VANJA JURIĆ, B.Eng.
E-mail: vanja.juric@tradeing.eu
Tradeing Ltd.
Jordanovac 119, 10000 Zagreb, Croatia
DINO ŽUPANOVIĆ, Ph.D.
E-mail: dino.zupanovic@fpz.hr
University of Zagreb,
Faculty of Transport and Traffic Sciences
Vukelićeva 4, 10000 Zagreb, Croatia

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ECOLOGICAL IMPACTS OF DIESEL ENGINE EMISSIONS

ABSTRACT

This article deals with the ecological impacts of chemical substances that are found in the structure of Diesel engine exhaust gases and provides an overview of legislation that limits their maximum allowable emissions. Special consideration is given to the previously mostly neglected negative impact of particulate matter compared to the impact of carbon dioxide. Negative impact of particulates is especially noted as direct negative impact on human health whereby the expenses associated with medical treatment exceed the financial savings resulting from the usage of Diesel powered vehicles. Therefore, the paper presents the knowledge acquired through previous scientific research in the economically most developed countries, as well as the tendencies for the reduction of negative impacts of Diesel exhaust gases.

KEYWORDS

Diesel engine, exhaust gases, ecological impacts, legislation

1. INTRODUCTION

Diesel engines represent one of the technological basements of our today's economy. Their usage is so diverse and widespread that their direct or indirect contribution is included in almost every product or service. However, the usage of Diesel engines results also in undesired impacts, particularly because their widespread usage takes on disturbing dimensions. Although they show a higher level of fuel use efficiency compared to the gasoline engines, the Diesel exhaust gases contain significantly higher concentrations of the most dangerous substances – the particulates [20] which have been the scientifically proven cause of some of the most severe diseases and may even lead to premature death.

The use of Diesel engines shows a tendency of significant growth following the 1980s that has continued also in the first decade of the 21st century (*Figure 1*). The reason for their increased usage lies primarily in their better profitability as the result of their intensive technological development compared to other types of vehicle engines during the mentioned period. Great contribution to their wide usage is also provided by the fuel pricing policy which has made Diesel engines most profitable, especially if used for on-road applications, i.e. passenger (*Figure 2*) and commercial (*Figure 3*) vehicles. However, the growing trend of their use is also observed in other market segments, i.e. as "working horses" in general, such as agricultural machinery, marine vessel, construction machine engines, etc.

Figure 2 shows market flexibility in the segment of passenger cars, i.e. substitution of the market share currently held by Diesel engine vehicles with new environmentally-friendly engines. This phenomenon is very easy to explain if we take into consideration that in the economically developed countries the passenger cars have a short period of depreciation, i.e. they are relatively often replaced with new models. On the other hand, according to *Figure 1* and *Figure 3*, there is a lack

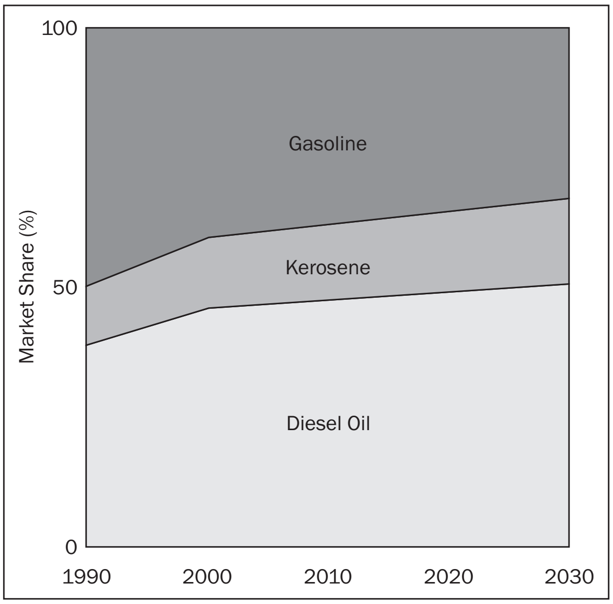

Figure 1 - Preview of market share by fuel type

Source: EBTP

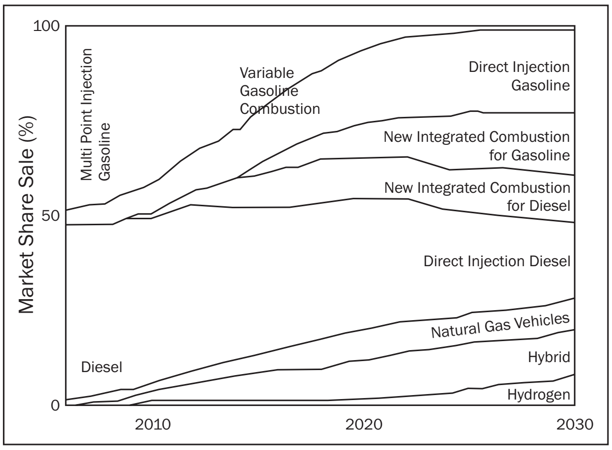

Figure 2 - Market share of new passenger cars & light commercial vehicles (<6t)

Source: EBTP

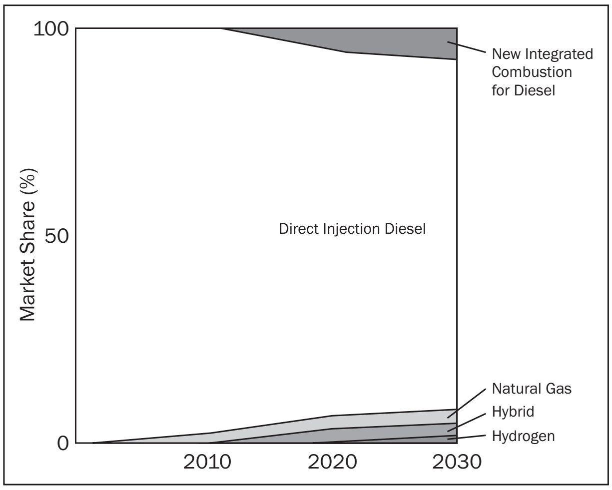

Figure 3 - Market share of new commercial vehicles (>6t)

Source: EBTP

of flexibility regarding the shift in the market segment of commercial and cargo vehicles which is currently held by the Diesel engines. This means that no significant change is expected in the following twenty years. The reason for this is certainly the current lack of alternative to Diesel engines for use in commercial vehicles. However, it should be considered that this vehicle category implicates higher purchasing costs, which in turn implicates a relatively longer payback period (as well as heavy machinery, marine vessels, agricultural machines, etc.).

Based on the abovementioned facts, it can be assumed in general that the usage of engines which use some of oil derivatives, due to the economic interests of the most developed countries in the world, as well as their wide presence in the global economy, will continue until the oil reserves are completely depleted.

Considering the described situation, i.e. relative lack of flexibility in the change of the Diesel engines market share, it should be emphasised that apart from their higher economic efficiency, Diesel engines can also have an extremely negative impact on the environment, as well as on the health of population. In developed countries, such as Switzerland, Germany, Austria, France, etc. this problem has been considered with increasing attention, so its serious research started already in the late 1970s. The results of these researches have proven that Diesel engine exhaust gases can have negative impacts and cause very high subsequent costs (for example medical treatment of people suffering from lung diseases) and in this way seriously challenge its usability and profitability. The most expressed awareness of the negative impacts of Diesel engine exhaust gases is present in Switzerland that introduced 10x stricter limit for sulphur content in Diesel fuel compared to the actual European norm EU590. At the same time, the obligation to use Diesel particulate filters for several Diesel powered applications has been legally regulated.

The current lack of studies in the Republic of Croatia that would deal more seriously with the problems mentioned above shows the necessity of making detailed analyses of Diesel engine emission impacts as well as plan activities to diminish it. It is time to focus on this topic and start resolving it now. In this way Croatia can prevent facing these open environmental issues by joining the European Union in the year 2013. This fact also represents the authors' basic motivations to work on this paper.

This paper is based on the data and results of various studies carried out in the European Union countries and partly in the United States of America. As already mentioned, since the economic development and the accompanying issues in the Republic of Croatia follow the trends of the economically high-developed countries, the authors think that the synthesized research results presented in this paper can also be used for identifying conditions as well as for searching for solutions applicable in the Republic of Croatia.

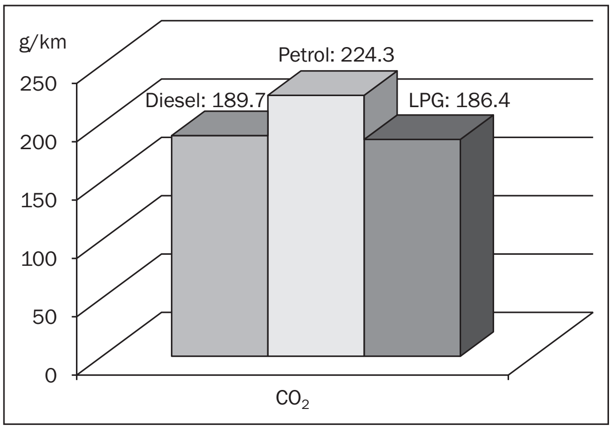

Figure 4 - Average CO_2 emissions for Diesel powered passenger vehicles

Source: EETP

In comparison with gasoline engines, Diesel engines have somewhat lower specific emission of carbon dioxide (CO_2) per kWh of delivered mechanical energy due to somewhat higher level of fuel efficiency (*Figure 4*). However, the Diesel engine exhaust gases contain multiply higher amounts of nitrogen oxides (NO_x) and particulates. Also, due to the nature of their process, the purifying of Diesel engines exhaust gases is technically a much more complex issue compared to the gasoline engines where the use of a single 3-way catalytic converter usually gives satisfactory results.

2. REVIEW OF GENERAL OBSERVATIONS AND RESEARCH RESULTS OF DIESEL EXHAUST GAS IMPACTS

According to the results of the research carried out in Switzerland, the scope of micro-particulate pollution indicates that about 40% of population are exposed to their excessive influence which means that about three million people are being threatened [20]. The extremely threatened part of population are those living in big cities, close to major transport hubs and those who are exposed to permanent or increased concentration of exhaust gases at their workplaces. It is emphasised that professional drivers have higher tendency to develop lung cancer by more than 50% from the average. As well as workers in civil engineering and tunnel construction (operators of excavators, bulldozers and other construction Diesel powered machinery), also railway personnel, farmers and agricultural workers who, due to the high average age of the tractors and other agricultural machinery, can be exposed to long-lasting high concentrations of soot particulates and other harmful substances of exhaust gases.

Starting from 1 January 2005 the European Union has limited the permitted quantity of microparticulates in the atmosphere to $50\mu g/m^3$, with up to 35 excesses per year. The actual average permitted amount of microparticulates in the European Union is limited to $40\mu g/m^3$ with a tendency of further decrease [19].

In extremely polluted areas only one breath intake brings into the organism more than 50 million particulates. While the currently valid standards limit the mass of particulates that the on-road vehicles are permitted to emit into the environment, more recent studies show that the harmful effect of particulates on human health is inversely proportional to their size. The ratio between the particulate surface and its volume and mass is higher the smaller the particulate. This is the reason why it would be more important to reduce the number of particulates rather than their total mass [23].

According to the research which was carried out and published in the year 2000 in Germany, between 1 and 2% of the total number of deaths are caused by the impacts of Diesel exhaust gases emitted from on-road vehicles. In absolute figures, in the same year, between 10,000 and 19,000 people died in Germany as a result of the environmental impacts mentioned above. However, even such a big figure is the result obtained by a conservative method. A more recent study, carried out jointly by Austria, Switzerland and France, showed that the consequences of the impact of nanoparticulates causes as much as 6% of the total annual mortality in these countries. Moreover, at least half of the emission of nanoparticulates comes from on-road applications.

According to the data published by the Swiss Ministry of Environment Protection, 3,700 of total 62,500 deaths in the year 2004 are attributed to the impacts of pollution with microparticulates [20]. For comparison, in the same year 600 people were killed in traffic accidents. The medical treatment costs of the diseases caused by this pollution have reached CHF 4.2 bn. [20]. According to the data provided by the World Health Organization 280,000 people died as consequence of the harmful effect of microparticulates in Europe in the same year [20].

In Switzerland, approximately 15,000 construction machines were retrofitted with Diesel particulate filters by September 2005. The total costs of the retrofit were estimated at approximately CHF 300 mil., but only medical treatment cost savings are expected to reach CHF 1.6 bn. [20].

Since the year 2001, the French automotive concern Peugeot-Citröen has included Diesel powered vehicles equipped with particulate filters in their production programme. Starting with 135,000 vehicles produced in that year, already in 2005 approximately one million delivered vehicles were equipped with diesel particulate filters. Today, every world-known on-road vehicle manufacturer produces vehicles equipped with such exhaust gas purifying systems.

3. REGULATION OF EXHAUST GAS COMPOSITION

Besides the awareness about the necessity of limiting the quantities and composition of Diesel exhaust, it was noted that in the economically developed countries certain standards in relation to the restriction of harmful substances in the composition of exhaust gases had been brought already before the Euro 1 standard came into force in 1992. This fact confirms that the economically developed countries have dealt with these pollution issues for years, showing continuous efforts to reduce the share of harmful substances in the composition of exhaust gases. This refers to different criteria that came into force before the 1 January 2011, since when it has been possible to register a new vehicle only if it complied with the Euro 5 standard, whose homologation started on 1 September 2009. Apart from the traditionally industrial countries of Europe and North America, the so-called new industrial countries such as China, India and Turkey have started to deal with these issues.

3.1 Overview of Diesel engine exhaust gas standards development in the European Union

The enclosed tables refer to Germany, but will be coming into force with specific dynamics in the European Union countries. Since the standardization of the exhaust gases composition is application-specific, enclosed Tables 1, 2, 3, 4 and 5 show the three most frequently used: off-road (primarily agriculture and civil engineering - Tier[2] standard), rail (Tier standard) and on-road (Euro[3] standard).

The presented Tables with the limit values show only a minor part of the regulations implemented in the European Union. It is known that the exhaust gas composition depends on a number of factors of which the most important ones are fuel type and quality, mode of engine operation and engine design. The above standards include also test cycles that could not have been presented in this paper. These test cycles regulation established conditions for obtaining repeatable and comparable measurement results in typical mode of operation for different ap-

Table 1 - Off-road application [21]

Power P_N (kW)	NO_x (g/kWh)	HC (g/kWh)	CO (g/kWh)	PM (g/kWh)	Date
	NO_x + NMHC				
Tier 4 - Phase I					
$37 \leq P_N < 75$	9.2	1.3	6.5	0.85	Apr 1999
$75 \leq P_N < 130$	9.2	1.3	5.0	0.70	1999
$130 \leq P_N \leq 560$	9.2	1.3	5.0	0.54	1999
Tier 4 - Phase II					
$18 \leq P_N < 37$	8.0	1.5	5.5	0.8	2001
$37 \leq P_N < 75$	7.0	1.3	5.0	0.4	2004
$75 \leq P_N < 130$	6.0	1.0	5.0	0.3	2003
$130 \leq P_N \leq 560$	6.0	1.0	3.5	0.2	2002
Tier 4 - Phase IIIA					
$19 \leq P_N < 37$	7.5		5.5	0.6	2007
$37 \leq P_N < 75$	4.7		5.0	0.4	2008
$75 \leq P_N < 130$	4.0		5.0	0.3	2007
$130 \leq P_N \leq 560$	4.0		3.5	0.2	2006
Tier 4 - Phase IIIB					
$19 \leq P_N < 37$	4.7		5.0	0.025	2013
$37 \leq P_N < 75$	3.3	0.2	5.0	0.025	2012
$75 \leq P_N < 130$	3.3	0.2	5.0	0.025	2012
$130 \leq P_N \leq 560$	2.0	0.2	3.5	0.025	2011
Tier 4 - Phase IV					
$56 \leq P_N < 130$	0.4	0.2	5.0	0.025	Oct 2014
$130 \leq P_N \leq 560$	0.4	0.2	3.5	0.025	2014

Table 2 - Locomotive engines [21]

Tier 4 Phase	Power P_N (kW) Cylinder vol. (l)	NO_x (g/kWh)	HC (g/kWh)	CO (g/kWh)	PM (g/kWh)	Date
IIIA	$130 \leq P_N \leq 560$	4.0	4.0	3.5	0.2	2007
	$560 \leq P_N \leq 2000$	6.0	0.5	3.5	0.2	2009
	> 2000 > 5 l	7.4	0.4	3.5	0.2	2009
IIIB	$P_N > 130$	4.0	4.0	3.5	0.025	2012

plications. The differences in the permitted limits are particularly evident between various measurement cycles in on-road applications. The European Steady State Cycle (ESC) and the European Load Response

Table 3 - Railroad motorcar engines [21]

Tier 4 Phase	Power P_N (kW)	NO_x (g/kWh)	HC (g/kWh)	CO (g/kWh)	PM (g/kWh)	Date
IIIA	P_N > 130	4.0		3.5	0.2	2006
IIIB	P_N > 130	2.0	0.19	3.5	0.025	2012

Table 4 - Limit values to test in ESC and ELR cycles for commercial vehicles [21]

Phase	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	PM (g/kWh)	Smoke m^{-1}	Date
Euro 3	2.1	0.66	5.0	0.10	0.80	Oct 2001
Euro 4	1.5	0.46	3.5	0.02	0.50	Oct 2006
Euro 5	1.5	0.46	2.0	0.02	0.50	Oct 2009
EEV	1.5	0.25	2.0	0.02	0.15	non obligatory
Euro 6	1.5	0.13	0.4	0.01		Jan 2013

Table 5 - Limit values for ETC test for commercial vehicles [21]

Phase	CO (g/kWh)	NMHC (g/kWh)	CH4 (g/kWh)	NO_x (g/kWh)	PM (g/kWh)	Date
Euro 3	5.45	0.78	1.60	5.0	0.16	Oct 2001
Euro 4	4.00	0.55	1.10	3.5	0.03	Oct 2006
Euro 5	4.00	0.55	1.10	2.0	0.03	Oct 2009
EEV	3.00	0.40	0.65	2.0	0.02	non obligatory
Euro 6	4.0	0.16	0.5	0.4	0.01	Jan 2013

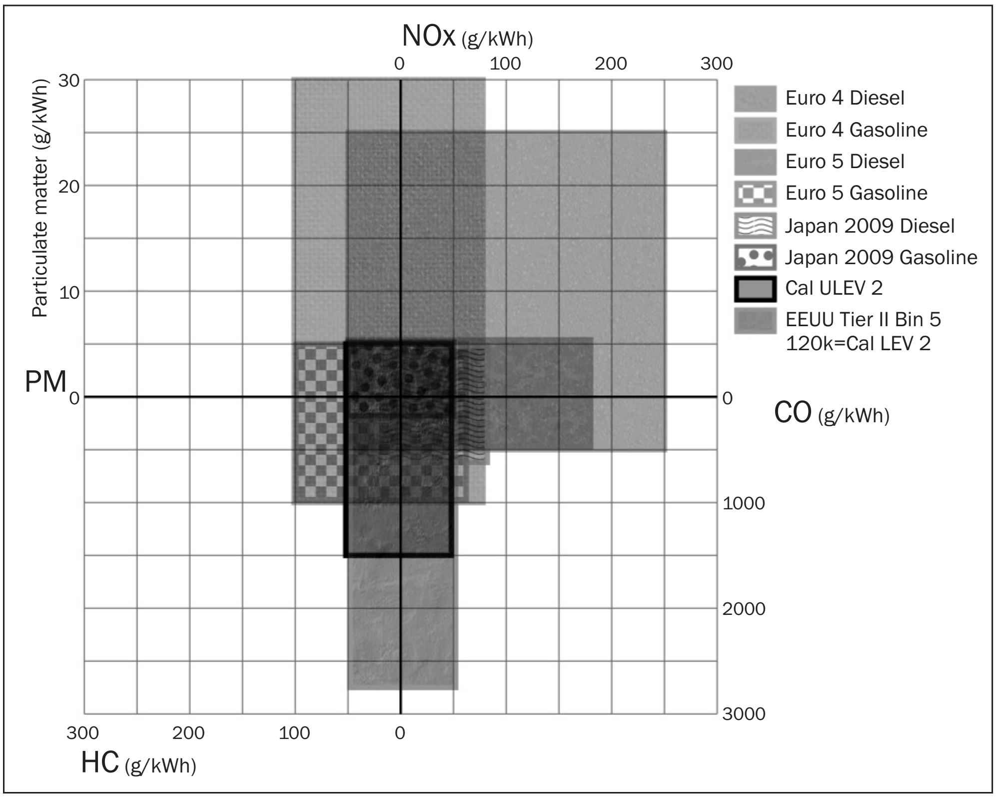

Figure 5 - Vehicle emissions standards in EU, USA and Japan

Source: Wikipedia, http://fr.wikipedia.org/wiki/Norme_européenne_d'émission_Euro

Test (ELR) regulate the measurements at different engine speeds i.e. different torques. The European Transient Cycle (ETC) regulates the measurements under dynamic conditions which simulate engine mode of operation in urban, interurban and highway traffic. This test cycle is obligatory for all vehicles exceeding 3.5 tons in category Euro 4 or higher and for Euro 3 vehicles equipped with Diesel particulate filter as well as for the Euro 3 vehicles equipped with DeNOx[4] system. As the highest concentrations of harmful exhaust gas substances are emitted during dynamic operating mode of the engine, the limit for the ETC test is significantly higher than for the ESC and ELR.

Due to the actual lack of affordable technologies, these standards do not cover Diesel engines in very low and very high power range, i.e. these power ranges are not included because of too high relative costs of the equipment compared to the price of the engine. With further development of the exhaust gas filtering and processing technology, as well as with the cost reduction of its implementation, these power categories will be covered by the standards as well.

In off-road use and in rail transport, apart from tightening the criteria, there is continuous expansion of the area of nominal engine power to which the standard is applied. However, the strictest standards are applied in road traffic (*Figure 5*), as the most visible and certainly the most significant polluter. Moreover, road vehicle lifecycle is much shorter than in off-road applications or in rail traffic.

Figure 5 presents the limits of dangerous substances in exhaust gases according to various standards. Quadrant I shows the nitrogen oxide limit (NO_x), Quadrant II shows the particulate matter limit (PM), Quadrant III shows the not combusted hydrocarbons limit (HC) and Quadrant IV shows the limit of carbon monoxide (CO).

3.2 Low Emission Zones (LEZ) and the advantages depending on the ecological category of the vehicle

LEZ are being introduced in a growing number of European cities in order to reduce air pollution caused by particulates coming from exhaust gases. On 1 March 2007 a new regulation came into force in Germany, allowing the introduction of LEZ in urban areas with the goal of improving air quality. This regulation includes traffic restrictions depending on exhaust gas limits in accordance to the Euro standards. Vehicles are classified into four ecological categories as follows:

- S1 (vehicle using Diesel fuel, Euro1 or lower and gasoline without catalytic converter),
- S2 (vehicle using Diesel fuel, Euro2 or Euro1 with particulate filter),
- S2 (vehicle using Diesel fuel, Euro3 or Euro2 with particulate filter),
- S4 (vehicles using Diesel fuel, Euro4 or higher or Euro3 with particulate filter).

The particulate filter is installed in a vehicle as a replacement for the exhaust system silencer. The so-called closed filter (trap) reduces emission of particulates, carbon monoxide and not combusted hydrocarbons up to 90% or even more. In Germany, the particulate filter installation is legally regulated according to the "Anlage XXVII", which is based on the EU Directive 2005/55/EG, 2006/51/EG and 97/68/EG. The state authorities financially support the transport companies with €2,000 per filter retrofitted truck (Program De-minimis).

To enter the LEZ, a vehicle must have a sticker displayed on the windshield whose color depends on the ecological category to which the vehicle belongs:

- red for category S2,
- yellow for category S3
- green for category S4.

With the introduction of LEZ, some vehicles are limited or completely banned from entering the territory of the zone. Today there are LEZ in 41 cities in Germany while approximately ten new ones are being planned. In the Netherlands LEZ are introduced in 11 cities, in Denmark 5 and in Italy in 12. Further, 8 LEZ are planned to be introduced in France, followed by Norway, Austria, the Czech Republic, Hungary and others.

In addition, in Germany vehicles are charged a different toll on highways based on their ecological category. For example, a toll for a heavy duty truck of category Euro4 or Euro3 with particulate filter is approximately 11% lower than for the same vehicle of category Euro3. A Euro5 category truck toll costs 24% less compared to Euro3. In Austria the difference is 13% and in Slovenia 11%, but the retrofit with particulate filter in these countries has not been regulated yet. In Croatia, heavy duty vehicles of Euro4 category get 3% discount, while Euro5 get 5% discount on toll if they are using the ENC toll payment system. In addition to the benefits mentioned above, in an increasing number of European countries, vehicle owners have tax benefits and reduced registration costs depending on ecological category of the vehicle.

4. DISCUSSION

Negative impacts of Diesel exhaust gases have been identified as the most harmful to human health and environment compared to all other types of currently available fuels (gasoline, Compressed Natural Gas – CNG, Liquid Petroleum Gas – LPG etc.) [20].

Contrary to the research results presented above, some studies carried out in the USA do not confirm any connection between Diesel exhaust gases in terms of their negative impact on certain human organs. More precisely, the attempt to find a correlation between bladder [9] or laryngeal carcinoma [10] in male persons more exposed to Diesel exhaust gases failed to prove any connection.

On the other hand, studies carried out in the economically most developed European countries (Switzerland, Germany, Austria, France) whose population is the most exposed to negative impacts of Diesel exhaust gases clearly shows that there is direct connection between certain types of malignant diseases and a level of pollution by Diesel exhaust gases, particularly in urban areas. It has been proven that the increase of nitrogen dioxide concentration in the atmosphere by $0.1 g/m^3$ causes approximately 4% increase in the mortality rate of heart and respiratory system diseases. It has also been proven that human organism is not capable of defence against the particulates which, due to the development of Diesel engines, have become so tiny (0.1 to $1 \mu m$) that they can penetrate through respiratory system and deposit in any part of the human organism, causing malignant diseases. Furthermore, the research carried out in the USA has proven that negative impacts of particulates on atmosphere warming are between 360,000 and 840,000 times higher compared to the same carbon dioxide mass, which was considered the main cause of global warming. The best illustration of the harmful impact of Diesel exhaust gases on the human health may be the fact that the cause of death for 3,700 people out of 62,500 who died in Switzerland in the year 2004 is considered to be in connection with pollution by microparticulates. In the same year 600 people died in traffic accidents.

It is important to say that the mentioned negative consequences of Diesel exhaust gases can be remarkably reduced by retrofitting vehicles with Diesel particulate filters (DPF). It has been noted that the retrofit costs are lower than the potential medical treatments of the diseases connected to the pollution by Diesel exhaust gases.

Apart from retrofitting vehicles with DPF which is a widespread technology used to reduce particulate emissions in Diesel exhaust gases, *Figure 6* shows a possible shift from Diesel to alternative fuels such as CNG and LPG for different types of on-road applications.

The results of a research entitled "2003 European Emissions Testing Programme" [11] have shown that gasoline engines emit approx. 20% more CO_2 per kWh of delivered mechanical energy in comparison with those using LPG fuel. Furthermore, the same research results show that Diesel engines produce 1.8% more CO_2 per kWh of delivered mechanical energy in comparison with LPG fuelled engines. The displayed difference is a consequence of the already mentioned higher efficiency level of Diesel engines which combined with characteristics of Diesel fuel results in lower CO_2 emission. Unlike small differences between the CO_2 emissions in Diesel exhaust gases compared with engines using LPG, the exhaust gases of Diesel engines produce remarkably higher specific NO_x emissions than those using LPG. This problem is significantly reduced with the introduction of Euro5 and technically solved by using SCR[5] catalytic converters. However, SCR process needs additional media which increases the price of the vehicle and its operating costs.

The introduction of the CNG powered vehicles which due to their slightly lower CO_2 emissions at first sight seem like environmentally friendly, implies significantly higher purchase price combined with shorter range of movement and high investments in infrastructure needed to fuel the vehicles. In addition, recent studies indicate that the CNG-powered vehicles emit

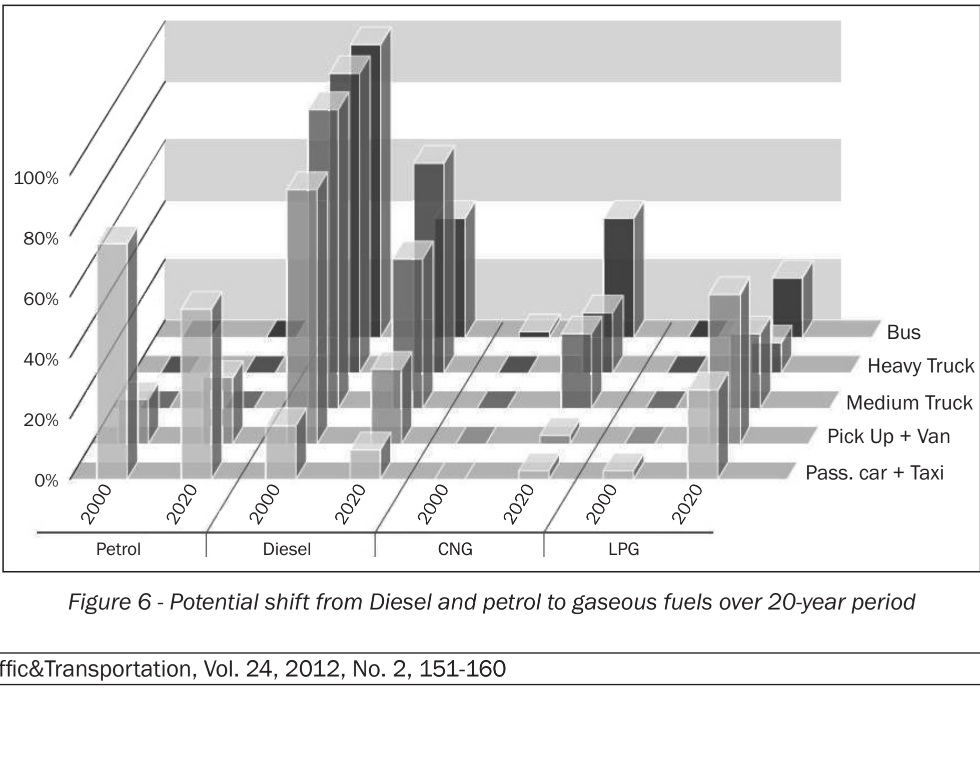

Figure 6 - Potential shift from Diesel and petrol to gaseous fuels over 20-year period

remarkable amounts of methane (CH_4) and nitrous oxide (N_2O) as most intense greenhouse gases, which is why their ecological acceptability is being questioned. For these reasons, this fuel did not reach significant market shares and some European cities have already stopped further investments in new vehicles and required supporting infrastructure.

The data presented above show that the level of indirect costs caused by uncontrolled emission of pollutants contained in Diesel exhaust gas already exceeds the direct financial benefit achieved by their use.

5. CONCLUSION

Diesel engine will most likely remain one of the technological foundations of economy for many years. Due to its efficiency, continuously present increase of energy prices, as well as due to current lack of economically and technologically acceptable alternatives, it can be expected that they will maintain a high share, particularly in on-road applications. As until now, we will be continuously exposed to direct and indirect impacts of exhaust gases which are practically inevitable, especially in urban areas. The presented results, as well as further increasing tendency of air pollution caused by Diesel exhaust gases, primarily by particulates and nitrogen oxides, show that while assessing their profitability, apart from the direct costs, the calculation needs to take into account also all indirect costs resulting from their usage.

The research carried out in the European countries and in the USA as the economically most developed parts of the world that are, at the same time, the most exposed to negative impacts of Diesel exhaust gases, clearly shows which direction should be taken by Croatia as a country that needs powerful economic development. Since Croatia is an important transit area because of its convenient geographic location and due to its future European Union membership, it is important to adopt, recognise and implement all the acts and standards mentioned in this paper. Apart from this, it is of utmost importance for Croatia to recognise all the negative medical and financial effects caused by the impact of Diesel exhaust gases on the population and on the environment. This also requires undertaking of all the necessary steps to reduce harmful emissions and their negative impacts.

VANJA JURIĆ, dipl. ing.
E-mail: vanja.juric@tradeing.eu
Tradeing d.o.o.
Jordanovac 119, 10000 Zagreb, Hrvatska
Dr. sc. **DINO ŽUPANOVIĆ**
E-mail: dino.zupanovic@fpz.hr
Sveučilište u Zagrebu, Fakultet prometnih znanosti
Vukelićeva 4, 10000 Zagreb, Hrvatska

SAŽETAK

EKOLOŠKI UČINCI EMISIJE DIESELOVIH MOTORA

Članak obrađuje ekološke posljedice djelovanja kemijskih spojeva iz sastava ispušnih plinova dizelskih motora, te donosi pregled zakonske regulative koja ograničava njihovu maksimalnu dozvoljenu emisiju. Poseban osvrt je stavljen na do sada većinom zanemarivan negativan učinak čestica koji se posebno očituje kroz štetno djelovanje na zdravlje ljudi. Pri tomu, financijski izdaci koji se izdvajaju za njihovo liječenje premašuju financijske uštede nastale korištenjem vozila s dizelskim motorima. Sukladno tome, iznesene su spoznaje dosadašnjih znanstvenih istraživanja u ekonomski najrazvijenijim zemljama, kao i tendencije za smanjivanje negativnih učinaka ispušnih plinova dizelskim motora.

KLJUČNE RIJEČI:

dizelski motor, ispušni plinovi, ekološki učinci, zakonska regulativa

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5. SCR (Selective Catalityc Reduction) is a method of converting nitrogen oxides (NO_x) and ammonia (NH_3) into nitrogen gas (N_2) and
6. steam (H_2O).

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