleaner environment for all of the city's residents. By conducting this research on various types of urban roads during peak hours of traffic, it is shown that it is possible to improve current condition regarding roadside air pollution by the introduction of LEZ. Measured traffic flow parameters, in terms of vehicle activity, were combined with vehicle fleet composition and appropriate emission factors. This made it possible to develop emission equations which were used for theoretical determination of roadside emission and possibilities for its reduction. Results showed that it is possible to achieve great emission reduction by changing vehicle fleet composition. Furthermore, it would also help reduce overall vehicle number which would increase road safety.

By conducting this method during the traffic peak hour, it is estimated that the introduction of LEZ would help achieve improvement in air quality in the City of Zagreb. By applying Scenario 1, it is possible to reduce NOx emissions by significant 66% and PM emissions all the way up to 81%. Once again, it is important to note that Scenario 1 represents a starting state of LEZ implementation with much lower traffic flow. Long-term achievement is accomplished with Scenario 2 which represents traffic flow stabilisation. By Scenario 2 it is possible to reduce around 40% of NOx emission and 80% PM emission. Scenario 3 showed that great reduction could be achieved by regulating light-duty vehicles during traffic congestions, while not much reduction is achieved during regular traffic.

In order to have a more detailed look into roadside emission and impact of LEZ introduction, further research should be directed towards including more road segments from inside the LEZ. Automatic counters, speed measuring tools and plates recognition software should be used in order to minimize field work and reduce measuring error possibilities. That kind of automated analysis would make it possible to develop software for gathering real-time emission estimation and combine it with air quality measuring stations in order to see their more detailed correlation.. If we want to avoid that scenario, we need to change our way of thinking, to educate young generations indicating the importance of environment protection and to act “green”

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POSSIBILITIES FOR THE USE OF BIOFUELS IN EUROPE AND IN SERBIA

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RESEARCH ARTICLE

ABSTRACT: Biomass is one of the major potentials of renewable energy sources in Serbia. Due to the lack of legal acts, regulations, and incentive systems by the state, this potential has not been sufficiently utilized. According to some estimates, the theoretical potential of biomass in Serbia amounts to about 3.2 million equivalent tonnes of oil. This paper gives an overview of the existing situation in Serbia, including a set of measures necessary to stimulate the production of biofuels, primarily for the purpose of more intensive development of agriculture, reduction of pollution of the environment, reduction of the import of crude oil and for the creation of new jobs. The aim of this paper is to present the possibilities, conditions, and obstacles in the production and use of biodiesel in Serbia, as well as the comparison of the use of biodiesel in the countries of the European Union. Special attention is paid to the economics of production and the ecological motive for the production of biodiesel, as well as the ability to reduce CO2 emissions and the environmental impact of transportation vehicles.

KEY WORDS: biofuel, renewable energy sources, transportation vehicles, environmental impact

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MOGUĆNOST KORIŠĆENJA BIOGORIVA U EVROPI I SRBIJI

REZIME: Biomasa je jedan od glavnih potencijala obnovljivih izvora energije u Srbiji. Zbog nedostataka pravnih akata, propisa i sistema podsticaja od strane države, ovaj potencijal nije dovoljno iskorišćen. Prema nekim procenama, teoretski potencijal biomase u Srbiji iznosi oko 3.2 miliona ekvivalenstnih tona nafte. Ovaj rad daje pregled postojeće situacije u Srbiji, uključujući niz mera neophodnih za stimulisanje proivodnje biogoriva, prvenstveno u cilju intezivnog razvoja poljoprivrede, smanjenja zagađenja životne sredine, smanjenja uvoza sirove nafte i stvaranje novih radnih mesta. Cilji ovog rada je da predstavi mogućnosti, uslove i prepreke u proizvodnji i upotrebi biodizela u Srbiji, kao i poređenje upotrebe biodizela u zemljama Evropske unije. Posebna pažnja je posvećena ekonomiji proizvodnje i ekološkom motivu za proizvodnju biodizela, kao i mogućnost smanjenja emisije CO_2 i uticaja transportnih vozila na životnu sredinu.

KLJUČNE REČI: biogorivo, obnovljivi izvori energije, transportna vozila, uticaj na životnu sredinu

POSSIBILITIES FOR THE USE OF BIOFUELS IN EUROPE AND IN SERBIA

Ivana Terzić, Vanja Šušteršič, Aleksandar Nešović, Mladen Josijević

1. INTRODUCTION

The total global oil consumption is almost 4 billion tonnes a year, whereas its reserves are estimated at around 120-160 billion tonnes, which represents one of the major problems in the field of energy. On the other hand, the natural and technical potential of renewable energy sources on a daily basis is about 20,000 times greater than the daily consumption of nuclear fuels and fossil fuels, together. Fossil fuels are largely the cause of global warming, generating the greenhouse effect through combustion. Spending on crude oil reserves and environmental problems related to its processing and utilization are the two main reasons why we should turn to bio-sources that convert into biodiesel and bioethanol.

Biofuels in the narrower sense include fuels derived from biomass and used for transportation purposes. This category of fuel includes methane, gas produced by the gasification process, alcohols, esters and other chemicals derived from cellulosic biomass. The basic raw materials for the production of biofuels are plant and tree plantations, sugar and oil crops, agricultural and forestry residues, as well as individual fractions of municipal and industrial waste. Oil reserves are steadily decreasing, so developed countries have been intensively engaged in biomass production processes over the past decade. In Europe, rape oil (82.8%) and sunflower oil (12.5%) are used as the dominant raw material for the production of biodiesel, whereas soybeans are used in the USA for the production of biodiesel [14]. Biodiesel is a non-toxic and biodegradable motor fuel derived from rapeseed oil or other vegetable oils (sunflower, palm, soybean oil) through esterification with methanol as well as from animal fats and recycled oils (Fig 1) [2, 14].

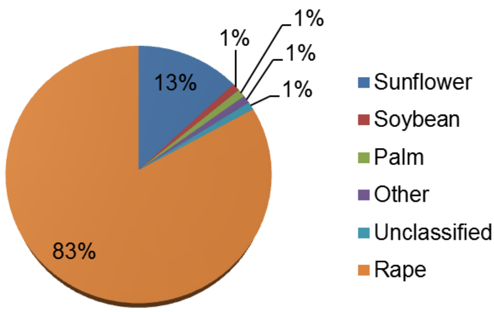

Figure 1. Graph of the most important raw materials for the production of biodiesel

In developed countries, already used oils and animal fats can be further utilised in the production of biodiesel. Such an environmentally friendly and renewable energy source is used as a substitute for mineral diesel. The use of pure biodiesel reduces the emission of harmful gases (NOx, CO2, SO2) and solid particles, does not contain sulfur, lead, nitrogen, toxic aromatic compounds, and is biodegradable so that its use reduces environmental pollution. Biodiesel is commonly used as a mineral oil additive to reduce emissions of solid particles, carbon dioxide, aromatic hydrocarbons, and other air pollutants resulting from the combustion in conventional diesel engines. Mixtures of a maximum of 20% biodiesel with mineral diesel can be used without the requirement to modify the engine in almost all conventional diesel engines. By-products in biodiesel production (such as glycerine, lecithin, and fatty acids) can be used in the pharmaceutical and cosmetic industry, whereas by-products from bioethanol production can be used as protein-rich foods [17].

One of the goals of the European Commission Directive 2009/28/EC [7], is to have 10% of energy demand in the transportation sector covered by the renewable energy sources (RES) by 2020. In other words, 50 billion litres of fossil fuels in the European Union (EU) will be replaced by biofuels [3]. In the United States, the Energy Act [4] (passed in 2005) and the 2007 Energy Security and Safety Act [5] both promote RES, including biomass primarily through liquid biofuels, and set the target of producing 136 billion litres of biofuel for the transportation sector in 2022. According to some forecasts, it is expected that more than 5% of the fuel in the road sector and 1% in air transportation in the world will be replaced by biofuels by 2030 [6]. Considering the great importance the biofuels have in the transportation sector, as well as the forecasts for their higher demand, the aim of this paper is to review currently available conventional liquid biofuels including advanced liquid biofuels and compare their properties with fossil gasoline and diesel, indicating the appropriate raw materials and the paths of their conversion. The work additionally contributes to the definition and differentiation in terminology of the basic concepts related to biomass and the classification of biofuels.

2. BIOFUELS AND THEIR DIVISION

According to the European Directive 2009/28/EC [7] and the National Action Plan for the Use of Renewable Energy Sources of the Republic of Serbia [13], based on the Directive, biofuels represent liquid or gaseous fuels produced from biomass and used in transportation. There are different approaches to the classification of biofuels considering the large variety of raw materials and the diversity of the involved conversion processes, which are evolving towards sustainability and the required fuel quality standards. The most commonly used biofuel classification in the literature [8, 14, 15], includes the following generations:

- 1st generation biofuels: bioethanol, biodiesel, vegetable oils (SVOs or "Pure Plant Oil" - PPO) and biogas / landfill gas
- 2nd generation biofuels (2G): bio alcohols (cellulose ethanol, bio methanol), BtL fuels (synthetic liquid fuels produced by thermo-chemical conversion of biomass, for example FT diesel and FT kerosene), biodiesel from waste materials, HTU diesel (bio DMF), hydro treated vegetable oils (renewable diesel), bio-dimethyl ether (bio DME), bio-synthetic gas (bio SNG) and bio-hydrogen
- 3rd generation biofuels (3G): algae biofuels (for example, algae bio alcohols, biodiesel and BtL fuels)
- 4th generation biofuels (4G): biofuels produced using genetically modified organisms, such as photosynthetic microalgae with a higher proportion of lipids and the ability to use larger amounts of carbon dioxide than those commonly used for photosynthesis processes, this way participating in carbon sequestration processes (removing carbon dioxide from the atmosphere) and consequent reduction of the greenhouse effect [8, 12, 18].

Figure 2 shows the classification of energy sources and their share in total global energy consumption [9].

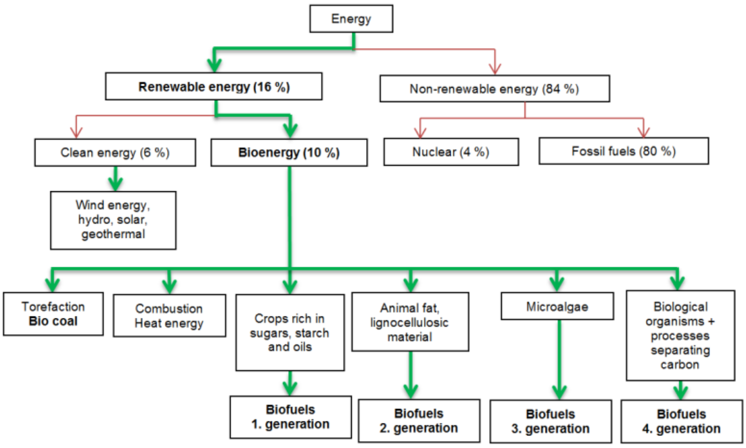

Figure 2. Classification of energy sources with the contribution to the global energy consumption [9]

Depending on the soil quality and climatic and economic conditions, different raw materials can be used to obtain biodiesel (see Table 1). In order to reduce the costs of biodiesel production, alternative raw materials are considered, such as inert vegetable oils and used oils and fat [9, 14].

Table 1. Row materials for biodiesel production [9]

Raw material for biodiesel production	Country
Soybean oil	USA, Brazil
Rape oil (80%) and sunflower oil (20%)	Europe
Palm oil	Indonesia, Malaysia
Flax and olive oil	Spain
Vegetable oils / animal fats	Canada
Animal fats, beef cattle and rapeseed	Australia

2.1 World total biofuel production and consumption

World total biodiesel production for the year 2017 in different countries is shown in Figure 3. With a production volume of around 3.3 billion litres, Argentina was ranked fourth that year. The United States and Brazil were among the largest biodiesel producers in the world, totalling some 6 and 4.3 billion litres, respectively. The United States are projected to reach production levels of over 1 billion gallons[1] of biodiesel by 2025. After the implementation of the Energy Policy Act of 2005 [4], which provided tax incentives for certain types of

[1] 1 gallon=3.79 l

energy, biodiesel production in the USA began to increase. The Volumetric Ethanol Excise Tax Credit is currently one of the main sources of financial support for biofuels in the USA. In 2010, the USA exported about 85 million gallons of their biodiesel products. Comparatively, Argentina accounted for over half of the world's total exports. The United States have one of the highest bioenergy capacities in the world, totalling 13,151 megawatts in 2017. Today, biofuels provide around 3% of total road transportation fuel consumption globally on an energy usage basis. Consumption of these fuels in some countries is considerably higher. According to International Energy Agency (IEA), Brazil met about 23% of the road transportation fuel demand with biofuels in 2009. IEA analysis shows that biofuels may have to play an important role if the world is to make meaningful reductions in carbon dioxide emissions and reduce reliance on crude oil at costs similar to those of gasoline and diesel in the medium-term. Global biofuels production and consumption are on the rise. According to the US Energy Information Administration (USEIA), there is no record found on biodiesel production and consumption before 2000. Most of the countries started using biofuel in the last decade. Many more countries are in the early stages of using biofuel and they are trying to develop the infrastructure and production technologies to follow the suite. Leading countries based on the biofuel production in 2017 (in 1,000 metric tonnes of oil equivalent) are presented in Figure 4, which indicates that the USA produced around 80% of the total biofuel in the world. Europe, Asia and Oceania are increasing their biofuel production. The remaining countries are in their initial stages of production.

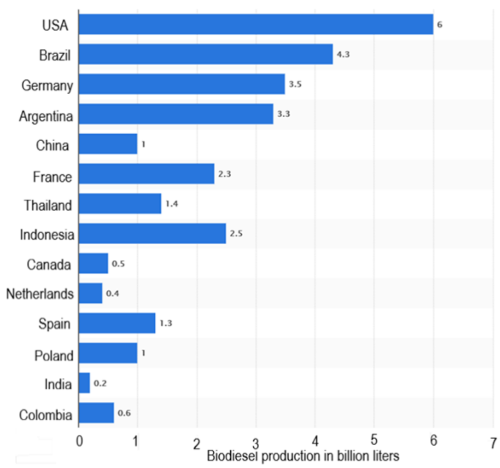

Figure 3. World total biofuel production in 2017 [24]

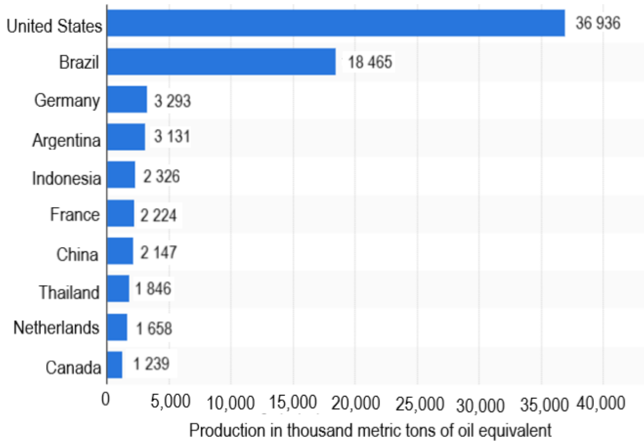

Figure 4. The leading countries based on biofuel production in 2017 (in 1,000 metric tonnes of oil equivalent) [24]

This statistic represents the leading countries in biofuel production in 2017. In Germany, production reached around 3.3 million metric tonnes of oil equivalent that year. That means, Germany is among the global top three countries in biofuel production.

2.2 Biofuel production in the Americas

Biofuels are characterized by fuels that obtain their energy through the process of biological carbon fixation. These hydrocarbons are made by or from living organisms in a relatively short period of time - in comparison to the formation of fossil fuels which requires millions of years. The United States were by far one of the largest producers of biofuel in the world in 2016, accounting for 43.5 percent of global biofuel production (Table 2, Figure 5) The country produced 35 million metric tons of oil equivalents that year, while Brazil produced 18.2 million metric tons of oil equivalents. Global biofuel production has gradually increased from 9.2 million metric tons of oil equivalents in 2000 to 84.12 million metric tons of oil equivalents in 2017.

Biofuels are commonly used as part of mixtures with fossil fuel sources or as additives. One of the largest consumers of biofuels in the USA is the national army. Many vehicles can be fueled using blends containing up to 10 percent of ethanol. In the beginning of the 20th century, many Ford T models were fueled with ethanol. Biofuels can also be generated through the consumption or conversion of biomass material. This conversion can occur thermally, chemically, or biochemically. Biomass consumption in the United States totaled 4,696 trillion British thermal units[2] in 2015.

[2] 1Btu=1.054 kJ

Table 2. Biofuels production [22]

Thousand tonnes oil equivalent	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Growth rate per annum			
											2016	2016	2005-15	Share 2016
US	10,670	14,709	20,934	23,761	28,044	31,184	29,808	31,057	32,890	33,849	35,779	5.4%	15.2%	43.5%
Canada	174	503	546	786	809	950	1,017	1,056	1,188	1,142	1,160	1.2%	22.8%	1.4%
Mexico	-	5	5	5	14	13	15	58	58	58	58	-	-	0.1%
Total North America	10,844	15,216	21,485	24,552	28,866	32,147	30,840	32,171	34,137	35,049	36,997	5.3%	15.4%	45%
Argentina	30	173	635	1,055	1,670	2,234	2,295	2,014	2,644	2,038	2,828	38.4%	71.7%	3.4%
Brazil	9,590	12,427	15,486	15,277	16,866	14,403	14,739	17,114	18,005	19,332	18,552	-4.3%	8.4%	22.5%
Colombia	144	155	158	320	455	572	627	650	676	693	626	-10%	46.2%	0.8%
Other S.& Cent. America	513	596	806	634	229	310	300	354	378	379	373	-1.9%	6.5%	0.5%
Total S. Cent. America	10,278	13,351	17,085	17,285	19,220	17,519	17,961	20,131	21,703	22,442	22,378	-0.6%	9.8%	27.2%
Total Europe & Eurasia	5,269	7,021	8,482	10,646	11,604	10,876	11,734	12,503	14,445	14,012	13,777	-1.9%	15.5%	16.7%
Total Africa	9	6	11	18	8	8	23	32	40	40	40	-	20.5%	0.05%
Total Asia Pacific	1,446	1,876	3,074	3,435	4,306	5,280	6,300	7,450	9,374	8,476	9,110	7.2%	25%	11.1%
Total World	27,848	37,471	50,138	55,936	64,008	65,834	66,863	72,293	79,703	80,024	82,306	2.6%	14.1%	100%

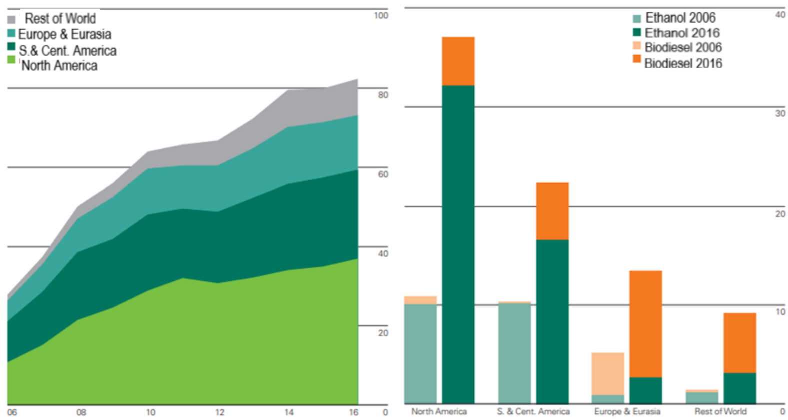

Figure 5. World biofuels production (million tonnes oil equivalent) [22]

Global biofuels production rose by 2.6 % in 2016, well below the 10-year average of 14.1 %, but faster than in 2015 (0.4%). The USA provided the largest increment (1,930 thousand tons of oil equivalent, or ktoe). Global ethanol production increased by only 0.7 % partly due to falling production in Brazil. Biodiesel production rose by 6.5 % with Indonesia providing more than half of the increment (1,149 ktoe).

World biofuels production increased by 3.5 % in 2017, well below the 10-year average of 11.4 %, but the fastest for three years. The US provided the largest increment (950 thousand tons of oil equivalent, or ktoe). By fuel type, global ethanol production grew by 3.3 %, contributing over 60 % to total biofuels growth. Biodiesel production rose by 4 % driven mainly by growth in Argentina, Brazil and Spain [22].

Global biofuel market is dominated by the USA in North America and Brazil in Central and South America. They have been producing huge amount of biofuels annually and trying to meet their major part of transportation fuel demand with biofuel. Currently, Brazil produces 27 billion liters bioethanol annually which is supported by the development of new sugarcane varieties and agricultural technologies. The USA widely used bioethanol from corn and grain, and biodiesel from soybean as an alternative fuel. They also aimed to replace 30% of fossil fuel with biofuel while Europe is aiming for 5.75% [1].

2.3 Production of biodiesel in the EU

The USA is the world's largest biodiesel producer. Biodiesel is also the most important biofuel in the EU and, on an energy basis, represents about eighty percent of the total transport biofuels market. Biodiesel was the first biofuel developed and used in the EU in the transportation sector in the 1990s. At the time, rapid expansion was driven by increasing crude oil prices, the Blair House Agreement and resulting provisions on the production of oilseeds under Common Agricultural Policy set-aside programs, and generous tax incentives, mainly in Germany and France. EU biofuels goals set out in Directive 2003/30/EC (indicative goals) and in the RED 2009/28/EC (mandatory goals) further pushed the use of biodiesel.

In 2017, EU FAME[3] and HVO[4] production did benefit from higher domestic consumption, as elevated imports only commenced in September that year. FAME production increased by 5 percent, mainly due to expansion in Spain, Italy, Portugal, Belgium, and Poland. HVO production increased by 5 percent, driven by elevated production in the Netherlands and Spain, and a new co-processing unit coming into production in Portugal (Tables 3 and 4).

Table 3. EU FAME Main Producers (Million Litres) [23]

	2011^r	2012^r	2013^r	2014^r	2015^r	2016^r	2017^e	2018^f
Germany	3,408	3,106	3,307	3,911	3,555	3,592	3,522	2,610
France	2,090	2,175	2,170	2,386	2,442	2,215	2,181	1,700
Spain	787	538	659	1,017	1,103	1,319	1,680	1,200
Netherlands	558	974	790	1,056	795	638	568	570
Poland	414	673	736	786	861	985	1,029	1,030
United Kingdom	261	352	640	554	572	496	503	510
Italy	704	326	521	452	625	398	599	560
Belgium/Luxemburg	536	568	568	568	535	521	568	570
Austria	352	301	247	332	386	349	352	365
Portugal	419	356	329	349	386	333	388	400
Other	1,667	1,214	604	203	811	977	1,007	1,375
Total	11,197	10,582	10,570	11,614	12,072	11,823	10,397	10,890

Ranked by production in 2018 r = revised / e = estimate / f = forecast.

Source: FAS EU Posts based on information in MT and converted to litres using a conversion rate of 1 MT = 1,136 litres

Table 4. EU HVO Production (Million Litres) [23]

	2009^r	2010^r	2011^r	2012^r	2013^r	2014^r	2015^r	2016^r	2017^e	2018^f
Netherlands	-	-	-	410	872	1,013	1,192	1,154	1,218	1,220
Finland	281	365	250	317	392	438	536	545	545	545
Spain	-	-	28	73	179	377	262	418	465	470
Italy	-	-	-	-	-	323	323	323	323	445
Portugal	-	-	-	-	-	-	-	-	32	32
France	-	-	-	-	-	-	-	-	-	128
Total	281	365	278	800	1,444	2,151	2,313	2,440	2,583	2,840

Ranked by production in 2018 r = revised / e = estimate / f = forecast.

Source: FAS EU Posts based on information in MT and converted to litres (conversion rate of 1 MT = 1,282 litres).

The structure of the EU biodiesel sector is very diverse and plant sizes range from an annual capacity of 2.3 million litres owned by a group of farmers to 680 million litres owned by a

[3] traditional first generation biodiesel
[4] hydrogenated vegetable oil

large multi-national company. Biodiesel (FAME) production facilities exist in every EU member state with the exception of Finland, Luxemburg, and Malta. In contrast, HVO production is concentrated in only six countries (Table 4). The majority of HVO capacity consists of dedicated HVO plants, while in Spain HVO is co-processed with conventional fuel in oil refineries. EU FAME production capacity is expected to decrease by 5 percent in 2018 to 20.3 billion litres, as plants are closed for good as a result of strong competition. In addition, numerous plants run below capacity or are temporarily shut down. For example, in Germany three plants announced to either temporarily (at least until the end of June) or until further notice run at half of their capacity. In France, Saipol announced that it would cut its production by between 400,000 and 600,000 MT in 2018. EU HVO production capacity is forecast to increase to 5.3 million litres in 2018, when two new facilities will start production in Italy and France [23].

3. PRODUCTION AND USE OF BIODIESEL IN SERBIA

The use of available energy sources is very high on the list of energy strategy priorities, primarily to meet energy needs, as well as to improve the conditions for energy production. By ratifying the Energy Community Treaty, the Republic of Serbia has accepted the obligation to adopt and implement a plan for the implementation of Directive 2003/30/EC on the promotion of the use of biofuels and other fuels from renewable energy sources in the transportation sector [21].

In Europe, biodiesel is defined in the standard EN 14214 in 2003, and in Serbia in the standard SRPS EN 14214 (standard for fuels for motor vehicles - fatty acid methyl esters for diesel engines) in 2006 [11]. EU Directive 2003/30/EC define biofuels and imposes on states the obligation to put 5.75% of biofuels on the market by the end of 2012 (of the total amount of fuel used in transport). Unfortunately, our country has not met the mentioned target for biofuels, and in the meantime a new EU directive 2009/28/EC has entered into force, which stipulates that by 2020, the target of 10% of biofuels will reach the market [7]. The proposal for the growth dynamics of RES share in the period from 2009 to 2020 in the transport sector is presented in Table 5.

In Serbia, over 600,000 hectares are available for the production of oil plants, which indicates that Serbia has the potential to produce biodiesel at the level of over 200,000 ton per year.

Tabela 5. Dynamics of growth of share Renewable energy source (%) in the sector of energy consumption [7]

2009 base year for the development of NAPOIE in accordance with the RES Directive 2009/28 / EC									
	2009	2013	2014	2015	2016	2017	2018	2019	2020
RNE – traffic (%)	0	0	0	2	3	5	7	8	10
NAPOIE – National Action Plan for Renewable Energy Sources									

In the European Union, one hectare of rapeseed provides enough grain to produce 1,090 litres of biodiesel fuel [10]. However, in Vojvodina, rapeseed, sunflower and soybean produce significantly lower yields than the European average (Fig.6). With an average seed yield of 1.69 t/ha, and oil seed content of 36%, 1 ha of rapeseed in Serbia provides 608 kg of oil or about 690 l of biodiesel fuel. The average yield of sunflower seed in Serbia is 1.79

t/ha, so with oil content 40% yield of sunflower biodiesel is 716 kg/ha or 816 l/ha. The average yield of soybean in Serbia is 2.25 t/ha, so the content of grain oil is 18%, yield of biodiesel 405 kg ha, ie 460 l/ha [19].

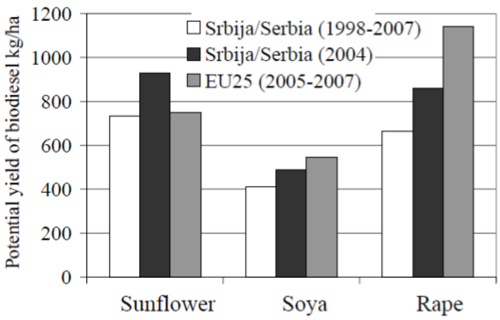

Figure 6. Potential yield of biodiesel per 1 ha of oilseed crops in Serbia and EU depending on the yield of oilseed crops [19]

The potential area in Serbia for cultivation of oilseeds for processing into biodiesel is estimated at approximately 350,000 ha (668,800[5] - (271,722[6] + 54,000[7])) (Table 6).

Theoretically, domestic biodiesel could be substituted by 13 to 16% of domestic fuel consumption (calculated on an energy basis). In fact, these figures are significantly smaller because of the impossibility of organizing economic production on crushed and intermittent agricultural holdings in Central Serbia.

For the organized production of large quantities of biodiesel, it is necessary consider the conditions and resources of raw materials for its production. The most important oilseeds produced in Serbia are: sunflower, soy and rapeseed rape. In Serbia, the sunflower is mostly cultivated over around 220,000 hectares on an annual basis, whereas the production of rapeseed is around 22,000 tonnes annually. In Serbia, there are sufficient cultivable areas meeting all the agro-technical conditions for growing rapeseed as a basic culture for the production of biodiesel. From the aspect of resources, this would provide the necessary conditions for Serbia to become an important European biodiesel producer. However, for the development of the biodiesel industry, it is necessary first of all to take measures at the state level to support investment in this sector of energy [19].

[5] Potential area for cultivation of oilseeds, 20% of the orange area
[6] for raw food oil
[7] from seeds and animal husbandry, from which 212,800 to 250,600 t of biodiesel could be provided

Table 6 Potential production of biodiesel on the area of 350,000 ha in relation to the sowing structure of oilseed crops [19]

Variants	Sowing structure	Potential production of biodiesel (t)	Potential substitution of fossil diesel with biodiesel	
			All sectors (%)	In agriculture (%)
I	100 % Oilseed Rape	212,800	13.49	46.67
II	70% Oilseed Rape 30 % Sunflower	224,140	14.21	49.16
III	50 % Oilseed Rape 50 % Sunflower	231,700	14.69	50.81
IV	70 % Sunflower 30 % Oilseed Rape	239,260	15.16	52.47
V	100 % Sunflower	250,600	15.88	54.96

3.1 Production economics and ecological motives for the production of biodiesel

One additional advantage of using biodiesel is that the consumer receives reliable and high-quality fuel at a lower price. For example, at petrol stations in the EU the difference between diesel and biodiesel is about 10 Eurocents per litre. The price growth trend in crude oil is much higher than in edible oil, which leads to the expectation that in the future biodiesel will be even more competitive. The production of renewable fuels leads to a reduction in imports of fossil fuels, which simultaneously affects exports. In order for biodiesel to be profitable, it is estimated that it must have the price that is about 8% lower than the price of fossil fuel.

Research in developed countries has shown that the environment is mainly polluted by motor vehicles (over 50%), then by thermal power plants and industrial plants. Fuel combustion emits many pollutants in the air, such as lead, inorganic chlorine and bromine compounds, hydrocarbons, nitrogen oxides, and sulfur oxides. For these reasons, the international community is increasingly compliant with the regulations that determine the quality of liquid petroleum fuels, (acceptable for the environment and human health), and increasingly stimulates the use of the fuel of plant origin (that have considerably reduce harmful emissions).

For the purpose of protecting the environment, a request is made that mineral fuel must contain as little sulfur as possible. Biodiesel does not damage the diesel engine. On the contrary, its increased lubricity compared to mineral diesel reduces the wear of vital parts of the engine. A mixture of biodiesel and mineral diesel reduces emissions of harmful gases, and maximum lubricity is achieved at 10% mixture [19].

Considering that in Serbia biodiesel is not yet widely used, the results of pollution testing using biofuels in Germany can be listed. The German Environmental Protection Association presented data of comparative testing conducted on 54 different diesel engines:

- CO2 emissions from biodiesel engines are 10% to 12% smaller than those from diesel engines
- Hydrocarbon emissions in biodiesel engines are 10% to 35% smaller
- Emission of solid particles in engines with biodiesel is less than 24% to 36%
- The soot emission for engines with biodiesel is 50% to 52% smaller.

All of the above results show that biodiesel is much more environmental friendly compared to conventional mineral fuel, either as a pure fuel or as a mixture with mineral diesel [20].

The ecological effect of using biodiesel is more favourable than when classical diesel is used, so that its effect on the environmental pollution is significantly smaller, as can be seen in Table 7 [16].

The reduction of fossil CO2 emissions is one of the main motivations behind policies and targets promoting a transition towards biofuels in the transportation sector. Unsurprisingly, an increasing biofuel share entails a higher emission reduction potential. This is more significant in scenarios where ethanol plants dominate, than in scenarios where methanol plants do. The reason is the high conversion efficiency to electricity and heat in ethanol plants, in combination with the in general significantly higher CO2 emission factors of displaced electricity and heat compared to displaced fossil transport fuels.

Table 7. Emission of harmful gases in biodiesel, and diesel combustion

Measuring parameters	100 %	
	Biodiesel	**Diesel**
CO [ppm]	92	179
NO [ppm]	113	129
NO_2 [ppm]	26.5	23.4
NO_x [ppm]	139	153
SO_2 [ppm]	5	102
H_2 [ppm]	11	19
O_2 [vol%]	17.7	17.5
CO_2 [vol%]	2,7	2.84
Particles of the soot [mgm^{-3}]	31.2	98.3
Benzene [mgm^{-3}]	<10	825
Toluene [mgm^{-3}]	<10	398
Xylene [mgm^{-3}]	<10	40

4. CONCLUSIONS

Our country needs to take appropriate measures to encourage the production of this ecological and renewable fuel. Such measures would ensure a more intensive development of agriculture, improve environmental protection, reduce crude oil imports, and create new jobs. Moreover, such measures are becoming an obligation, since all EU members, in proportion to the estimated resources, are obliged to increase the production of biofuels. Given that our country has significant potential for growing plant cultures for the production of biodiesel, it is expected that the domestic biodiesel industry will intensify in the forthcoming period.

The advantage of conventional biofuels, especially biodiesel, is that they can be produced in decentralized and smaller plants, representing an advantage for the development of rural environments. Contrary to that, the production of advanced biofuels is mainly related to large plants in order to achieve better economic performance. At the same time, large investments are needed that can only be provided by large companies. Therefore, such companies will dominate the market of advanced biofuels and control the raw materials prices to a great extent, thereby limiting the benefits of the production of biofuel for the rural environment.

In 2010, production and use of biodiesel was not recorded in Serbia, although our country has significant land potential for the production of raw materials for processing into biodiesel. From such a surface it is possible to provide raw materials for production of over 200,000 tonnes of biodiesel per year.

State policy and production costs of biofuels, as well as requirements for competitiveness, can significantly influence the prices of biofuels and agricultural raw materials. Our country has accepted international obligations and has the available potential of biomass, so it is necessary to take all incentive measures as soon as possible in order to reach the binding target of 10% share of biofuels in transportation sector by 2020 (EU Directive 2009/28/EC).

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INDUSTRY 4.0 BASED ON INDUSTRIAL AND SERVICE ROBOTS WITH APPLICATION IN CHINA

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RESEARCH ARTICLE

ABSTRACT: In the last ten years, digital technology has significantly contributed to the change of people's lives worldwide, because its application has caused a rapid transformation of all aspects of human life, and especially fast transformation in the design, production, operation and maintenance of the production system, which caused an unexpected jump in productivity. It can be said that fourth industrial revolutions on-going process, which can be labelled a variety of ways, such as "intelligent factory", "smart industry" or "advance manufacturing". Development of the digital technologies in the last twenty years has introduced us from third in the fourth industrial revolution. The first time the term “Industry 4.0” appears in the Germany in year 2011 whose government promotes automation of production processes by introducing digital technologies. Germany is one of the most technologically developed countries in the world and it is logic that this revolution begins there. This example follows the other countries in the world. Fourth technological revolution depends on a number of new and innovative technological achievements. It is necessary to integrate production processes in all production phases and further applications by using ICT technologies for digitalization. The automation of production processes must include advanced sensors and intelligent robots that can be self-configured to be able to make specific product. It is necessary to collect large amounts of data to be analysed and used in the production processes.

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It is also necessary to realize network communication (include mobile and internet technology) between machines in the production process, the production system and the operator, as well as suppliers and distributors. Application of previously mentioned leads to the intelligent manufacturing processes that have a wide range of change of production processes. To intelligent process we can come only by applying intelligent industrial robots because they represent one of the cornerstones of the fourth industrial revolution. In this paper an analysis of industrial and service robot application in production processes. With the implementation of digital technology, robot technology and other advanced technology we, as a society, strive for intelligent automation, and intelligent factories, and thus create a society in which wealth, created through the strengthening of global competitiveness, will serve for resolving social issues in society.

KEY WORDS: industry 4.0, digital technology, production processes, M2M, intelligent automation, industrial robot, service robot

INDUSTRIJA 4.0 NA OSNOVU INDUSTRIJSKIH I SERVISNIH ROBOTA SA PRIMENOM U KINI

REZIME: U poslednjih deset godina digitalna tehnologija je značajno doprinela promeni ljudskih života širom sveta jer je njena primena izazvala brzu transformaciju svih aspekata ljudskih života, a posebno brzu transformaciju u projektovanju, proizvodnji, radu i održavanju proizvodnog sistema, što je izazvalo neočekivan skok produktivnosti. Može se reći da je četvrta industrijska revolucija proces koji traje, i koji se može označiti na različite načine, kao što su „inteligentna fabrika“, „pametna industrija“ i „napredna proizvodnja“. Razvoj digitalnih tehnologija u poslednjih dvadeset godina nas je uveo u treću industrijsku revoluciju. Prvi put se pojam „Industrija 4.0“ pojavljuje u Nemačkoj u 2011. godini, čija vlada promoviše automatizaciju proizvodnih procesa uvođenjem digitalnih tehnologija. Nemačka je od tehnološki najrazvijenijih zemalja u svetu i logično je da ova revolucija počinje tamo. Ovaj primer slede druge zemlje u svetu. Četvrta tehnološka revolucija zavisi od niza novih i inovativnih tehnoloških dostignuća. Neophodno je integrisati proizvodne procese u sve faze proizvodnje i dalje primene koristeći ICT tehnologije za digitalizaciju. Automatizacija proizvodnih procesa mora uključivati napredne senzore i inteligentne robote koji se mogu sami konfigurisati da bi mogli napraviti određeni proizvod. Potrebno je prikupiti velike količine podataka koje treba analizirati i koristiti u proizvodnih procesima. Takođe je neophodno ostvariti mrežnu komunikaciju (uključujući mobilnu i internet tehnologiju) između mašina u proizvodnom procesu, proizvodnog sistema i operatera, kao i dobavljača i distributera. Primena prethodno pomenutih dovodi do inteligentnih proizvodnih procesa koji imaju širok spektar promena proizvodnih procesa. Do inteligentnog procesa možemo doći samo primenom inteligentnih industrijskih robota, jer oni predstavljaju jedan od kamena temeljaca četvrte industrijske revolucije. U ovom radu analizirana je primena industrijskog i servisnog robota u proizvodnim procesima. Primenom digitalne tehnologije, robotske tehnologije i drugih naprednih tehnologija, mi kao društvo nastojimo ka inteligentnom automatizacijom i inteligentnim fabrikama, i tako da stvorimo društvo u kojem će bogastvo, stvoreno kroz jačanje globalne konkurentnosti, poslužiti za rešavanje socijalnih pitanja u društvu.

KLJUČNE REČI: industrija 4.0, digitalna tehnologija, proizvodni procesi, M2M, inteligentna automatizacija, industrijski robot, servisni robot

INDUSTRY 4.0 BASED ON INDUSTRIAL AND SERVICE ROBOTS WITH APPLICATION IN CHINA

Isak Karabegović, Ermin Husak

1. INTRODUCTION

Automation of production processes in the industry began in sixties of the last century when in the automation industrial robots have been included and continues to this day. However it must be recognized that it was rigid and not flexible automation. Reason for this is the fact that if another product is in the same production line, it was necessary to reprogram each robot, change the tools and end effectors etc. This required a delay in production. It lasted long as it meant the additional cost in production. We have to mention the fact that industrial robots have been fenced off for reasons that would hurt operators who worked in the production process. In the last 20 years digital technologies have been developing that are being implemented and in production processes. Many believe today that we are on the beginning of the new industrial revolution. It is considered that this is for humanity fourth step which can be entitled fourth industrial revolution or “Industry 4.0”. This term first time have been emerged in 2011 in Hanover Fair in Germany. This is development concept which is mostly coincides with development in European countries. Can be called as “Intelligent factories”, “Smart industry” or “Advance manufacturing”. Fourth industrial revolution is nothing else then set of rapid transformations in design, manufacturing, work and maintenance of the manufacturing systems, which causes sudden jump in productivity and change of human life in whole world. Fourth industrial revolution is successor of three earlier industrial revolutions (Figure 1). As already known, first industrial revolution begins with year 1784 in the middle of the 18th century when steam engines had been implemented in manufacturing processes. The second industrial revolution begins in year 1870 in the end of the 19th century when electrical energy had been used significantly. Mass production is implemented on the moving lines driven by electrical motors. The thread industrial revolution begins in year 1970 in 20th century by implementation of electronics and informational communication systems and industrial robots which additionally automatize manufacturing processes. Currently we are in the beginning of fourth industrial revolution which is characterized by so-called “Cyber-physical systems” (CPS).

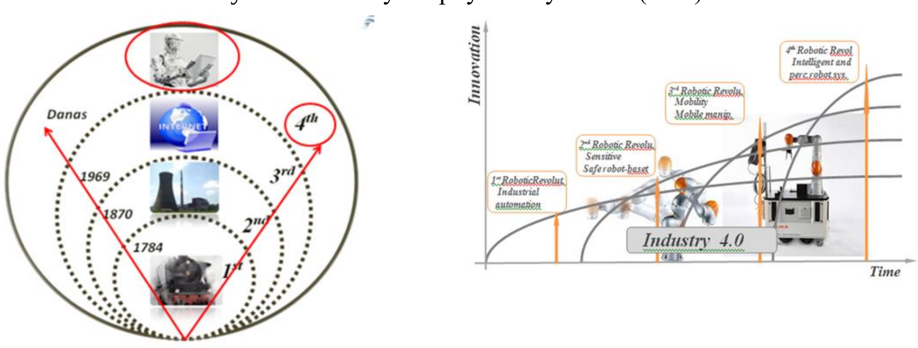


Figure 1. Technology industrial revolutions in time periods and development of robotic technology

Potential for transformations of manufacturing processes in Europe and whole world in upcoming period is in using digital technology, sensor technology, robotic technology and other advanced technologies which leads to applications of new sensors, expansion of network communications, layout and networking of robots and machines, increase of computer capacities by lower prices. The fourth industrial revolution gives us greater flexibility in production processes, maximum adjustment of production to rapid change in the direction of customer requirements, increasing the speed of production, better quality and increased productivity. Companies to stay on the market and to be competitive need to use these advantages invest in new equipment, information and communication technology (ICT) and perform data analysis that will be on hand throughout the global value chain. The development of digital and advanced technologies, as well as innovation in production processes represents a challenge for the development of all technologies including robotic technology [1,12-21,23,24,25,26]. The convergence of digital and other technologies, primarily referring to the sensor technology have influenced to develop robotic technologies as indicated in Figure 1.The first generation of industrial robots is the first robotic revolution that occurs in sixties to seventies of the last century, and it is the industrial automation that is most implemented in the automotive industry, and many other manufacturing processes. Digital technologies, ICT technologies, sensor technologies and many advanced technologies change this situation which led to development of second generation robots. Today we are in second generation of robots where robots have more power to sense environment and there is no need to separate them with fences. Humans collaborate with robots. Fourth industrial revolution "Industry 4.0"has contributed to the development of the robotic technology because strategies of the leading courtiers are to go to the full automation of production processes or "intelligent automation". This leads to the fourth robotic revolution in robotic technologies when all robots is going to be intelligent. The second generation of robots has created new requirements for increased productivity and surpassed the industrial robots of the first generation. The reasons for this are many: making robots easier to program and use, enhanced the ability to manipulate (does a diverse array of tasks), reduced size and cost of the robot, robots are working in a wide range of dynamic environment and work together with people. Challenges for the development of robot technology from the first generation of industrial robots to service robotics, or most important technology for shaping the future ability of robots lie in the direction of three technical areas as indicated in Figure 2.The first technical area is knowledge which gives the robot the ability to perceive, understand, and plans to move into the real world. This feature improves cognitive robot capabilities so that the robot can operate independently in different complex environments. The second technical area is manipulation which gives to robot precise control and a competence to perform manipulation of objects in his environment. In this way, a significant improvement exists in the robot control, which gives the possibility that the robot can assume a greater variety of performing tasks in a variety of manufacturing processes.

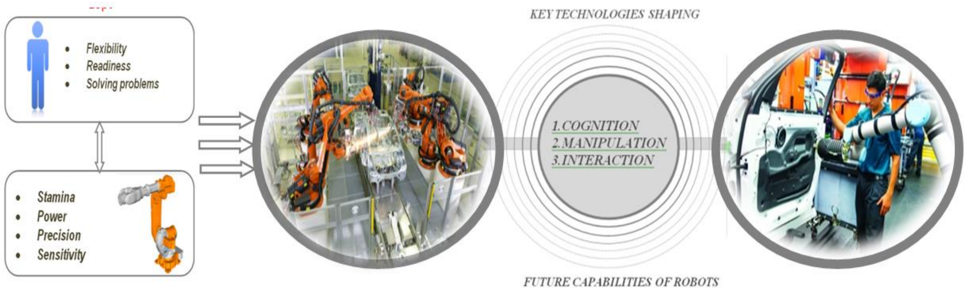
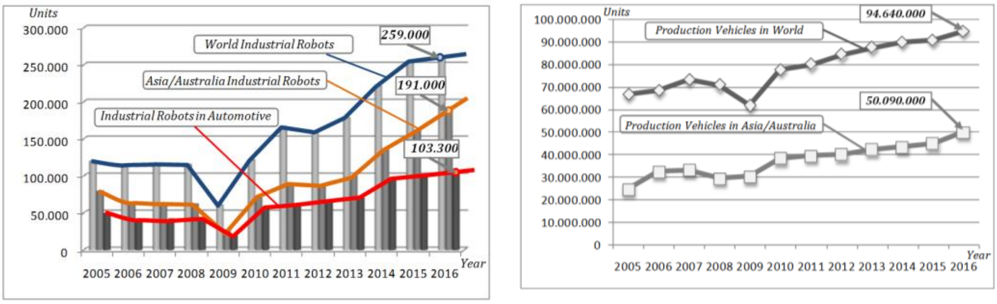


Figure 2. Significant technologies in capability shaping of the future robots

Third technical area is interaction. Represents one of the most important areas because it gives the robots to learn and collaborate with people. Also improving interaction robot - human for the verbal and non-verbal communication. The robot has the ability to observe and copy human behaving and learning from experience. Safety first is the absolute prerequisite for the operation of robots with people in the neglected environment. Digital technology made possible the development of many digital devices (microprocessors that are the brains of digital devices and systems) tremendous acceleration through the Internet in the industry by: video cameras, RFID readers, mobile phones, tablets, computers, improving the quality, safety, production, maintenance plants, increase efficiency and effectiveness in all areas.

2. IMPLEMENTATION OF INDUSTRIAL ROBOTS IN PRODUCTION PROCESSES IN THE WORLD AND CHINA WITH REFERENCE TO AUTOMOTIVE INDUSTRY

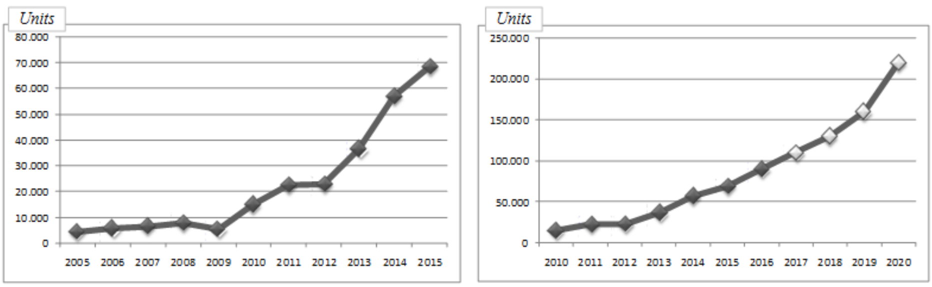
Today it is impossible to imagine the production process in any industrial branch without industrial robots. In order to get an actual idea on the modernization and automation of production processes in the industry, and given that we are in the 21st century, but also that we are currently in the fourth industrial revolution called "Industry 4.0", it is necessary to make a review of the representation of industrial robots in the past ten years. The statistical data for the above analysis of the number of industrial robots were taken from the International Federation of Robotics (IFR), the UN Economic Commission for Europe (UNECE) and the Organization for Economic Cooperation and Development (OECD) [2-11, 22,24], whereas the data on the number of produced vehicles were taken from the Verband Deutscher Verkehrsunternehmen (VDV) [11, 12, 22, 24], which are graphically shown in Figure 3a). Having in mind that the largest companies for vehicle production are located on three continent Asia/Australia as well as the fact that the highest number of industrial robots has been installed in the automotive industry production processes, we have conducted an analysis of the representation of industrial robots and vehicle production on the three continents in the period 2005-2015, as shown in Figure 3b). Analysis of the diagram displaying the representation of industrial robots in the world in the period 2005-2015 (Figure 3a) brings us to the conclusion that the presence of industrial robots in the world for the period 2005-2006 was nearly constant and was about 115.000 robot units. In 2009 the application of industrial robots has dropped significantly to around 60.000 robot units as a result of economic and industrial crisis in the world. In the period 2009-2015, the representation of industrial robots is growing on annual basis and in 2015 it reached the value of about 254.000 robot units. The diagram of the representation of industrial robots in the world in the automotive industry and the tendency of application of industrial robots in all industries are completely similar, except that application is lower, ranging from 32-40% of the total application of robots depending on the year. Thus, in 2015 industrial robots in the automotive industry are represented with about 98.500 robot units which is about 38.75% of the total application of industrial robots in the world in this year. As can be seen, the largest number of industrial robots is represented in the automotive industry in the automation and modernization of production processes, which resulted in the number of vehicles produced in the world, as shown in the third diagram in Figure 3a).



a) Industrial Robots b) Vehicle production

Figure 3. The tendency of representation of industrial robots and vehicle production in production processes in World and, Asia/Austarlia in period 2005-2016 [2-11,24]

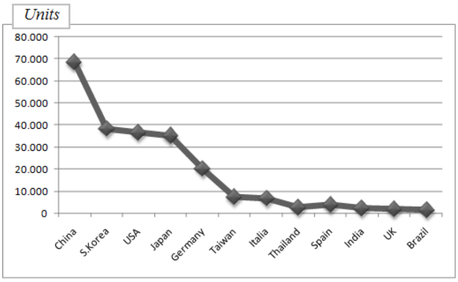
When the vehicle production is in question, the tendency is growing annually, so that from 66 million vehicles produced in 2005, in only ten years the production increased to 94.6 million vehicles. We can conclude that with the increase of the representation of industrial robots in the automotive industry in the world in ten years, vehicle production increased for 40%, which seems logical as the automation of production processes in the automotive industry such as body welding, body painting, assembly and control, lead to decrease of the processing time and increase in vehicle production. Based on the diagrams in Figure 3b), the representation of industrial robots in manufacturing processes in all industry branches on all three continent of Asia/Australia in the period 2012-2016, we see that there is a growing tendency of application of industrial robots on all three continents. In 2009 world recorded the lowest representation of industrial robots (as shown in diagram 3a), because there was the economic and industrial crisis in the world that also affected the application of robots on all three continents. We can conclude that in period 2009-2015 all three continents experienced a growing trend of representation of industrial robots in production processes, with the exception of a slight decline in the application of industrial robots in 2012 in Asia. In the period 2005-2009 the tendency of application of industrial robots in Asia/Australia is declining. The highest representation of industrial robots in the world is on the continent of Asia/Australia for example; in 2016 they applied 191.000 industrial robot units in all production processes. Such high representation of industrial robots is reflected in the production of vehicles, thus making Asia/Australia the first in the world in the production of vehicles. The tendency of vehicle production in Asia/Australia in the period 2005-2016 is continuously growing from year to year, so that in 2016 the production of vehicles reached the amount of approximately 50.090.000 units of vehicles. The consequence of the tendency of increasing vehicle production in Asia/Australia is continuous increase in the representation of industrial robots during automation of production processes and in the automotive industry. In addition, the fourth industrial revolution is leading to "smart factories" that are expected in a decade, for which the most responsible is the application of robotic technology and information technology (IT). Since we came to the conclusion that Asia/Australia is the first place in representation of industrial robots, as well as the first in the number of produced vehicles in the world, we need to conduct an analysis of the representation of industrial robots in the country that produces the most vehicles in Asia. On the continent of Asia, China is in the first place by the representation of industrial robots in production processes, particularly in the automotive industry, a result of which is that China is the first in the world in the vehicle production annually. This is not random tendency because China adopted a national ten-year strategy named "Made in China 2025" which aims to make China the leading country in technology development in a few years. In order to see the tendency of representation of industrial robots and vehicle production in China, we used statistical data given in the literature [2-11, 22], while diagrams are shown in Figure 4.



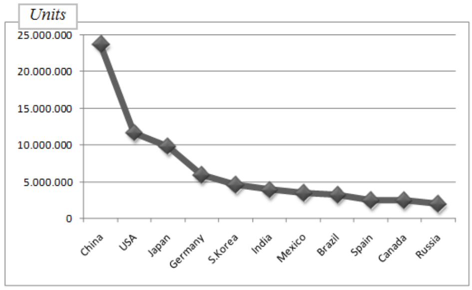
a) Industrial robots b) Predicting the representation robots

Figure 4. The tendency of representation of industrial robots in production processes in China in period 2005-2015,and the tendency of predicting the representation by 2020 [2-8]

On the continent of Asia, China is in the first place by the representation of industrial robots in production processes, particularly in the automotive industry, a result of which is that China is the first in the world in the vehicle production annually. This is not random tendency because China adopted a national ten-year strategy named "Made in China 2025" which aims to make China the leading country in technology development in a few years. In order to see the tendency of representation of industrial robots and vehicle production in China. If we analyse the representation of industrial robots in production processes in China (Figure 4), we can conclude that China is consistently implementing its national strategy "Made in China 2025", because the representation of the robots increases annually. The increase is not per linear function, but rather exponential function, so that in the last six years the representation increased from 5.525 robot units in 2009 to 68.556 industrial robot units, which is the increase of almost twelve times, which in the last ten years has not happened, nor recorded in any country in the world. The tendency of application of industrial robots in China is growing in the period to come. The predictions are that in 2020 China will reach 220.000 industrial robot units, which presents over 45% of the total representation of industrial robots in the world in that year.



a) Industrial robots



b) Production vehicle

Figure 5. The representation of industrial robots in top twelve countries in the world in the period 2005-2015, as well as vehicle production in top twelve countries in the world in 2015 [2-8,22]

Among twelve countries in the world that have the highest representation of industrial robots in production processes in 2015 are the following: China, North Korea, USA, Japan, Germany, Taiwan, Italy, Spain, India, UK and Brazil. As we can see based on Figure 5a), the first place is held by China with 68.556 industrial robot units, followed by the countries in which the automotive industry is highly developed, such as North Korea, USA, Japan and Germany. If we look at the representation of industrial robots in production processes in China in the last ten years, Figure 5a), we see that it holds the first place in the last years, the reason being the strategy developed by China named "Made in China 2025", which aims to make China the leading technology country in the world. Based on the image 5b), we conclude that China has installed most industrial robots in production processes in the automotive industry because they are the first in the world in vehicle production [18,23]. In 2015 China produced close to 25 million vehicle units, followed by countries that are among top five countries in the representation of industrial robots in 2015: USA, Japan, Germany and North Korea. In addition to development and increase of application of industrial robots in production processes, the development and increase of application of service robots in the production process.

Robotic technology in the world is used to the greatest extent in the industry, especially where flexibility of the manufacturing process is a strategic factor of competitiveness. Statistical data for analysis of number of service robots for application of logistics in production processes were taken from the International Federation of Robotics (IFR), United Nations Economic Commission for Europe (UNECE) and Organisation for Economic Cooperation and Development (OECD) [2-11, 22, 24]. The application of service robots for logistics in production processes is mostly used in automotive production processes which are shown in Figure 6.

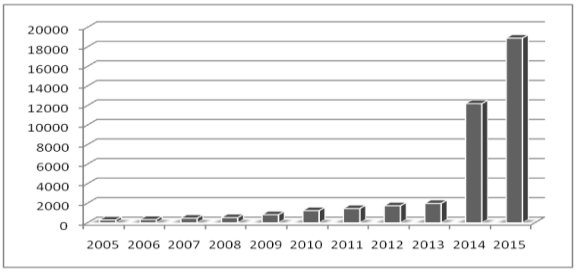


Figure 6. The representation of servisnih robots in automotive production pocesses for 2005-2015[2-8]

Based on the diagram shown in Figure 6, we come to the conclusion that in the last three years the application of service robots for logistics in all branches of production processes has increased rapidly, mostly in the production processes of the automotive industry.

Figure 7. Service robots AGV applied in various manufacturing processes [2-8]

The consequence of the sudden changes is the development of robotic technology, digital technologies, or all new technologies deserved for the development of various types of logistics service robots that are completely intelligent. Such service robots for logistics applied in production processes are shown in the Figure 7.

3. DIGITAL TECHNOLOGY AS A DEVELOPMENT GENERATOR IN MACHINE TO MACHINE COMMUNICATION M2M

As is well known, leading paradigm in every automation of the production process is limiting of human intervention, and hand tasks to the machine, robot, devices and systems. Digital technology with information and communication technologies with microelectronics, sensors, actuators and fixed and wireless networks give possibility of creating communication machine with the machine. This digital interaction between and within the machine and the systems is nothing but the heart of the fourth industrial revolution. Strategy of industrial development of any country in the world are moving towards industrial automation of manufacturing processes using digital and advanced technology and define M2M communication in the context of human and machine. Companies engaged in robotic technology have developed second-generation of robots that have the ability to work together with humans, where human during the work are safe. Industrial robots of the first generation had to separate by fences because of the safety of workers and other plants. Human-Machine Interface (HMI) and Machine-to-Machine communication is expected to be a key element in the expansion of production automation systems. With these applications are come to the "intelligent automation" which is the goal of the fourth industrial revolution, i.e. to improve performance by increasing the total efficiency of installed capacity (equipment) [12-30].Here we must note that it is not only the goal communication machine with the machine in a manufacturing process in the industry, but the goal is the application of digital and other advanced technology for communication of all sorts of devices and systems. In other words M2M applications can be directed to individuals, companies, communities, organizations in the public and private sectors, as shown in Figure 8. This is about a pioneering industrial internet which will cover all production machines, apparatuses, devices and systems which perform certain tasks. This systems can communicate with each other just by implementing the above digital technology, so that in this communication may, for example exchange the following information: I produced 20 units and I have to stop because my inbox is empty, I have the ability to work 12% faster in how my inbox is always full, of produced 30 pieces of products two products have been discarded, i waited for 20 minutes to produce because the inbox was empty, i am able to reduce its energy consumption for production as much that my equipment was idle while waiting. Please check? To the right temperature I worked five minutes, etc.

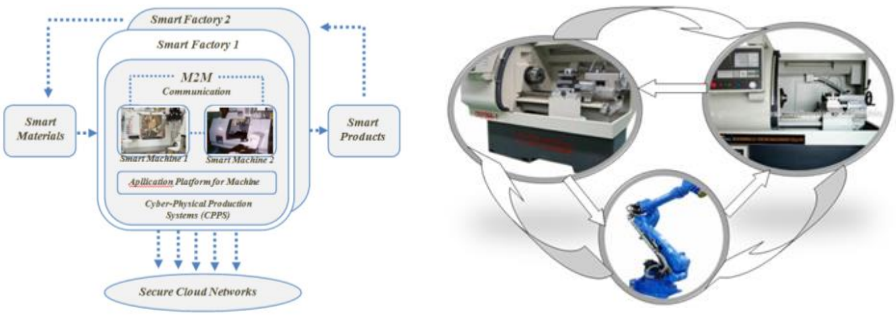


Figure 8. Concrete example of application M2M in production process in industry

This type of communication between M2M machines, appliances, devices and systems forms the basis for "intelligent automation" or "intelligent factory", and applications can be in heavy industry, food industry, production of goods, and in all segments of society and different sectors. Modern M2M applications using micro-electronics and wireless digital technology, with which these devices can collect and distribute data in real time. In this way can be accessed at dozens of billions of connections at will and at any time. M2M applications use sensors and counters for different events in the range of temperature, through the communication network (fixed, wireless or hybrid), to the application software that converts the raw data into meaningful information. Telecommunications companies in particular recognize the opportunity to expand their services and to gain access to operational aspects of their clients. At the stage of the research are different architecture for M2M systems and technologies that enable the development and deployment of these systems.M2M communication systems are in development when it comes to its integration and adaptation of existing technologies and communications systems that are currently used different processes. It is necessary to train the algorithms to ensure functionality, effectiveness, reliability and safety of the M2M system. Predictions are that by 2020, in the world, 20 to 50 billion devices will be able to communicate with M2M systems. It is essential when using M2M system to expectuberisation and this is one of the sub-categories of "disruption". The term used for the enormous changes which the new companies through technological innovation will cause in every industry branch. Convergence of digital technologies with other technology created the second generation of industrial robots. We think that rapidly will come the third generation of industrial robots which will be smaller, cheaper, more autonomous, flexible and fully cooperative compared to previous generation of robot with simplifying programming so that they can be programmed by workers. The third generations of industrial robots are intelligent and autonomous robots whose improvements will be in the direction of: identifying specific objects, manipulation, knowledge, increase computing performance, numerically controlled remotely, working with miniature and complex products that require adjustment in the assembly, reliability and precision which exceeds human ability. For these reasons the industrial and service robots are at the center of automation of production processes today, and in the future, and it is impossible to make "intelligent automation" and "intelligent factory" without the participation of a new generation of robots. The second generation of industrial robots can be very easily programmed so they can be used by the average workers who are without knowledge of robotics and computer science, in other words we do not need professional developers that are very expensive. Some companies for development of robots developed autonomous industrial robots so that they can work together and automatically adjust their activities in making other products. Also some second generation industrial robots perform tasks by imitating workers. The advantage of the second generation of robots is that it becomes a tool that improves efficiency. They are very affordable, easy to install, have a very low rate of investment in them, it is not necessary to reorganize the manufacturing process for its installation because it is not necessary to separate workers with fences and they are without special safety equipment.

4. CONCLUSIONS

The fourth industrial revolution accelerates exponentially. This is the third phase of acceptance of digital technology, but it was preceded by digital competence and digital use. Digital transformation enables innovation and creativity in a single domain, not just the application of traditional, but adopted technologies. IoT (Internet of things) represent new ways in which we communicate with machines, as well as the manner in which the devices that we use at home, at work, transport, to be connected. From communication M2M is expected to be a key element in the expansion of automation in the manufacturing process, which will, with the participation of sensor and robotic technology lead to "intelligent automation". Also new way to communicate with devices that are used in the home, transport to work, etc., is the key to the implementation of the fourth industrial revolution, so it is estimated that by 2020, about 50 billion devices will be interconnected, of which will be about 10 billion traditional computer devices. In the next five years, the largest application of digital technology will achieve global companies; hence they will reduce costs, increase productivity, and allow extension of the implementation to the new areas. With digital design and virtual modelling of the production process we are able to reduce the time between the design of a product and its delivery to the market. In this way we come to the great improvements in product quality and a significant reduction of defects in manufacturing. Intelligent automation allows greater flexibility in the production, so that different products can be produced in the same production facility. In the first place in the world in representation of industrial robots in the automotive industry is China, but also the first in the world in the production of vehicles. It is expected that in the following period there will be an increase in the representation of industrial robots in production processes worldwide, with new types of industrial robots that will be able to work together with workers, and in particular in the automotive industry because the current structures of industrial robots are such that they need to be separated by the compartments in order not to harm the workers. The predictions are that China will still be the leader in the world in terms of the representation of industrial robots, as well as the production of vehicles. The fourth industrial revolution which includes digital and other technologies bring us to the "intelligent production" in the next 10 years. Fourth industrial revolution provides technology available to everyone. It is assumed that technology in the future will not provide a competitive advantage, but competitive advantage will be in manner in which we used it.

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EXPERIMENTAL AND NUMERICAL MODAL ANALYSIS OF BRAKE SQUEAL NOISE

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RESEARCH ARTICLE

ABSTRACT: In addition to different kinds of pollutants emitted by the vehicles, noise can also negatively effect on human health. It does not only threaten drivers, but also people living near major intersections and roads, as well as roads where traffic-flow is high. One of the biggest problems of the vehicle is the noise that occurs in the braking process. Despite the large scope of research into the development of brake systems, there are still no reliable procedures during the development phase to evaluate the robustness of these systems with respect to friction-induced vibrations. Therefore, the identification of the modal properties by using experimental methods has become even more important. Experimental and numerical modal analysis of the venting disc with radial ribs was performed in this paper. This approach enables the determination of the natural frequencies of the brake disc, as well as the verification of results obtained by the numerical methods. Changes in modal properties-resonance frequencies and modal damping values due to variation in operating conditions were also analysed.

KEY WORDS: vehicle, braking, noise, disc with radial ribs, natural frequency

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EKSPERIMENTALNA I NUMERIČKA MODALNA ANALIZA BUKE KOČNICA

REZIME: Osim emisije zagađujućih materija koje emituju vozila, buka takođe može negativno uticati na zdravlje ljudi. Nisu samo ugroženi vozače, već i ljude koji žive u blizini velikih raskrsnica, kao i puteva na kojima je protok saobraćaja visok. Jedan od najvećih problema vozila jeste buka koja se javlja u procesu kočenja. Uprkos velikom obimu istraživanja pri razvoju kočnih sistema, još uvek nema pouzdanih procedura u fazi razvoja za procenu otpornosti ovog sistema na vibracije izazvane trenjem. Međutim, indentifikacija modalnih osobina upotrebom eksperimentalnih metoda postala je jako važna. U radu je izvršena eksperimentalna i numerička analiza ventilirajućeg diska sa radijalnim rebrima. Ovakav pristup omogućava određivanje prirodnih frekvencija kočnog diska, kao i verifikaciju rezultata dobijenih numeričkim metodama. Analizirane su i promene modalnih karakteristika-rezonantnih frekvencija i vrednosti modalnog prigušenja usled varijacija radnih uslova.

KLJUČNE REČI: vozilo, kočenje, buka, disk sa radijalnim rebrima, prirodna frekvencija

EXPERIMENTAL AND NUMERICAL MODAL ANALYSIS OF BRAKE SQUEAL NOISE

Nadica Stojanovic, Jasna Glisovic, Ivan, Grujic, Sunny Narayan, Sasa Vasiljevic, Bojana Boskovic

1. INTRODUCTION

Noise affects the heart and cardiovascular system and has a significant effect on various psychosomatic diseases. Different opinions of the authors have been noted in relation to the noise effect on the cardiovascular system, while one considers that there is an increased blood pressure, and the others, in contrast to its decrease. Research conducted for study the prevention of ischemic heart disease in people living in cities or parts of the city, where the level of public noise exceeds 65 dB, has shown a relative risk of disease from ischemic disease. Today, cardiovascular diseases are one of the most common causes of death, and these data has a high public health and social significance. It has been found, by investigating ECG waves and a cardiac rhythm that sounds of higher intensity have a greater impact on the occurrence of cardiac disorders [1].

It can be said that traffic noise is one of the most prevalent urban polluters in the city environment. Moreover, WHO (World Health Organization) categorizes the noise as the second worst ecological cause of poor health (PM2.5 is the first) [2]. This means that road traffic is the most dominant source of environmental noise, it is estimated that 125 million people are exposed to a noise level higher than 55 dB. While noise causes at least 10.000 cases of premature death in Europe each year, 8 million people have a sleep disorder, hypertension occurs in 900,000 inhabitants, and only 43.000 are examined by a doctor. A research performed by the Environmental Protection Agency of Ministry of Environmental Protection for 2016 was carried out in 14 cities in the Republic of Serbia at 195 measuring points. Statistics included residents exposed to a noise level of 55 dB and more for all sections of the state road network for which SNM (strategic noise map) was made, where the average annual flow is over 3.000.000 vehicles. During 24 hours, the largest number of inhabitants is exposed to a noise level of 55-59 dB, Figure 1. If it's a residential area, the noise level exceeds the allowed values, and in the case of the city centre, the zone along highways, main and urban roads, then it is below the allowed values [3]. The largest number of people exposed to night noise is 43.132, and the noise level ranges from 45-49 dB, Figure 2. Results of measurement of night-time noise, which represents the noise in the period from 22 to 06 hours, vary depending on the area in question. If it is a residential area, then it exceeds the permissible values, and in the case of a city centre or zone along highways, the main and city roads then it is below the permitted limits [3].

People primarily use passenger cars for their own personal needs, such as going to work, vacation, shopping, etc., simply saying, to travel from one point to another. The biggest problem with today's vehicles is the comfort and noise produced by the vehicle during its exploitation. The level of noise inside the vehicle has been steadily falling over the past few years. So the appearance of any sound can lead to disturbance of the driver, as well as to his distrust in his own vehicle. One of the vehicle components occasionally produces unwanted vibrations, and unpleasant sounds are their braking systems. Manufacturers of brake and friction materials face very challenging requirements [5]. They need to know what are the characteristic noise, as well as the cause of the noise generation [6].

Dynamic oscillations in friction brakes that cause noise, vibration and rigidity can be classified into two groups [7]:

- Dynamic instability which results in a constant resonant frequency independent of rotor and
- Mechanical vibration with a frequency related directly to rotor speed.

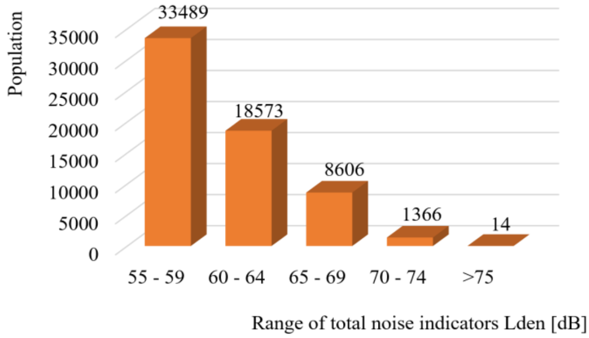


Figure 1. Population exposed to road traffic noise expressed over the range of total noise indicator Lden [4]

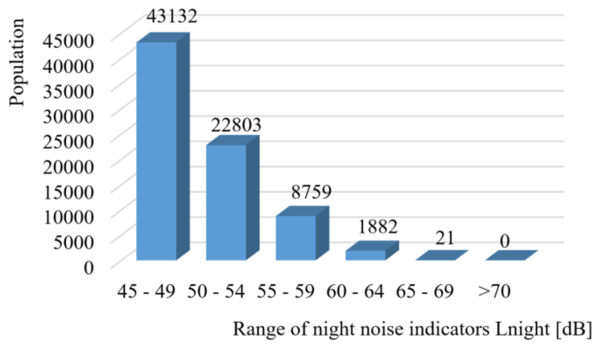


Figure 2. Population exposed to night road traffic noise expressed over the range of average night noise level Lnight [4]

The brake noise usually occurs in the range from 100 Hz to 20 kHz (which is the upper limit of human hearing) and in the case of classic brakes, the braking squeal occurs in the range of 1-6 kHz, where the human ear is the most sensitive. Within the definition of noise and brake judder, there are many subcategories of noise and judder of the brake [7, 8], Figure 3. A typical estimate of the proportion of warranty claims based on the different categories of brake NVH (Noise, Vibration and Harshness) is shown in Figure 4.

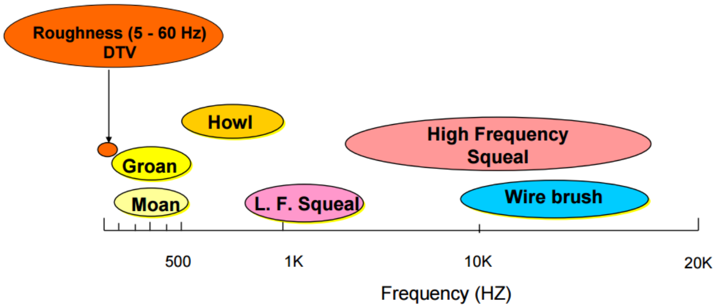


Figure 3. Frequency range of different vibro-acoustic phenomena generated by vehicle brakes [9]

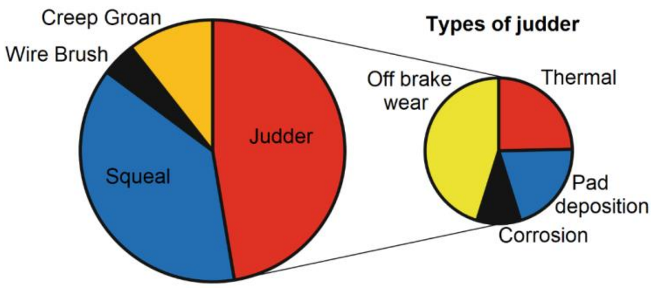


Figure 4. Typical distributions of warranty issues reported by high performance vehicle manufacturer [7]

There are several basic methods for determining the resonance vibrations of a brake disc such as [10]:

- Using a pulsator with any of the commonly used excitation functions, e.g., sine, random, transient
- Using a dynamometer and braking system, and
- Impact Hammer.

The most commonly used method is the impact hammer method. The reason for this is the cost of the equipment, as well as the simplicity of the experiment. As is the case in this study, in a large number of analysed researches, the response to the excitation is measured by acceleration sensors, while in some studies, the measurement was performed by a microphone [11]. If the measurement is done by acceleration sensors, the number of sensors used in the experiment can range from one to four sensors [12-14]. In addition, depending on the sensor, it also depends on the connection to the brake disc itself. For example, the sensor can be coupled with brake disc by using the beeswax [15]. Competition on the market is only possible if the experiments are fast, and this is achieved only by the use of numeric analysis. Of course, the accuracy of the results obtained this way should not be omitted, and this is achieved if the numeric analysis is calibrated with the experiment [16]. If the obtained numerical results are satisfactory, they can be used for further analysis [12].

However, an experimental study of structural dynamics has always contributed greatly in understanding and controlling the vibrational phenomenon that is encountered in practice.

Regardless of the fact that today, there are computers with high performance and capabilities, but the need for an experiment is the same as before, for several reasons [17]:

- Determining the nature and level of vibration that occurs during operation
- Verification of the theoretical models and the prediction of various dynamic phenomena which are collectively referred to as "vibrations", and
- Measurement of the basic properties of materials due to the effects of dynamic loads, such as damping, friction and fatigue endurance.

The problem of structural vibrations continues to be a huge danger and design constraints for a wide range of engineering products. These disorders in the system may be unacceptable for the system's planned operation. In this case, the engineer must determine how to minimize or eliminate unwanted vibrations occurring within the system. However, it can sometimes be very difficult when the cause is unknown [18]. At the end, it is most important that the vibration level is reduced to permissible level.

One of the aims of the paper is to determine the natural frequency of the passenger car’s brake disc experimentally, then to modify numeric analysis based on the results obtained by the experiment. So for the future research it is not necessary to conduct experiment first.

2. MODAL ANALYSIS

In the past two decades, modal analysis has become one of the main technologies for determining, improving and optimizing the dynamic characteristics of the different types of structures. Application of modal analysis is very wide, engineering disciplines where she found the application in engineering, aerospace and civil engineering [19]. The reason for the application is [20]:

- Revealing the causes of unpredictable material behaviour
- Construction modification
- Sensitivity analysis
- Simplification of mathematical models
- Predicting the response on disturbance force and
- Detection of structural damage.

Modern constructions are expected to have a small mass and to be a simple as possible, and at the same time sufficiently strong [20]. The requirement to reduce the mass of the construction is highest in the automotive and aviation industry. Unless sufficient attention is paid to reduce the mass, unwanted vibrations may occur in certain exploitation regimes. Modal analysis represents the process of determining the basic dynamic characteristics of the structure, such as natural frequency, damping and oscillation modes, in order to formulate the dynamic behaviour of the model [21].

There are two approaches to the modal analysis, the so-called experimental modal analysis, where the modes are determined by using the acceleration and displacement sensors. The second approach is the theoretical modal analysis, where the prediction of modes is performed by using the appropriate mathematical methods (FE-based eigenvalue extraction or MBD analysis of the vibration behaviour of the brake assembly) [9]. Today's software for modes determination is working according to the principle of mentioned mathematical models. The lack of experimental research is reflected in the fact that they cannot be examined during exploitation, or more accurate in road conditions. The vehicle must be examined in the laboratory, on dynamometer rollers, or the brake assembly must be mounted on the appropriate dynamometer for testing. If a person conducting a test, rather than a robot, the repeatability of the results is almost impossible. Verification of results obtained by the numeric analysis requires that they must be approximate to the experimental results or to be a very close to them. So after the experiment, numerical analysis can be performed. The research in this paper is performed by using the experiment and numeric analysis. The braking disc that was research subject in this paper is the vented disc with radial ribs, Figure 5.

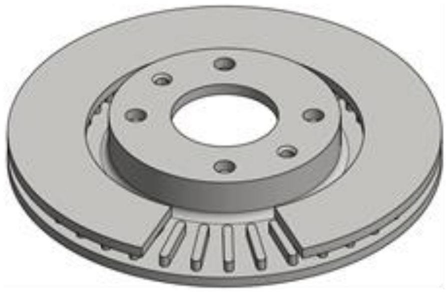


Figure 5. 3D model of vented brake disc

2.1 Experimental analysis

The applied experimental method is based on using impact hammer and with this method, it is necessary to provide the following:

- Impact hammer with head which can measure input force
- Acceleration sensor
- FFT analyser for determining the frequency response function, and
- Software for data processing and results showing.

Before starting the experiment, it is necessary to provide the appropriate conditions. This refers to base on which the measurement object will be placed, in this case the brake disc. It can be noticed, In reviewed literature that the disc can be located on a sponge, or to hang on elastic ropes that are used for securing cargo during the transportation, or to be fixed [12, 13, 22-24]. In this research, the chosen way of mounting the brake disc is to place a disc on the sponge. Measurement installation used for the experiment is shown in Figure 6. Experiment is performed using the NetdB 12 acquisition device. Excitation of the brake disc is performed by impact hammer (PCB Piezotronics 086C03). The impact hammer consists of a top, a force sensor, a balancing mass and handles. The top, which is placed on the impact hammer, is a soft impact cap. The force sensor is a piezoelectric and is embedded in the hammer's head to capture the impact force. The response is measured by acceleration sensor AC102, marked with a black circle in Figure 6. The acceleration sensor is connected to brake disc by the magnet. Figure 7 shows the disc with the sensors used for measurement, as well and disc placement. The experiment results have been stored on a computer, which was later processed.

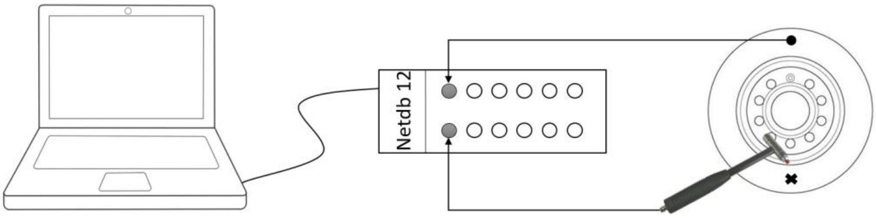


Figure 6. Measurement installation scheme

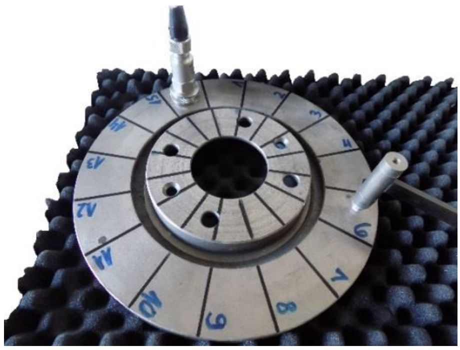


Figure 7. Brake disc with sensors

When performing such an experiment, two conditions must be provided are:

- The location of the acceleration sensor is very important to get the best record of the response. If the acceleration sensor is placed where impact impulse is very small, it will be very difficult to record FRF. Acceleration sensor should be placed where high structure responses are expected. By analysis that is earlier performed on different variants of the disc, it can be concluded that highest modes occur on friction ring of a brake disc [25].
- The applied top for the impact hammer - the top to be used is the one that activates as many natural frequencies as possible [15].

The Frequency Response Function (FRF) describes how the system will react to the impulse. If a particular amplitude and frequency impulse is introduced into the system, the system will start vibrating at the same frequency as the impulse, but with the phase shift. The response amplitude depends on the amplitude and frequency of the impulse. The relationship between the amplitude of the response and the excitation impulse is the FRF and is phase-shifted to any frequency [26].

2.2 Numerical analysis

First, the brake disc shown in Figure 5 is created in CATIA software package, and as such is imported into the analysis software – ANSYS. 3D model of brake disc is created in real size.

The conditions in which the experiment was conducted are also defined in the analysis software. This means that it is first necessary to define the temperature at which the experiment was performed. The used type of final elements is tetrahedral; the number of elements is 21.137, while the number of nodes is 38.978. As the disc is tested under static conditions, the degree of freedom is zero, which is also defined in the analysis software. In order to bring the results of the numerical analysis closer to the values obtained by the experiment, it is necessary to get the accurate data on the used material characteristics. The results of the modal analysis carried out by using numerical analysis are most influenced by the Young's module, which has proven both in this research and in the research of other authors [15, 27]. The characteristics of the disc brakes' material are shown in Table 1.

Table 1. Material characteristics of the brake disc

Density, kg/m^3	Young's module, MPa	Poison ratio
7600	197,000	0.26

The results obtained by numerical analysis are presented in the form of nodal diameters since they are the most dominant in the occurrence brake squeal. The reason for this is that the disc tends to vibrate around one or more node diameters at the same time, Figure 8. The operation of nodes in this case causes the disc to get a waveform. The number of node diameters is based on the number of nodes and anti-nodes that appeared on the surface of the disc that is in contact with the brake pads [7]. The number of nodal diameters gives the so-called number of vibration modes. The result of this phenomenon in the form of a brake disc noise is usually due to one or more nodal diameters.

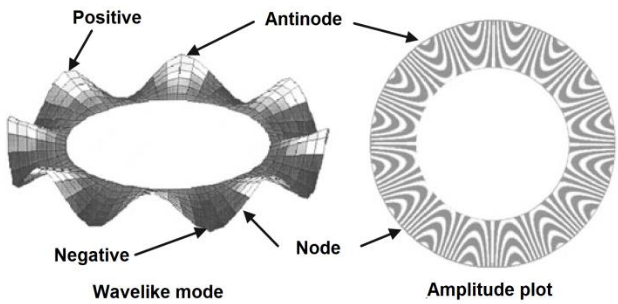


Figure 8. Typical 8 diametrical mode of vibration—16 antinodes [7]

2.3 Results and discussion

The result frequencies of the experiment and numerical analysis are in range up to 11 kHz. This value corresponds to the upper limit of high-frequency brake noise. The numerical analysis has been modified so that the deviations between the values of the experiment and the numerical model are as small as can be seen in Figure 9, while the error values are given in Table 2.

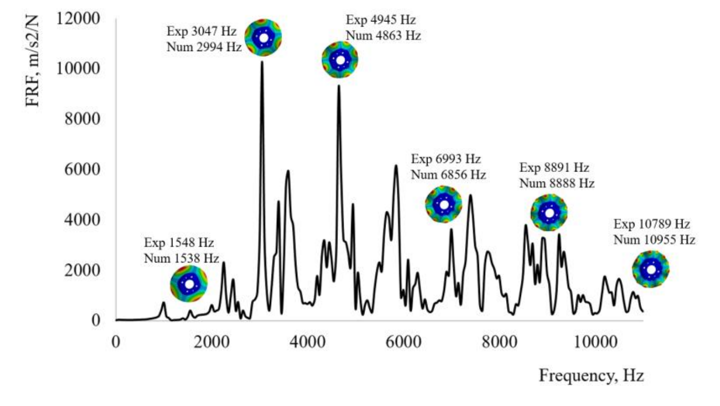
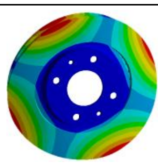
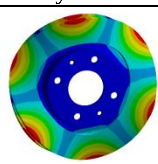
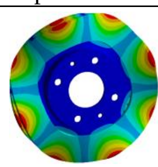
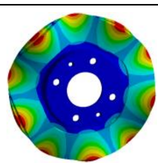
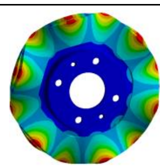
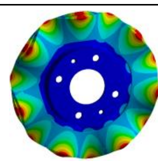


Figure 9. Experimental and numeral response of the free-free disc

The optimum choice of material's characteristic has resulted in a maximum obtained error value of 1.96%, Table 2. The error between the results of the experiment and the numerical analysis is small, so for the future research the characteristics of the materials shown in Table 1 can be used. The number of nodes can be displayed related to the frequency, which should be approximated by the smooth curve [7], shown in Figure 10. If this condition is satisfied, the results obtained by the numerical analysis can be accepted completely. For better illustration of the frequency, the geometry of the disc is observed. This means that the frequency means can be represented related to the angle between the nodal diameters. Analysing Figure 11, it can be noticed that as the frequency increases, the angle decreases. The higher the frequency, the higher the number of nodes is, which directly affects the reduction of the angle between them.

Table 2. Error between numerical analysis and the experiment

			
Experimental, Hz	1548	3047	4945
Numerical, Hz	1538	2994	4863
Error, %	0.65	1.74	1.66
			
Experimental, Hz	6993	8891	10789
Numerical, Hz	6856	8888	10955
Error, %	1.96	0.03	-1.54

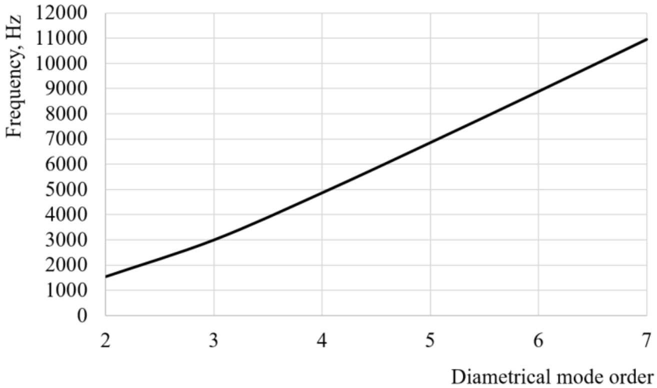


Figure 10. Natural frequency of free-free in function of number of nodes

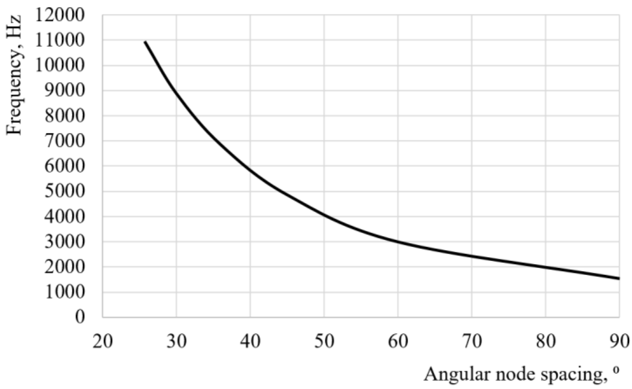


Figure 11. Frequency in function of antinode angular spacing

3. CONCLUSIONS

Traffic noise is one of the dominant sources of noise in urban areas. Today there is a tendency to reduce noise to a greater extent. One of the main reasons is that noise has a very negative impact on the health of humans living in her immediate vicinity. Car manufacturers have, in recent years, been able to reduce the noise generated by the vehicle during the exploitation. So any sound that occurs during the exploitation can cause distrust from the driver and that the vehicle spent most of the time on the service instead of what is its primary purpose. One of the most undesirable and irritating sounds that can occur during the exploitation is the brake noise. The experimental methods for determining the brake noise are the application of pulsator, dynamometer or impact hammer method. The method used during research represented in this paper was using the impact hammer. It is very important to determine the natural frequency of any system and tries to reduce it as much as possible. In this process, it must be ensured that there are no disturbances of other characteristics that are very important for the safety of vehicles in traffic.

The modal analysis was performed by the experiment, and then, based on the results of the experiment, the verification and modification of the numerical analysis results were performed. The numerical results do not deviate to a large extent, so that for future research, the initial parameters for the performed analysis, or the characteristics of the material, can be used. Further research can be carried out on determining the natural frequency for the other components and verification of the numerical data based on the results obtained by the experiment. The next step would be to determine the natural frequency for the assembly as well to determine the frequency during braking process.

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