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Comparison of emissions depending on the type of vehicle engine

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***Abstract*—Road transport is showing growth in the period of globalization. Its task is to transport cargo as well as people to the required location within the shortest possible time and at the lowest price. Thus, road transport plays a crucial role in enabling the globalization to be developed and improved. However, the internal combustion engine hat prevail among the vehicles of freight and passenger transport are the producers of gaseous emissions from the exhaust gases. Many developed countries of the world has committed themselves, inter alia also trough the Paris Agreement, to reduce global warming, and thus to reduce the production of harmful gaseous emissions. The result is the endeavour to replace the internal combustion engine vehicles that burn carbon fuels with the vehicles powered by electric motors consuming electric energy. The reason of such trying claims that road transport using the internal combustion engine vehicles is environmentally aggressive, and the problem would not be solved by implementation of the vehicles with electric motors. Such claim is based on the fact that an electric car does not produce any of primary emissions. From an overall perspective, it is also necessary to take into account secondary emissions that are produced during the electric energy production by which is the vehicle with electric motor powered. The purpose of this article is to assume the possibility of reducing global pollution by replacing the internal combustion engine vehicles with the vehicles powered by electric motors in dependence with producing the emissions during the production of electric energy.**

***Index Terms*—electric energy, emissions, electric vehicle, internal combustion engine, global pollution**

I. INTRODUCTION

It is a well-known fact that the Earth is warming up and the average temperatures are rising [1]. This causes melting of the ice on both poles of the Earth. It is caused by the greenhouse effect which is the result of CO_2 emitits [2]. This gas is considered the main gas causing the greenhouse effect, although not the only one [3]. Other gases also contribute to the greenhouse effect and their impact on the total warming is calculated by coefficient [4]. If we want to slow down global warming and thus slow down melting of the ice and rising of sea levels, the only way is to reduce emits of the greenhouse gases [5]. Melting of ice and associated rising of sea levels is a big threat for maritime countries which could loose vast areas [6]. Therefore, the only solution is to reduce the emits of greenhouse gases. Transport is considered one of the main producers of these gases, specifically, internal combustion engines which use the energy of hydrocarbon fuels [7]. One of the often claimed solutions is that by the use of electric energy this problem would be eliminated [8]. Another frequently used statement is that the road transport is not ecological [9].

Emissions of road vehicles

Road vehicles get the energy necessary to overcome road resistance by combustion of hydrocarbon fuels [9]. Burning at high pressure and temperature generates many gaseous emissions which are contained in the exhaust gases [9]:

nitrogen – N_2,
oxygen – O_2,
water, water vapour –H_2O,
carbon monoxide – CO,
carbon dioxide – CO_2,
sulphur dioxide – SO_2,
hydrocarbons – HC,
nitrogen oxides – NO_X,
particulate matter [8].

Carbon dioxide CO_2

It is regarded as the most spread greenhouse gas with the share of about 55%. Carbon dioxide is colourless, non-toxic gas, heavier than air. Thanks to photosynthesis in plants it cyclically returns back to biosphere. Combustion of fossil fuels releases into air about $1,4.10^{10}$ t CO_2 every year. At present, the amount of carbon dioxide increases annually by 0.2% [15].

Sulphur dioxide SO_2

is colourless, non-flammable gas with pungent odour. It causes respiratory diseases. In exhaust gases it is contained only in small amount if sulphur containing fuel was used [16].

Hydrocarbons HC

are the result of a poorly burned fuel. They exist in many various forms as unburned or partially burned fuel components. Some hydrocarbons irritate sense organs, others are carcinogenic (benzole) [17].

Nitrogen oxides NO_X

Combustion of hydrocarbon fuels at high temperature and pressure and sufficient amount of oxygen results in the occurrence of nitrogen oxide NO and nitrogen dioxide NO_2. Their percentage in exhaust gases is 10 – 20 % in CI engines, compression ignitigion, and 2% in SI engines, spark ignitions engines. They react with haemoglobin and modify the iron in haemoglobin from Fe^{2+} to Fe^{3+} and thus create a haemoglobin modification - methaemoglobin, which is stable and unable to bind oxygen. In large concentrations they react with moisture in lungs and create nitric acid and nitrous acid which cause acute respiratory disease [18]. Nitrogen oxides aggravate:

- heart diseases,
- cyanosis (blue-purplish discolouration of skin and mucous membrane by insufficient oxygenation of blood caused by the increase of the amount of reduced haemoglobin to over 50 g/l),
- they have vasodilating effect which causes lowering of blood pressure,
- they cause pneumonia and swelling of lungs,
- leaves of plants turn pale, get smaller and, finally, wither,
- nitrogen oxides catalyse oxidation of SO_2 to more harmful SO_3.

Nitrous oxide, N_2O, is a colourless gas with pleasant odour and sweetish taste. It disrupts the ozone layer and causes greenhouse effect 310-times more effectively than CO_2. The life of nitrous oxide in the atmosphere is estimated at 150 years. It is toxic for humans and when inhaled it has caustic effect on mucous membranes. In small amounts it causes intoxication and in higher doses it acts as a narcotic. It causes deterioration of psychomotor performance, worsens the ability to learn and remember [8].

Nitrogen oxide, NO, is created at temperature higher than 1300 °C (at the end of expansion the temperature inside cylinders reaches up to 1000 – 1800 °C). In contact with oxygen it reacts to nitrogen dioxide and in combination with water it creates nitric acid. It reacts with metals and organic substances. It creates weak acids in rainfall water and contributes to the creation of photochemical smog. In organism it has an important biological function. It secures communication between the cells [9].

Nitrogen dioxide, NO_2, is created by oxidation of nitrogen oxide in flame as well as in the free air. It is more toxic and more active than nitrous oxide and nitrogen dioxide. It is a malodorous gas and when inhaled it causes irritation. When inhaled by asthmatic it causes an asthmatic attack. Ultraviolet radiation causes a chemical reaction resulting in the occurrence of ground-level ozone [19].

Particulate matter PM

The EU set the limit for their occurrence at 50 mg/m^3 as a 24-hour average for the concentration of microparticles smaller than 10 µm – PM10. (1 µm = 10^{-6} m). Particles with the size of 10 and more µm collect in the nose and mucous membranes. Particles smaller than 2 µm penetrate deep into the lungs and can damage the lung cells [20].

The emissions of particulate matter in the EU cause 25 million respiratory diseases and 32 thousand premature deaths annualy [8]. Increase in the concentration of particulate matter in the air by 10 mg/m^3 leads to 1% mortality growth. Increase of the particle concentration by every 30 mg/m^3 results in the increase of asthmatic attacks by 12%. The risk of lung cancer is higher for the people living in cities than for people living in cleaner areas [8].

Every one of these gases is really harmful or dangerous. That is why their amount in vehicle exhaust gases is limited and these limits are regularly tightened [21]. Development of the permissible values is shown in Table 1 and 2. The amount of allowed emissions differs based on the type of combustion cycle for SI engines and CI engines of the category M1 vehicles and for other motor vehicles.

Table 1 Emission limits for passenger vehicles M1 [22]

Stage	Date	CO	HC	HC+NOx	NOx	Particulate matter
		g/kWh				
CI engines						
Euro 1	07/1992	2.72		0.97		0.14
Euro 2	01/1996	1.0		0.7		0.08
Euro 3	01/2000	0.64		0.56	0.50	0.05
Euro 4	01/2005	0.50		0.30	0.25	0.025
Euro 5	01/2011	0.50		0.23	0.18	0.005
Euro 6	09/2014	0.50		0.17	0.08	0.005
SI engines						
Euro 1	07/1992	2.72		0.97		
Euro 2	01/1996	2.2		0.5		
Euro 3	01/2000	2.3	0.20		0.15	
Euro 4	01/2005	1.0	0.10		0.08	
Euro 5	01/2011	1.0	0.10		0.06	0.005
Euro 6	09/2014	1.0	0.10		0.06	0.005

Emission limits for CI engines in heavy goods vehicles is shown in Table 2.

Table 2 Emission limits for CI engines in heavy goods vehicles [22]

Stage	Date		CO	HC	NOx	Particulate matter	smoke opacity
			g/kWh				m^{-1}
Euro I	1992	<85 kW	4.5	1.1	8.0	0.612	
		>85 kW	4.5	1.1	8.0	0.36	
Euro II	10/1996		4.0	1.1	7.0	0.25	
Euro III	10/2000		2.1	0.66	5.0	0.10	0.8
Euro IV	10/2005		1.5	0.46	3.5	0.02	0.5
Euro V	10/2008		1.5	0.46	2.0	0.02	0.5
EEV			1.5	0.25	2.0	0.02	0.15
Euro VI	01/2016		1.5	0.13	0.4	0.01	

These are the limits specified for gases discharged from the exhaust system of the engine. For comparison purposes we can use the emission data published by the electricity producer and calculate their amount as per produced kWh of electric energy at the power plant terminals. This information is specified in Table 3

Table 3 Emissions of power plants in Slovakia [23]

	Year						
	2011	2012	2013	2014	2015	2016	2017

SO_2 [t]			40 184	33 980	31 381	25 152	47 265	6 393	7 248
SO2 [g/kWh]		thermal	15.25	13.18	13.73	11.35	22.19	3.10	3.30
		SR in total	1.79	1.53	1.37	1.14	2.14	0.34	0.37
CO_2 [t]					2675000	2453000	2536000	2305000	2409000
CO_2 [g/kWh]		thermal			1170.7	1106.9	1190.6	1119.5	1096.0
		SR in total			117.1	111.0	114.7	121.4	123.9
CO [t]			838	777	721	707	700	1144	974
		thermal	0.3180	0.3014	0.3155	0.3190	0.3286	0.5556	0.4431
		SR in total	0.037	0.035	0.032	0.032	0.032	0.060	0.050
NO_x [t]			4,856	4,145	3,449	3,373	3,885	1,887	1,824
NO_x [g/kWh]		thermal	1.84	1.61	1.51	1.52	1.82	0.92	0.83
		SR in total	0.216	0.186	0.151	0.153	0.176	0.099	0.094
TZL [t]			541	340	313	313	533	169	102
TZL [g/kWh]		thermal	0.205	0.132	0.137	0.141	0.250	0.082	0.046
		SR in total	0.0241	0.0153	0.0137	0.0142	0.0241	0.0089	0.00525
Power production at terminals [GWh]	nuclear		14,574	15,495	15,720	15,499	15,146	14,774	15,081
	thermal		2,635	2,578	2,285	2,216	2,130	2,059	2,198
	Hydroelectric		2,880	1,711	1,896	2,006	1,981	2,146	2,163
	Gabčíkovo		2,375	2,459	2,619	2,043	448	na	na
	In total		22,463	22,245	22,843	22,105	22,105	18,981	19,444
% share of thermal plants on the total power production			11.73	11.59	10.00	10.02	9.64	10.85	11.30

II. SIMULATION

If we compare Table 1, 2 and 3 we conclude that the legislation did not take into consideration production of SO_2 by motor vehicles [21]. This is due to the fact that 1 kg of diesel oil may contain only less than 10 mg of sulphur. This means that if the company Slovnaft Bratislava produces 3 million tons of diesel oil a year [20], this may contain only 30 tons of sulphur. Even after increasing the weight after combination with oxygen it is definitely less than what is produced by power plants. Other components are compared in Table 5. For the category M1 vehicles we considered the energy intensity of a single urban cycle 0.48 kWh at the travelled distance of 1.013 km [19]. The CO_2 production in SI engines was substituted by the value specified in the vehicle fuel consumption and adjusted it with regard to the energy intensity of the urban cycle. Slovakia is one of the countries where the share of thermal power plants reaches deep under the EU average. Table 4 shows the overview of the share of fuel type in the EU power production in 2015.

Table 4 % share of the fuel type in the EU power production in 2015 [23]

fuel type	Coal	Oil	Natural gas	Nuclear energy	Renewable sources	Other
share [%]	18.9	9.0	14.0	28.9	26.7	2.5
in total for thermal plants [%]	41.9			28.9	26.7	2.5

III. Results

We added one line in Table 5 which converts the amount of emissions to the share of electric energy in the whole EU. If we want to be thorough we have to state that even the production of electric energy by nuclear power plants or by photovoltaic cells is not without emissions. According to [7] we can consider production of CO_2 by photovoltaic panel at the level of 45 g/kWh and by nuclear power plant at 20 – 40 g/kWh.

Table 5 Comparison of the emissions produced by power plants and the latest applicable limits for vehicles

	g/kWh			
Emission	CO	CO_2	NO_x	Particulate matter
Heavy goods vehicles	1.5	-	0.4	0.01
SI engines for M1 vehicles	0.989	253	0.06	0.06
Total production of power in SR	0.050	123.9	0.094	0.00525
Thermal plants in SR	0.443	1096.0	0.83	0.046
Emissions in EU for the share of thermal plants 41.9%	0.186	459.2	0.348	0.019

It would be suitable to offer another perspective of the issue. Emissions that we were comparing were emissions in exhaust gases of cars, but we compared them with emissions directly generated in the electricity production. And this has to be somehow transported to the electric cars. Electric cars use direct current. In this conversion we can consider the efficiency of $\eta_{rectification}$ = 90 %. Produced electric energy must be several times transformed and there are also losses in the distribution. The efficiency of this process at $\eta_{transfer}$ = 98 %. The accumulator does not emit the total stored energy either. Efficiency of this exchange varies with regard to the type of accumulator. Table 6 shows an overview of the efficiency of accumulators [24].

Table 6 Accumulator efficiency [8]

Accumulator	Charge/discharge efficiency [%]
Li-ion	80 – 90
Pb	50 – 92
NiMH	66

Electric cars are equipped with Li-ion accumulators so we can estimate their efficiency at $\eta_{accumulator}$ = 85 % [7]. While the electric energy gets into the electric motor, part of the produced electric energy disappears (1).

$$\eta_t = \eta_{transfer} \cdot \eta_{rectification} \cdot \eta_{accumulator} \quad (1)$$

$$\eta_t = 0{,}98.0{,}9.0{,}85 = 0{,}75$$

Then we can rewrite Table 5 into Table 7 which considers also losses of the transferred energy.

Table 7 Comparison of the emissions produced by power plants and the latest applicable limits for vehicles

	g/kWh			
Emission	CO	CO_2	NO_x	Particulate matter
Heavy goods vehicles	1.5	-	0.4	0.01
SI engines for M1 vehicles	0.989	253	0.06	0.06
Total production of electric energy in SR	0.067	165.2	0.125	0.007
Thermal plants in SR	0.591	1461.3	1.107	0.061
Emissions in EU for the share of thermal plants 41.9%	0.248	612.3	0.464	0.025

For the sake of better transparency and possibility to make a comparison, the values from Table 1 – 5 are also shown in the form of graphs, Fig. 1 – 5.

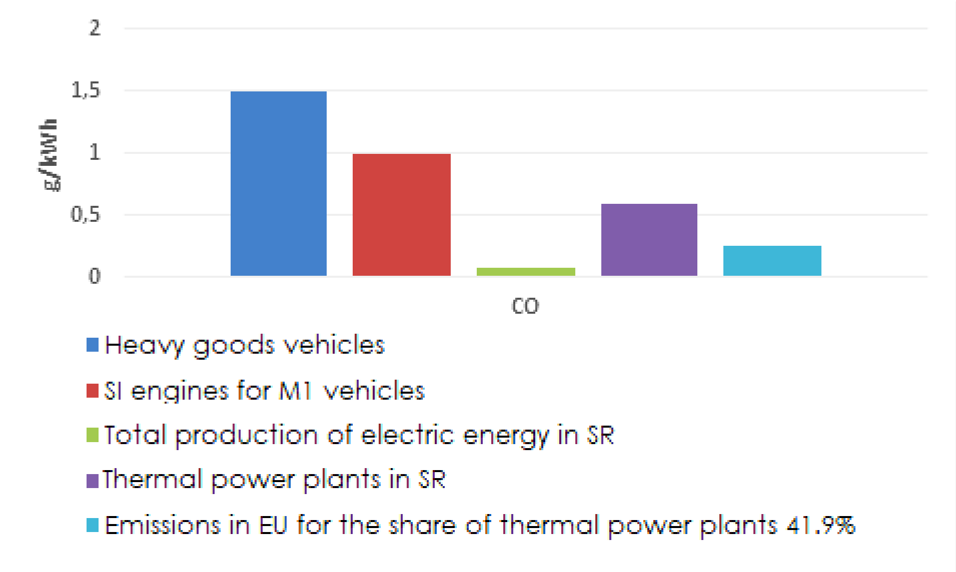

Figure 1 Production of CO per g/kwh

As follows from the Fig. 1, the heavy goods vehicles and SI engines for M1 vehicles have the biggest share in production of CO emissions after their recalculation into G/kwh. It is necessary, for the sake of objectiveness, to note that just those vehicles with a internal combustion engine are driving most across populated regions, and the population is, thus, exposed to adverse effects of CO on their health [29].

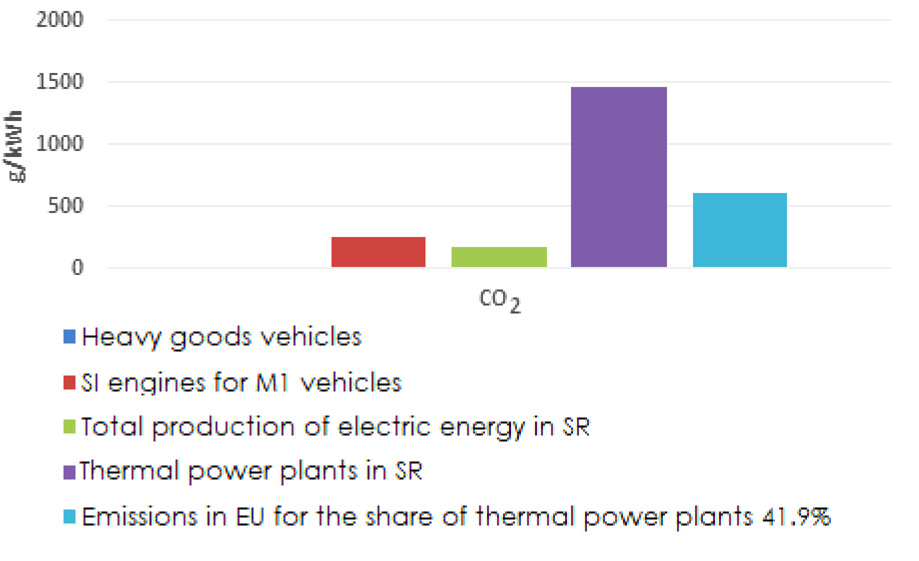

Figure 2 Production of CO_2 per g/kwh

Concerning the production of CO_2 grams per 1 KWH, the thermal plants definitely got the worst results. Their share on overall production of electric energy within the Member states of the European Union also was reflected in CO_2 emissions evaluation from all the European plants. Since Slovak plants are underrepresented, the production of CO_2 in g/kwh is lower than vehicles of category M1.

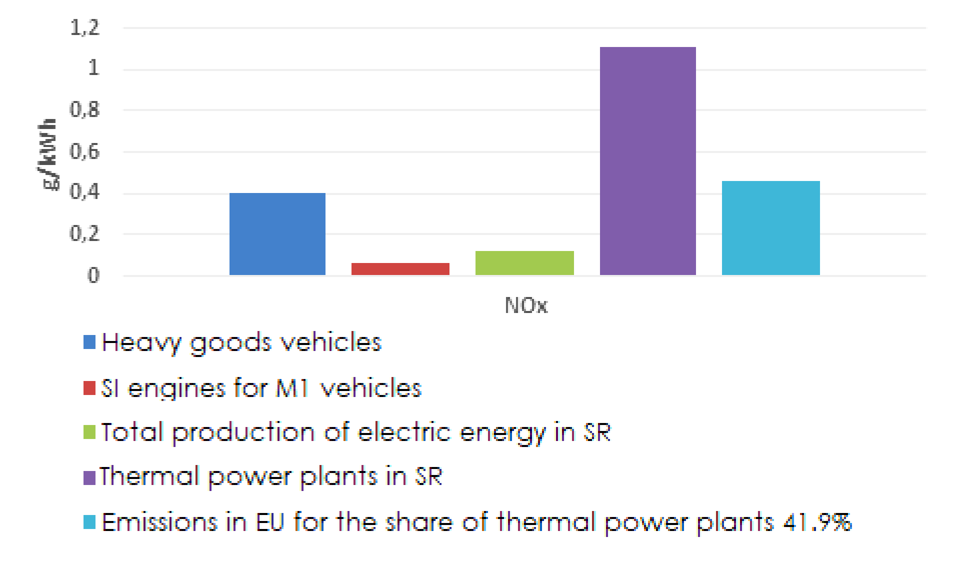

Figure 3 Production of NOx per g/kwh

Concerning NO_x production, these pollutants are significantly produced merely by the electric energy plant. NO_x are formed in a combustion space of the engine under the conditions of high temperature, high pressures as well as high excess of oxygen [26]. These parameters are reached by CI engines in heavy goods vehicles [27]. SI engines of vehicles category M1 create such conditions exceptionally only and, therefore, NOx emissions are the lowest of all categories compared [26].

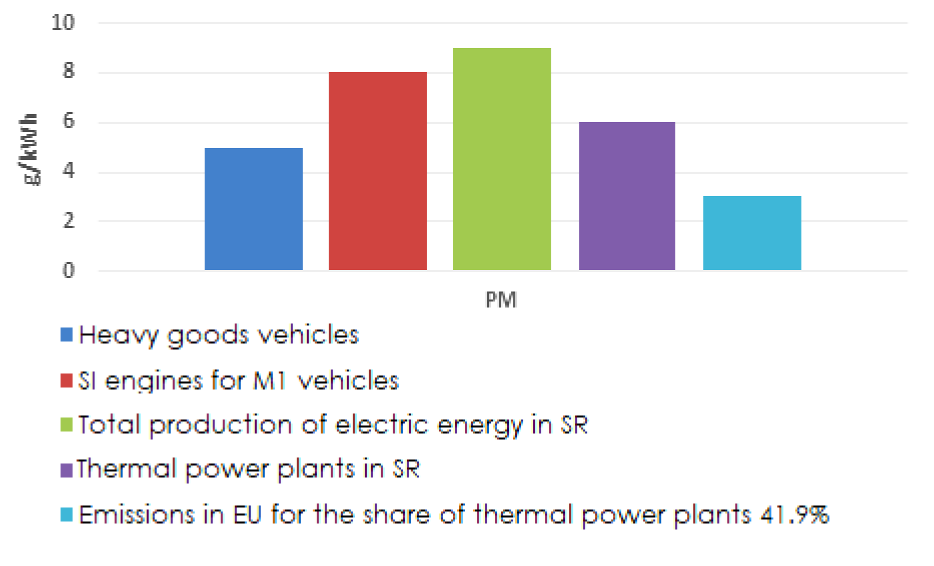

Figure 4 Production of PM per g/kwh

Relating to a comparison of production of particulates, producing an electric power in Slovakia has the most negative effect on the production of emissions.

IV. CONCLUSION

The results of calculations from this article made possible to compare the pollutants produced by particular types of vehicles and plants. Based on the calculations in this article, two assumptions can be made. The first assumption is that the expansion of electric vehicles in the European Union would reduce carbon monoxide and particulate emissions. The second assumption is that emissions of carbon dioxide and nitrogen oxides have been increased. As also mentioned in the text above, disadvantage of vehicles with a combustion engine is that they produce pollutants in populated regions. However, their harmful effects can be eliminated by creating low-emission zones, by prohibiting heavy goods vehicles to enter densely populated areas and their further partial replacement with electric cars [28]. Electric cars are also producers of harmful emissions, even indirectly. They use the energy which can lead to the production of emissions, although not directly in populated regions. To speak about electric traction as emission-less is rather debatable. Naturally, there are countries which produce their electric power from renewable sources, such as Norway, Iceland and some other, and for which the shift to electric traction will really be beneficial, but the global shift of the entire EU is, in our opinion, not an optimum solution.

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