Zoran Lulić
Eduard Missoni
Rudolf Tomić

ISSN 1333-1124

THE RELEVANCE OF GHG EMISSIONS FROM MOTOR VEHICLES

UDC 504.3.054:656.1

Summary

The Earth's atmosphere contains not more than 2% of greenhouse gases (GHG), and only 3.4% of them are produced by human activities. GHG emissions from road transport amount to less than 0.3 % of global GHG emissions. In spite of that, even in the Kyoto Protocol, road transport is pointed out as one of the most important targets when the global GHG emission reduction is concerned. In April 2009, the European Commission adopted the regulation (EC) 443/2009, setting CO_2 emission performance standards for new passenger cars. The paper briefly describes the global economic impact of the Kyoto Protocol on developing countries. Then, total GHG emissions of various types of vehicles are reviewed, and the emerging vehicle technologies, focusing on reducing GHG emissions and replacing fossil fuels with alternative energy resources, are discussed. A well-to-wheel (WTW) analysis of a midsize electric car operating in Croatia has been carried out in the case study. Finally, the main conclusions are drawn: further reduction in GHG emissions from road transport would result in marginal global effects and, compared to all new power train systems, internal combustion engine running on fossil fuels still has great potential for further improvements thus remaining the most viable solution for the future.

Keywords: *GHG emissions, motor vehicles, relevance, powertrain systems*

1. Introduction

Road, sea and air transport are undoubtedly lifelines of the modern world. It is also true that they produce approximately one eighth of human-induced GHG emissions (**Figure 2**) and that the automotive industry has come under most fierce attacks as a source of GHG emissions. On the other hand, the fact is that the automotive industry has made the most significant breakthrough in the effort to reduce harmful emissions in the last twenty years. For example, since 1990 (Euro 0) until now (Euro 5), CO_2 emissions from the most widely used M1 category of vehicles propelled by petrol engines have been reduced by more than 97%, and HC/NO_x emissions by almost 96% [1].

The policy of accepting the obligation to reduce GHG emissions is fatal to the future development of the Republic of Croatia for two reasons. Firstly, the Kyoto Protocol [2] sets 1990 as the reference year for emission levels, i.e. the year in which the industrial production level in Croatia was very low. Secondly, and more importantly, Croatian GDP per ton of CO_2

is very low (**Figure 1**). Since the volume of industrial production is directly proportional to energy consumption, to accept the low levels of the allowed GHG emissions means to accept the death sentence to the restructuring and development of Croatian industry. Analysing the International Energy Agency (IEA) data ([3]: CO2highlights.xls) the following results could be obtained for 2009: the EU-27 countries produced 1.60 times more GHGs per capita than Croatia. In addition, the EU-27 population has a 1.85 times higher GDP per every ton of emitted GHGs, which finally results in a 2.96 times higher GDP per capita[1].

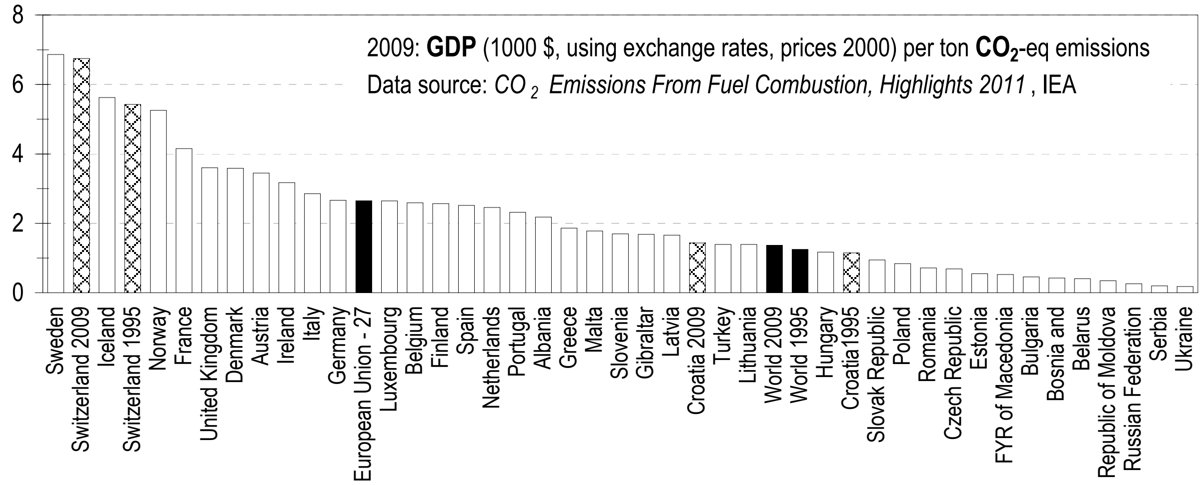

Fig. 1 Energy efficiency in industries of European countries in relation to GDP per ton of carbon dioxide equivalent emissions. Low GDP values indicate both the use of advanced technologies in highly developed countries, such as Germany, and small-scale industrial production in underdeveloped countries, such as Croatia. Data source: IEA [3].

Bernstein et al. [4] analyzed the global economic impacts on different regions of the world of the Kyoto Protocol to limit carbon dioxide emissions. They divided the world in ten characteristic regions and developed a multi-sector, multi-region trade (MS-MRT) model with a focus on the international trade aspects of the climate change policy. The model was calibrated to the benchmark year 1995, and the forecast ended in 2030. Their estimates are presented with a set of sensitivity tests to assess the extent to which the conclusions depend on elasticity and baseline assumptions. The authors concluded that with global trading, energy-intensive industries move out of developing countries, because these countries have the least energy-efficient industries and therefore are the most vulnerable to a uniform, global increase in energy costs. The same authors (reference 36 in [5]) also calculate reduction from the predicted level of GDP in 2030 in less developed countries and regions (Angola, Nigeria, Venezuela, Middle East, Northern Africa, Congo, Algeria) as a result of the implementation of the Kyoto Protocol. The reduction ranges from 1.7 to 2.7% comparing to the base year 2000.

2. Global GHG Emissions and the Contribution of Transport

The relationship between increasing GHG emissions and global warming was established in 19th century, when Fourier, Tyndall and Arrhenius published their articles. Fourier (1824) [6] noticed that the short-wave solar radiation can pass the atmosphere, but the long-wave infra-red radiation is trapped by it; this is called the greenhouse effect. Tyndall (1859) [7] identified the water vapour as main GHG contributor. Arrhenius (1896) [8]

---

[1] Ratio (EU-27) : (CRO)
[CO_{2e}] per capita (table: CO2-POP) = 7.1483 : 4.4599 = 1.60 : 1.00
[GDP (exchange rates)] per capita (tables: GDP, POP) = (9481.592/500,368) : (28.347/4.432) = 2.96 : 1.00
{[GDP (exch. rat.)] / [CO2 emissions]} per capita (table: CO2-GDP) = (1/0,3772) : (1/0.6973) = 1.85 : 1.00.

concluded that the doubling of atmospheric CO_2 concentrations leads to a significant increase in surface temperatures. These papers laid the foundations for today's science on climate change, which became the basis for the policy carried out by the Intergovernmental Panel on Climate Change (IPCC). However, a part of the academic community is strongly opposed to such a view[2] [3] [4], pointing out the misinterpretation of research results.

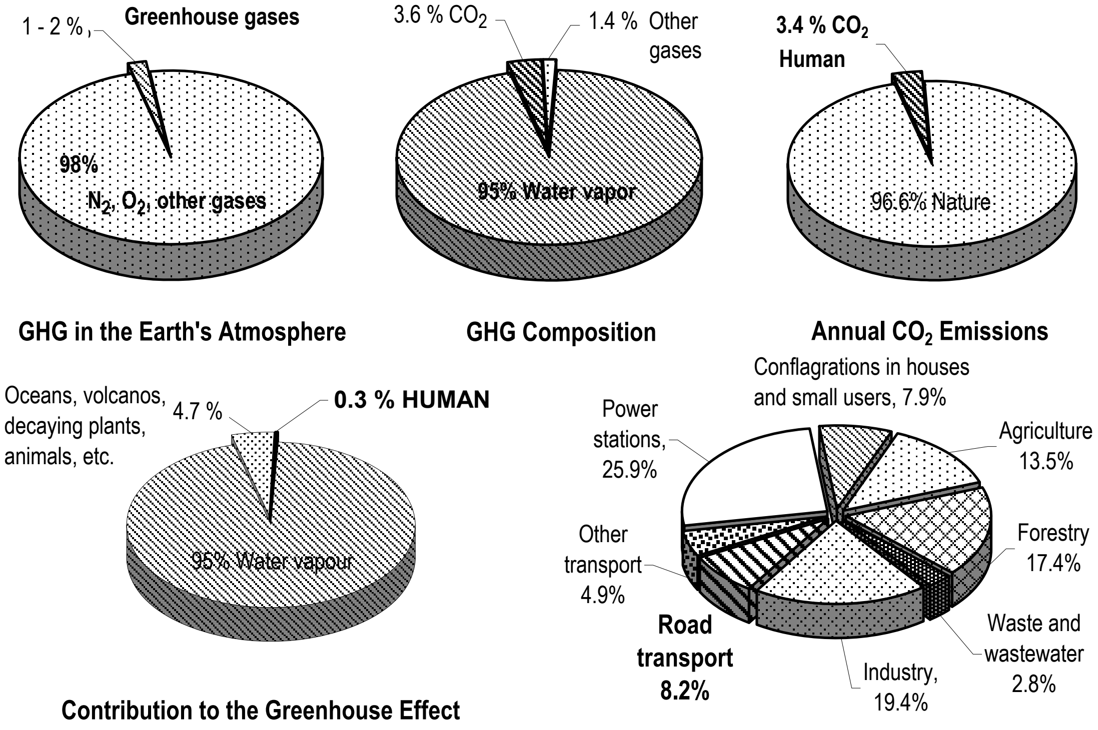

Fig. 2 Total GHG emissions in the Earth's atmosphere (*above* and *below*, *left*, sources: [5] and [15][5]) and the composition of anthropogenic emissions in 2004 (*below, right*, source: IPCC [12] and TU Wien (published in [16])). "Contributions on Greenhouse Effect" are defined as concentrations adjusted for global warming potential, relative to CO_2 [15].

Total anthropogenic GHG emissions amounted to 29.0 Gt in 2009, according to IEA [3]. The share of road transport in these emissions was only 4.88 Gt or 17%, the total share of transport was 6.54 Gt or 23%. The proportions shown in **Figure 2** differ to a certain extent

---

[2] *"I can only see one element of the climate system capable of generating these fast, global changes, that is, changes in the tropical atmosphere leading to changes in the inventory of the earth's most powerful greenhouse gas - water vapour."* Dr. Wallace Broecker, a leading world authority on climate, Lamont-Doherty Earth Observatory, Columbia University. Lecture presented at R. A. Dal Lecture at the American Geophysical Union's spring meeting in Baltimore, Md., May 1996. [14]

[3] *"Water vapour constitutes Earth's most significant greenhouse gas, accounting for about 95% of Earth's greenhouse effect. Water vapour is 99.999% of natural origin."* This information is often withheld, although it has resulted from studies and investigations carried out by the world's leading scientists, see references listed in [14].

[4] *„There is no convincing scientific evidence that human release of carbon dioxide, methane, or other greenhouse gases is causing or will, in the foreseeable future, cause catastrophic heating of the Earth's atmosphere and disruption of the Earth's climate. Moreover, there is substantial scientific evidence that increases in atmospheric carbon dioxide produce many beneficial effects upon the natural plant and animal environments on the Earth."* Petition to the US government signed by more than 31,000 American scientists including more than 9,100 with PhDs [17].

[5] Autor: Lee C. Gerhard, PhD, Senior Scientist Emeritus, University of Kansas, former director and state geologist, Kansas Geological Survey, USA., http://heartland.org/lee-gerhard

from those presented in the 2004 IPCC report (in 2009, according to [12], the total emissions were 10.2% higher than in 2004). On the other hand, according to the United Nations Framework Convention of Climate Change (UNFCCC), emissions from deforestation have been approximately 5.8 Gt per year ever since 1990 [8]. This is 21% more than the amounts emitted from road transport, and 13% more than the amounts emitted from transport in general.

Table 1 Key greenhouse gases, their sources and conversion factors

	Nature	Transportation	g CO_2 equivalence per 1 g
Water vapour	●	●	
Carbon dioxide (CO_2)	●	●	1
Methane (CH_4)	●	●	21
Nitrous oxide (N_2O)	●	●	310
Ozone (O_3)	●	●	
Nitrogen oxides (NO_x)		●	
Chlorofluorocarbons (CFC)		●	
Source	IPCC [9]	[10]	IPCC in [13], [11]

The total *anthropogenic* CO_2 emissions amount to only 3.4% of total CO_2 emissions in the Earth's atmosphere[6] (**Figure** 2). Thus, road transport has a share of only 0.28% in the *total* CO_2 emissions. It is hard to believe that there are reliable methods which can distinguish the effect on climate changes of such a small increase in the GHG concentration in the atmosphere from the effect of significantly higher emission levels from other sources. Moreover, the arguments of those who claim that global warming is not related to GHG emissions but rather to the processes taking place on the Sun's surface sound convincing.

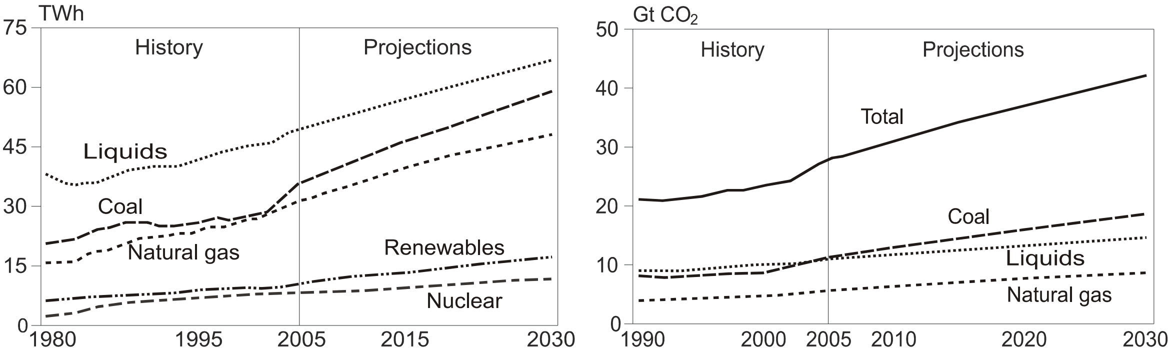

Fig. 3 World energy consumption and projections by fuel types (*left*) and GHG emissions from these fuels expressed in CO_2 equivalents (*right*). Coal is most often used for electricity generation and in industry, but also for the production of synthetic liquid fuels. Source: DOE/EIA [20].

---

[6] According to other sources, the share of anthropogenic GHG emissions is even lower. Kessel [19] estimates these emissions to be 0.5% to 1.5% out of all GHG emissions in the Earth's atmosphere. A thorough analysis [14] of data on GHG emissions in 2000 issued by the US Department of Energy shows that greenhouse effect caused by human activities is about 0.28% if water vapour is taken into account, and about 5.53% if this is not the case.

3. CO_2 Emissions from Road Transport

The Kyoto Protocol lists transport as one of the main sources of CO_2 emissions. As a consequence, in 1998 the European Automobile Manufacturers' Association (ACEA), followed by Japan Automobile Manufacturers Association (JAMA) and Korea Automobile Manufacturers Association (KAMA), agreed to reduce average CO_2 emissions of new sold cars to 140 g/km by 2008. They also agreed to review the rate of progress to reach the next reduction step of 120 gCO_2/km by 2012. But, as the annual emission reductions achieved were too low, only 0.6 to 2.2% between 1998 and 2006, the European Commission adopted the regulation (EC) 443/2009 in April 2009, setting CO_2 emission performance standards for new passenger cars (**Figure 4**). A closer look at numbers in **Figure 2** shows that the share of CO_2 emissions from road transport in total GHG emissions in the Earth's atmosphere amounts to only 0.28%. So, these measures will have a negligible impact on global GHG-emissions. However, they will contribute to improving air quality and reducing dependency on foreign oil, which is also becoming increasingly expensive.

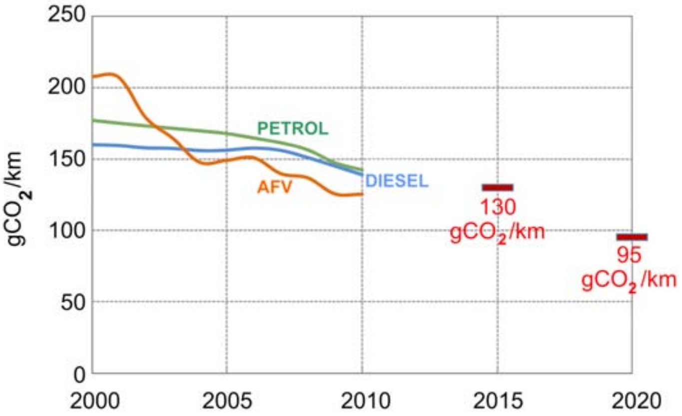

Fig. 4 Development of CO_2 emissions from new passenger cars (AFV – alternative fuel vehicles) by fuel type (EU-27[7]) and the targets set by the Regulation (EC) No 443/2009 [21] for the emission of average new car fleet (130 gCO_2/km by 2015 and 95 gCO_2/km by 2020). Source: EEA [22].

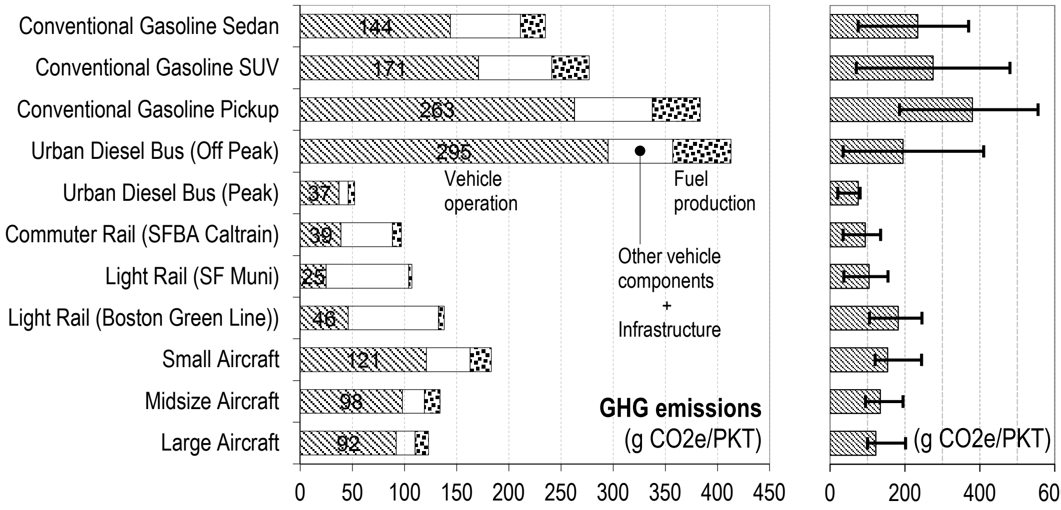

Fig. 5 *Left:* Total GHG emissions (CO_2 equivalent) of various types of vehicles per passenger kilometre travelled (PKT) in US. Other vehicle components: manufacturing, maintenance end insurance. Infrastructure: construction, operation, maintenance, parking and insurance. *Right:* Average occupancy and occupancy sensitivity. Source: University of Berkeley [23]

---

[7] The geographical scope of the data changes over time from EU 15 to EU 25 and EU 27.

Hidden emissions. In most of studies the direct consequence approach to transport emissions is very common. But a lot of transport components are interrelated. It is not possible, for example, to drive a car without having roads and the rest of the infrastructure. The environmental impacts of transport should include the lifecycle components, not only the fuel consumption and the emission during vehicle operation. In this sense the Berkeley study [23] is pathbreaking. Within this study, the researchers selected a range of transport to be assessed, including a saloon car, an urban bus service and a mid-sized aircraft. They compared assessed GHG emissions during peak and off-peak periods. In their analysis the authors included also the impacts of non-operational components, such as vehicle manufacturing, fuel production and infrastructure, road construction, street lighting, maintenance etc. The results can be seen in **Figure** 5.

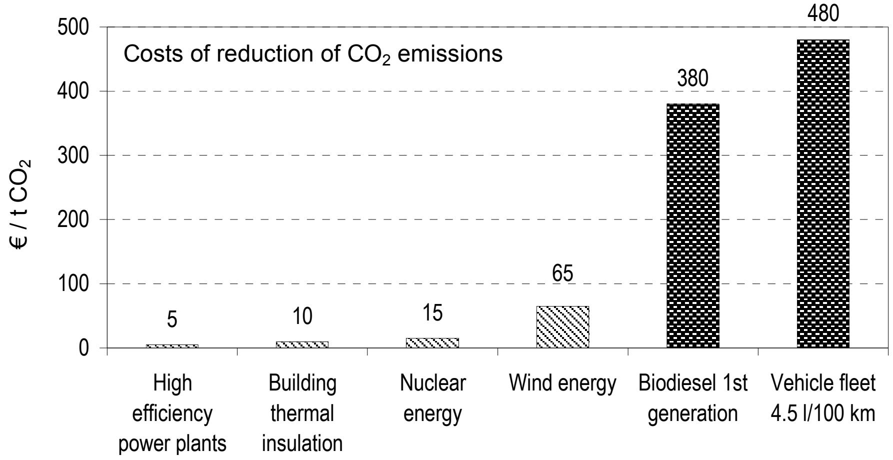

Fig. 6 The costs of the reduction of 1 t CO_2 emissions. Source: VDA [39].

Compared to the road transport, in all other sectors a significant reduction can be achieved more cost-effectively and efficiently (**Figure 6**).

4. Emerging Vehicle Technologies

A constant rise in energy prices and the pressure to reduce greenhouse gases at the end of the last millennium provided the impetus to develop alternative power systems. Considerable progress has been made in the field of hybrid electric vehicles, battery electric vehicles and fuel cell vehicles. In spite of large investments in research, the main problem has not been solved: energy density of the new media, i.e. electric batteries and hydrogen, fall short of the energy density of fossil fuels, making it very unlikely for this to change any time soon (**Figure 7**).

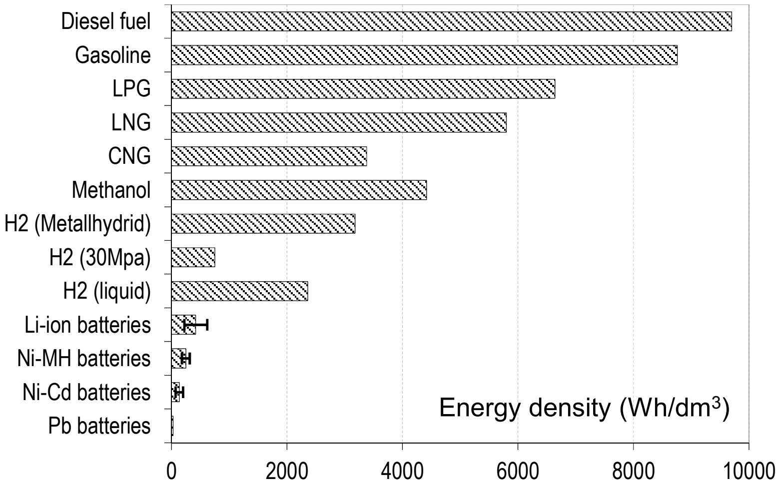

Fig. 7 Energy density of various storage media shows the advantage of fossil fuels, which cannot be caught up in the medium term. Data sources: [24], [25], [26].

Development of new technologies led also to research expansion in a number of directions. In the field of power systems, however, research focuses on several areas which include also the vehicle as a whole: further development of conventional internal combustion engines, development of hybrid and pure electric power systems, and development of fuel cell powertrain systems.

4.1 Improved Conventional Systems

The diesel engine has had significantly lower fuel consumption than the spark ignition (SI) engine, and thus lower CO_2 emission, brought currently into focus, ever since its third approved functional prototype that started to run in 1897. Nevertheless, it took almost 80 years for the diesel engine to become suitable for a small passenger car. The first big success in this respect was the Volkswagen Golf from 1976, a diesel-powered version. In 1987, the first automobile propelled by a direct injection diesel engine, Fiat Croma, came on the market. That was a major breakthrough for the diesel engine in the field of passenger cars that had been dominated almost exclusively by SI engines. Further improvements, such as turbo-charging, common rail direct injection and downsizing, have resulted in a very powerful, compact diesel engine running at a very low noise level. A great deal of effort has been put into the development of the new Homogeneous Charge Compression Ignition (HCCI) process, which has a low particle emission level, like the SI engine, and low fuel consumption, like the diesel engine. There are also other new promising technologies, such as variable valve trains, variable intake, and variable compression ratio. However, to achieve the emission target of 95 gCO_2/km by 2020, at the level of the yearly produced vehicle fleet, both the engine and the powertrain improvements will be needed, as well as improvements in the vehicle in general (**Figure 8** and **9**). It is therefore no surprise that internal combustion engines will probably maintain their complete domination for at least two more decades.

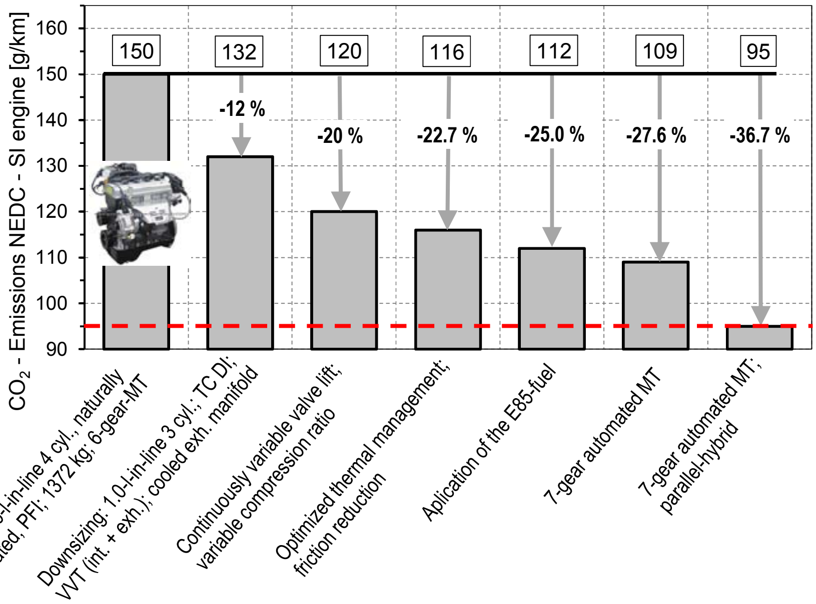

Fig. 8 The emission target of the passenger car fleet of 95 gCO_2/km by 2020: methods for future reductions in emissions of vehicles propelled by SI engines. [27]

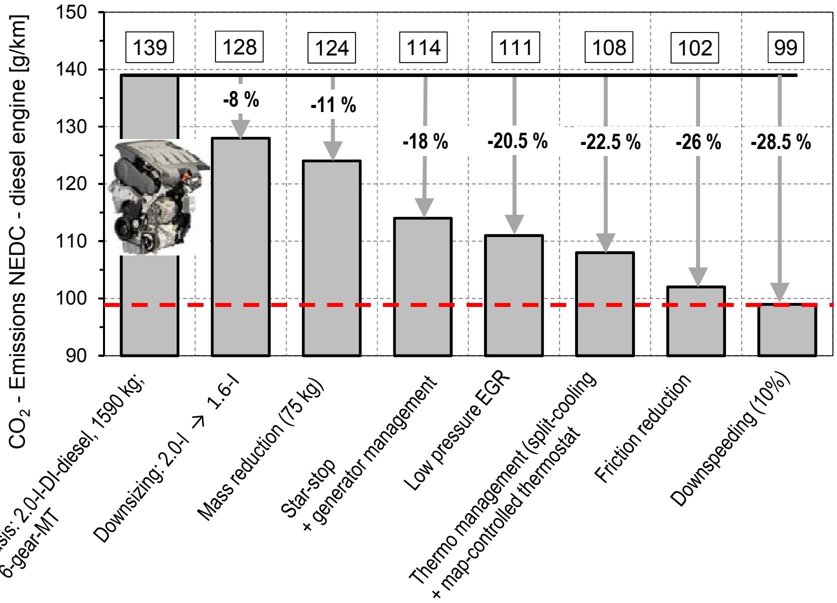

Fig. 9 The emission target of the passenger car fleet of 95 gCO_2/km by 2020: methods for future reductions in emissions of vehicles propelled by CI engines. [27]

4.2 Hybrid Electric Vehicles and Electric Vehicles

In hybrid electric vehicle (HEV), an internal combustion engine (ICE) and at least one electric motor-generator are used for driving the vehicle. The engine and the motor consume energy from two different storages: a tank for liquid or gaseous fossil fuel and an electric battery. The engine and the motor propel wheels of the same or of different axles, simultaneously or separately. With an appropriately chosen configuration of a hybrid power system, wheels are propelled by the electric motor, whereas the internal combustion engine is turned on periodically in order to power the electric generator charging the electric battery. The engine works in a narrow range of maximum efficiency. Reduction in fuel consumption achieved in such a manner must suffice to cover the losses in a much more complex hybrid powertrain system as well as provide additional savings to compensate for the high price of the vehicle itself. A typical application is city driving, with small speeds and frequent braking and accelerating, when a conventional vehicle engine consumes a lot of fuel.

Plug-in hybrid electric vehicles (PHEV[8]) are supplied with a quite larger battery, they can travel longer distances using only electric motor, and the driver can charge his vehicle from the grid. Typical battery capacity for midsize car, for the near term, is about 1-2 kWh for HEV, about 4-30 kWh for PHEV-10 to PHEV-60[9], and 30-60 kWh for battery electric vehicles (BEV) with a 150-200-mile electric range. In these vehicles only Li-ion batteries are used, due to their high energy density. Unfortunately, their price has not gone down from 2000 until 2009, ranging from 660 US$/kWh to 2,200 US$/kWh, where lithium accounts for 75% of the price. Nowdays, the price of the battery of a medium size car amounts to 10,000 US$. Such a high price is the main obstacle to a faster market penetration of these vehicles. Unlike PHEVs, where the IC engine ensures mobility even in the case of an empty battery, for BEV passengers a traffic jam on a snowy road is a terrifying danger, when one has to keep the passenger compartment warm and windows clear of fog.

---

[8] If a PHEV is supplied with a very small internal combustion engine, which is called range extender.

[9] PHEVs are differentiated according to their all-electric range (AER), i.e. the distance driven electrically up to the point at which the IC engine first turns on. PHEV-60 refers to a 60-mile electric range.

Further, recharging an empty battery takes 30 long minutes even on a fast charger (home charger can take from 8 to 12 hours), and a completely new electric infrastructure for charging is needed, as well as new management of electric energy generation. In spite of that, the facts that oil is becoming more expensive and electric energy can be obtained from other sources are still in favour of PHEVs.

The usage of hybrid electric vehicles is described by the Utility Factor (UF). The UF is defined as the ratio of the vehicle-km travelled in an all-electric mode to the total annual vehicle-km:

$$UF = \frac{VKT_{\mathrm{elec}}}{VKT_{\mathrm{elec}} + VKT_{\mathrm{fuel}}} \ ,$$

where: VKT_{ELEC} - the annual vehicle-km travelled on electrical energy,
VKT_{FUEL} - the annual vehicle-km travelled on chemical energy.

The typical utility factor in the US is estimated to be around 40% for a PHEV-30, i.e. a PHEV-30 would substitute electrical energy for petroleum consumption in 40% of the total vehicle-miles travelled [29]. The shorter the daily trips, the higher the utility factor will be, because most of the distance will be driven on electric mode (depending on the AER capability of the PHEV). In the EU, about 80% of the total daily distance driven consists in short trips. This means that the plug-in hybrid electric vehicle would satisfy daily transport needs of over 50% of all drivers without fossil fuel consumption and its own CO_2 emissions. This would significantly reduce fuel consumption and CO_2 emissions from vehicles (**Figure 10**).

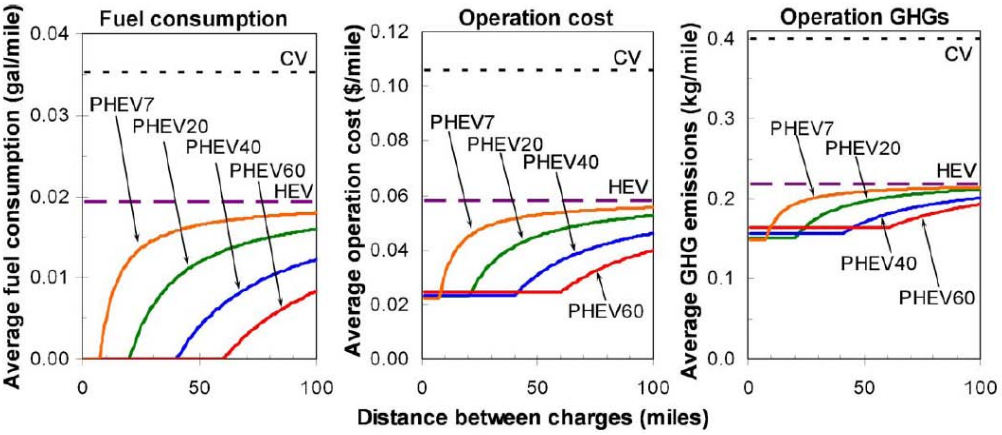

Fig. 10 Operation-associated fuel consumption, cost and GHG emissions for conventional vehicle (CV), hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) with all electric ranges (AER) of 7, 20, 40 and 60 miles respectively between charges. Source: Shiau at al. [30].

In order to comply with the obligations to reduce CO_2 emissions, the automotive industry has brought hybrid propulsion systems into the focus of interest. These systems used in urban driving enable a reduction in fuel consumption of up to 25% (**Figure 11**). Plug-in electric vehicles (PHEV) that can be recharged from the electric grid look promising in that respect. This would lead to the application of electric propulsion systems in automobiles. On the basis of current prices of fuel and electricity, one can conclude that driving electric cars would be much less expensive than driving cars propelled by internal combustion engines (**Table 2** and **Figure 14**). However, the global reduction in greenhouse gas emissions depends on the energy source used for the generation of electricity. The electric car will undoubtedly bring two new problems. The first will be an increase in the costs of electrical energy for all consumers. The immediate effect will be that the poverty of the most poor will be aggravated, much in the same way as the disputable production of biofuels has increased the costs of food and caused the spread of famine. The second problem is that the humankind is still in search of an abundant source of ecologically clean electrical energy. The 2011 Fukushima nuclear accident in Japan clearly showed how dangerous nuclear power plants can be. Perhaps this disaster will finally respond to the absurd situation in which one tries "to protect" the Earth from an increased levels of greenhouse gases in the atmosphere, while the nuclear waste, that will remain radioactive for the next ten or even hundred thousands of years, is deposited into the ground of the same planet Earth.

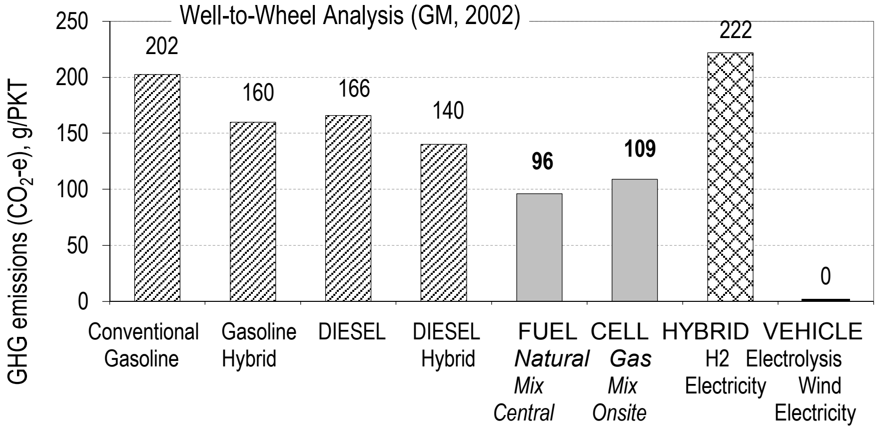

Fig. 11 The General Motor's study on GHG emissions per passenger kilometre travelled (PKT) from powertrain systems with internal combustion engines and with hydrogen fuel cells. Even when hydrogen for fuel cells is obtained from natural gas, CO_2 emissions are still lower than those from diesel engines, although the mass content of carbon in natural gas is three times higher than the mass content of hydrogen. (Results from the study "GM Well-to-Wheel Analysis …, 2002", published in [28].)

4.3 Hydrogen

Some ten years ago automotive industry started publicly announcing hydrogen fuel cell vehicle as a solution for sustainable mobility in the near future [31], [32], [33]. In the meantime, this has proved to be a disputable orientation for several reasons. For example, fuel tanks of modern vehicles are not adequate for storing hydrogen, especially not for a longer period of storage. In light of this fact, the storage and transport of hydrogen can hardly be imagined. Even if these problems were solved, what would remain disputable is the main condition on which the whole concept is based and on which automotive industry relies, and that is the generation of large amounts of ecologically clean electrical energy required for the production of hydrogen at an acceptable cost. This problem could be solved by nuclear fusion, but the technology is said to be feasible in some fifteen years or so. Also, this has been in announcements for some forty years. The system of photovoltaic power stations to be placed in the Earth geosynchronous orbit is probably a more promising solution.

Hydrogen can be produced from natural gas as well as from coal. But, the production of hydrogen from natural gas, for example, does not make sense from the point of view of CO_2 emissions. Natural gas consists primarily of methane (80-98%) and 1 kilogram of methane contains only 25% of hydrogen and 75% of carbon (which will not be used and will finally be burned into CO_2). If 1 kg of diesel fuel (43 MJ/kg, 0.832 kg/dm^3, 1 kg = 0.86 kgC + 0,13 kgH$_2$) were substituted by hydrogen (120 MJ/kg) produced from natural gas (1 kgNG ≈ 1 kgCH$_4$ = 0.75 kgC + 0.25 kgH$_2$), then 1.43 kg of natural gas (which contains 1.075 kgC) would be needed in order to produce the same amount of energy. However, if natural gas was used to produce hydrogen (steam reforming), then the mass of the remaining carbon would be even slightly greater than the mass of fossil diesel fuel that should be replaced. For Croatia (4,437,460 inhabitants in 2001), which consumes 1.5 million tons of diesel fuel, it would result in 363 kg of carbon, i.e. 1,331 kg of CO_2 per capita. Where would such a vast amount of carbon dioxide be stored and at what expense? The only solution seems to be electrolysis.

However, even if the production of cheap and GHG-free electric energy were feasible, the chances of hydrogen would be to be only the energy buffer storage, a very expensive one, and not the primary energy source for sustained mobility.

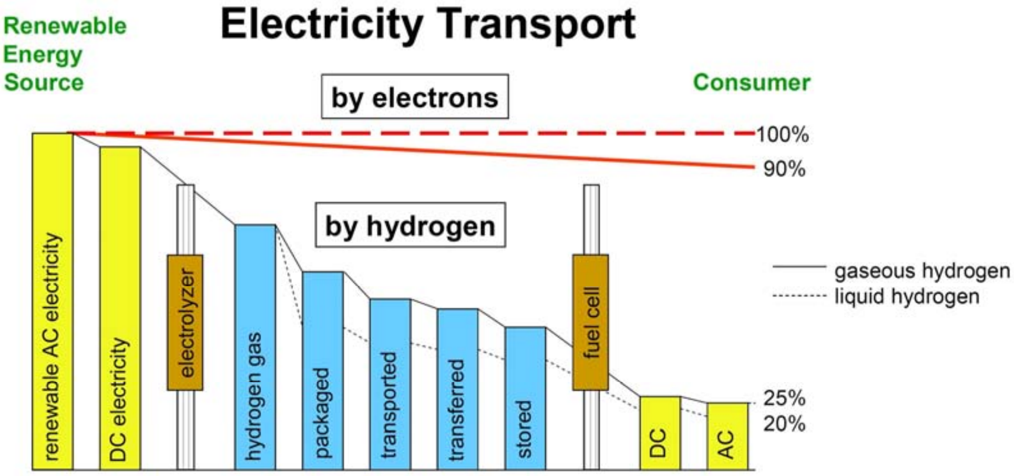

Fig. 12 Electric energy is much more efficient if used for recharging BEVs or PHEVs instead of producing hydrogen to propel fuel cell vehicles. Source: [34]

4.4 Case Study: a WTW Analysis of Midsize Passenger Car Operating in Croatia

The uncertainty over energy supply and the unpredictable and unstable prices of petrol and diesel fuel have lead to the automotive industry and the market turning to other fuels, e.g. liquid petrol gas and natural gas, to hybrid electric vehicles, and to a speedy development of fully electric vehicles. In order to study the influence of the use of various fuels and electric energy taken from the grid on the production of GHG emissions in Croatia, a simulation of a compact passenger vehicle (Ford Focus) drive has been performed according to the New European Driving Cycle (NEDC). The Urban Driving Cycle, in which fuel consumption is greater due to the unfavourable engine load in city traffic, is analysed. A fully electric plug-in system, with batteries being charged from an electric network at household electricity prices while the vehicle is not in motion, has also been taken into consideration.

On a straight horizontal road the total running resistance of a vehicle F_{W} consists of the rolling resistance F_{Ro}, the aerodynamic drag F_{L} and the acceleration resistance F_{Acc}:

$$F_{\mathrm{W}} = F_{\mathrm{Ro}} + F_{\mathrm{L}} + F_{\mathrm{Acc}}\,, \ \mathrm{N}$$

$$F_{\mathrm{Ro}} = f \cdot m_{\mathrm{V}} \cdot g\,, \qquad F_{\mathrm{L}} = \frac{1}{2} \cdot \rho \cdot v^2 \cdot c_{\mathrm{d}} \cdot A\,, \qquad F_{\mathrm{Acc}} = m_{\mathrm{red}} \cdot a\,,$$

where: $\boldsymbol{A}$ = 2.1 m^2 – the largest cross-section of the vehicle; $\boldsymbol{a}$, m/s^2 – acceleration; $\boldsymbol{c_d}$ = 0.31 – drag coefficient; $\boldsymbol{f}$ = 0.013 – coefficient of rolling resistance for pneumatic tires on concrete and/or asphalt; $\boldsymbol{g}$ = 9.81 m/s^2 – gravitational acceleration; m_{red}, kg – reduced vehicle mass i.e. total vehicle mass plus all rotating masses reduced to the drive axle; m_{V}, kg – vehicle mass including driver; $\boldsymbol{v}$, m/s – vehicle speed; $\boldsymbol{\rho}$ = 1.202 kg/m^3 – air density at 200 m altitude.

The reduced mass can be obtained from the law of conservation of energy. Total kinetic energy of the vehicle consists of the kinetic energy of translation $E_{\mathrm{kin,t}}$ and the kinetic energy of rotation of all rotating masses $E_{\mathrm{kin,r}}$:

$$E_{\mathrm{kin}} = E_{\mathrm{kin,t}} + E_{\mathrm{kin,r}} = \lambda \cdot E_{\mathrm{kin,t}}\,.,\ \mathrm{J}$$

This yields:

$$m_{\text{red}} = m_{\text{V}} \left(1 + \frac{J_{\text{W}} + J_{\text{DS}} \cdot i_{\text{Fi}}^2 + J_{\text{E}} \cdot i_{\text{Gbx}}^2 \cdot i_{\text{Fi}}^2}{m_{\text{V}} \cdot r_{\text{dyn}}^2} \right) = \lambda \cdot m_{\text{V}}\,, \ \text{kg}$$

where: $\boldsymbol{J}$, kgm^2 – inertia moment; W - wheels including the brake drum or brake disk and axle shafts; DS – drive shaft; Fi – final drive; E – engine; Gbx – gearbox; r_{dyn}, m – dynamic wheel radius; $\boldsymbol{\lambda}$ – rotational inertia coefficient which expresses the proportion of the total mass that is rotating. The results shown in **Table 2** were calculated from the following values (Lechner [35], Wallentowitz [36]): for ICE and manual gearbox $\lambda_{1/2/3} = 1.35/1.15/1.10$ for 1st/2nd/3rd gear, respectively, and for EV $\lambda = 1.05$.

Acceleration $a = dv/dt$ is obtained from the velocity $v(t)$, which is defined by the NEDC. The running-resistance power, which must be transmitted through driven wheels to overcome the running resistance, is:

$$P_{\text{W}} = F_{\text{W}} \cdot v\,, \ \text{W}.$$

The total energy consumed at the driven wheels in one Urban Driving Cycle, which takes 195 s, is obtained as the surface integral under the power curve:

$$E_{\text{NEDC}} = \int_{t=0}^{t=195} F_{\text{W}}\, dt\,, \ \text{J}$$

The results are shown in **Figure 13** and **Table 2**.

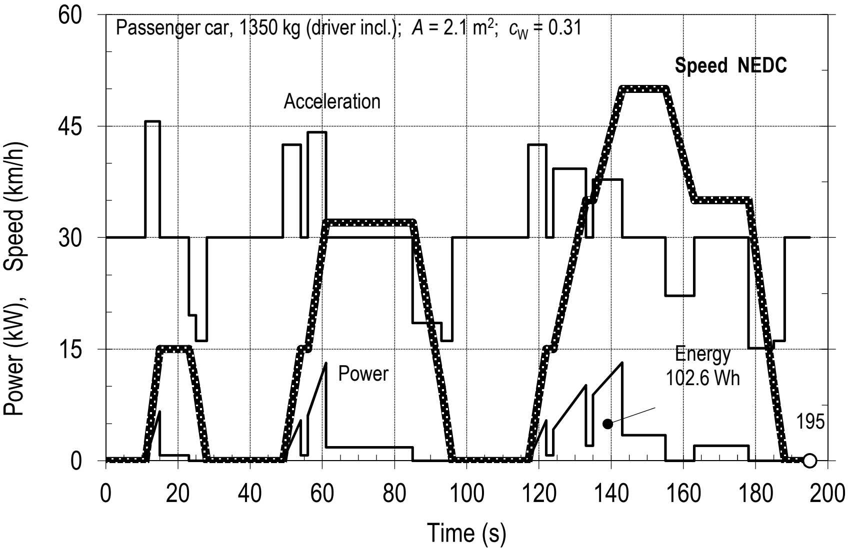

Fig. 13 Calculated energy consumption by a medium size passenger car in a single urban NEDC (195 s, 1,016.4 m).

Table 2 Calculated CO_2 emissions and fuel / energy costs (Croatia, November 2, 2012) of an electric (EV) and a conventional vehicle for 100 km distance in one urban driving cycle (NEDC). Reference car: Ford Focus (2008), 1,350 kg (SI engine), 80 kW, A = 2.1 m^2, c_d = 0.31. Energy consumption in a single urban cycle NEDC (1,016.4 m; no recuperation): 102.6 Wh (100.94 Wh/km).

Power train system - Energy / Fuel / CO_2-eq				LHV	Price	100 km driving urban cycle			Efficiency		CO_2	Energy costs	
						net energy required	fuel consumed	energy consumed	TTW	WTW			
(Vehicle mass including driver)	Unit	gCO_2/ unit	€/ unit	kWh/ unit	€/ kWh	kWh	units	kWh		(d)	g/km	€/ 100km	Index
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10 = 7 / 9)	(11)	(13=3x9)	(14)	(15)
EV - HEP (1600 kg), Residential, White-High	kWh	600	0.151	-	0.151	11.986	-	18.161	← (9=7/11)	66%	109	2.74	**23**
EV - HEP (1600 kg), Residential, White-Low	kWh	600	0.075	-	0.075	11.986	-	18.161	← (9=7/11)	66%	109	1.36	**11**
SI ICE - Gasoline (1350 kg) Eurosuper 95 (a)	dm^3	2330	1.387	8.9	0.155	10.094	8.7	77.938	13.0%		203	12.07	**100**
CI ICE - Diesel (1400 kg) Eurodizel (a)	dm^3	2640	1.326	9.8	0.133	10.605	5.8	57.639	18.4%		153	7.69	**64**
SI ICE - LPG (1380 kg) (b)	dm^3	886	0.770	46	0.110	10.467	11.5	80.697	13.0%		102	8.84	**73**
SI ICE - CNG (1450 kg) (c)	kg	2682	0.996	13.5	0.074	10.950	6.3	85.331	12.8%		169	6.27	**52**

EV- HEP – electric vehicle powered from the grid of HEP (Croatian Electricity Company), Tariff model: Residential, White-High(07-21h)/-Low(21-07h), source: http://www.hep.hr/ods/en/customers/Tariff.aspx; ICE – internal combustion engine; SI – spark ignition; CI– compression ignition; LHV – Lower Heating Value; TTW - Tank-to-Wheel; WTW - Well-to-Wheel. Fuel data: LHV, density: gasoline 43 MJ/kg, 0.75 kg/dm^3; diesel fuel 43 MJ/kg, 0.832 kg/dm^3; LPG (propane:butane=1:1) 46 MJ/kg, 0.54 kg/dm^3; CNG: CH_4 96%vol., C_2H_6 2.5%, N_2 1.5%; (a) – Fuel consumption: manufacturer's data; (b) – Assumption: the same engine thermal efficiency as with gasoline; (c) – Ford Focus sedan 2008 Greenpower, [37]; (d) – assumed "Power Plant-to-Wheel" efficiency of electric generation, distribution, charging and vehicle powertrain system, source: Perlo (Fiat) [38].

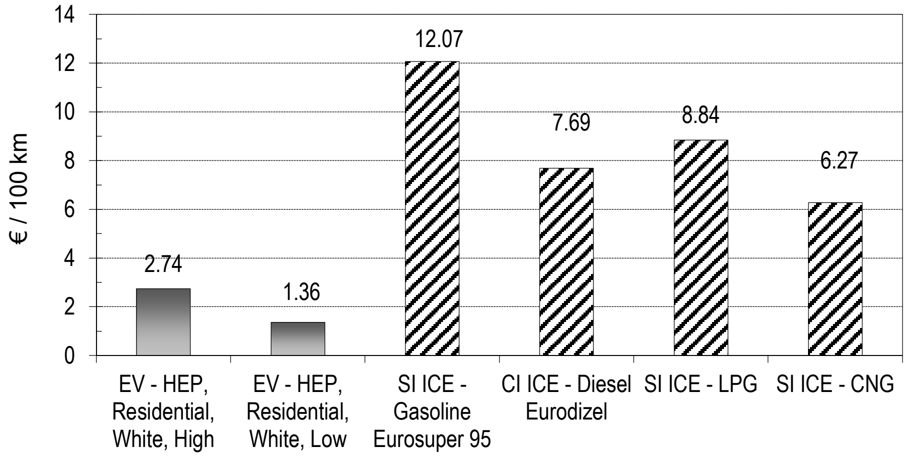

Fig. 14 Calculated costs of energy and of fuel in Croatia for 100 km travelled by a midsize passenger car according to NEDC (**Table 2**). If electric energy from the grid were used, the running costs would be 10 times lower that those of gasoline.

4.5 European Electric Vehicle Market

In spite of the efforts of the automotive industry, both the supply of electric and hybrid vehicles and the number of buyers are still small. On the strongest European market, Germany, between January and July 2012 only 2,331 electric vehicles were registered[10]:

- Opel Ampera – 629
- Nissan Leaf – 269
- Citroën C-Zero – 256
- Peugeot iOn – 200
- smart fortwo electric drive – 131
- Mercedes A-Klasse E-Cell – 623
- Mitsubishi i-MiEV – 47
- Tesla Roadster – 44
- VW Golf Blue-e-Motion – 32

The most registered vehicle, Opel Ampera, is actually a range extender and not a purely electric car. Although the input energy savings are much lower for electric than for conventional vehicles, much less electric vehicles have been sold worldwide than expected. Because of that General Motors temporarily suspended the production of their electric vehicle Chevrolet Volt beginning of fall 2012. In Europe, the French car manufacturer PSA asked their Japanese partner Mitsubishi to stop the delivery of electric vehicles. The most important reason for such a small interest in electric vehicles is surely their high price. Furthermore, only few of electric vehicles have built-in fast chargers, and the charger attachment has not been standardized yet. The situation with HEVs is also not any more favourable. Although HEVs have an internal combustion engine which guarantees a safe fuel supply and thus mobility, their price is too high as well. A cost effectiveness analysis of the Audi hybrid Q5 carried out by ADAC (ADAC Motorwelt 12/2011) showed that in comparison with the same vehicle powered by a Diesel engine the fuel consumption of the hybrid car was barely lower

---

[10] *Elektroauto Verkaufszahlen – Markt weiterhin schwach*, (13. August 2012): http://www.goingelectric.de/2012/08/13/news/elektroauto-verkaufszahlen-markt-weiterhin-schwach/ The list is biassed. Opel's Ampera, which is actually a HEV, is on the list, but its rival, Toyota's Prius, is not included; perhaps because Prius is by far the best-selling HEV in the world and the only real hit.

and only so in urban driving. The conclusion was that the 10,000 € more expensive PHEV would become level with the cheaper conventional version only after 380,000 km.

5. Conclusion

"There is no dispute at all about the fact that even if punctiliously observed, (the Kyoto Protocol) would have an imperceptible effect on future temperatures - one-twentieth of a degree by 2050." Dr. S. Fred Singer[11]

The consequences of climate change over the last decade are obvious. The polar ice sheet is melting rapidly and summer floods and hurricanes occur in areas where previously there were none. According to the Kyoto protocol those changes are results of global warming caused by man induced CO_2 emissions. However, one part of the academic community strongly opposes this view, stating that the human impact is insignificantly small compared to other factors, such as variations in solar radiation for example. On the other hand, IPCC as the main international body which monitors climate changes does not mention at all the ratios of natural and anthropogenic emissions of CO_2 in its documents. Such a non-transparent policy will hardly convince the poor countries of the necessity to reduce their own greenhouse gas emissions, when the rich countries already developed their industries at the cost of high emissions of greenhouse gases.

If all people have the same right to live on this planet, why do not all have the same right to equal CO_2 emissions?

With respect to GHG emissions from road transport, the following conclusions may be drawn:

- Water vapour, the most powerful greenhouse driver (95%) comes from natural sources. The greenhouse effect caused by human activities is nearly 0.3% of the total greenhouse effect if water vapour is taken into account. The share of road transport in human-induced GHG emissions amounts to some 8.2%, and to some 0.010% of total GHG emissions on Earth including water vapour. Whatever is done to reduce GHG emissions from road transport, the global impact on climate change would be negligible.
- Conventional internal combustion engines powered by fossil fuels still have great advantages in comparison with new alternative propulsion systems. Energy storage density is much higher than that of electric batteries, and gasoline tank and diesel fuel tank are much simpler and cheaper than a hydrogen tank container. Internal combustion engines, exhaust gas after-treatment systems and fuels have reached their reasonable maximum as far as harmful emissions are concerned. Although there is not much more that can be done in this respect, the application of new technologies such as downsizing, the convergence of SI and CI engines and new engine-vehicle-driver management systems promise further reductions in fuel consumption. But it should be pointed out that in all other sectors, a significant reduction can be achieved more cost-effectively and efficiently.
- Electric vehicles have several key disadvantages, all having the same source: an electric battery. The major disadvantages are the small energy density of electric batteries, long charging time, and finally, the high price that does not tend to decrease. The huge drop in battery capacity at low ambient temperatures results not only in the

---

[11] Dr. S. Fred Singer, atmospheric physicist, Professor Emeritus of Environmental Sciences at the University of Virginia, and former director of the US Weather Satellite Service; in Sept. 10, 2001 Letter to Editor, Wall Street Journal. [14]

need for a different source of energy for heating, but it also presents a threat to the driver that the vehicle will suddenly stop due to the low battery. Not even significantly lower costs of driving energy cannot compensate for these drawbacks. Therefore, it is unlikely that electric cars would take any significant market share, which has already been confirmed by the results of present sales. However, the chances of electric propulsion in combination with an internal combustion engine, as PHEV or range-extender, are very good. Nevertheless, it is uncertain to what extent these new propulsion systems will be accepted on the market.

- In addition to the unresolved problem of the fuel container, hydrogen technology has a series of other weak points. The most important ones are expensive and energy inefficient hydrogen production, and the transportation and storage of hydrogen. Therefore, hydrogen has a chance only as a buffer storage of surplus environmentally friendly electric energy. It is quite uncertain whether a way of its production would be found before the remaining oil becomes unbearably expensive.

Acknowledgement

The presented results have been obtained during the work on the scientific project “Biofuels - a necessity for sustainable mobility in the Republic of Croatia” supported by the Ministry of Science, Education and Sports of the Republic of Croatia.

REFERENCES

[1] Šagi G., Tomić R, Ilinčić P.: *The Development of Regulations on Approved Harmful Substances Emissions From IC Engines*. Fuel and Lubricants, Vol. 48, No. 2, 2009, ISSN 0350-350X, p. 174-188.

[2] *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. http://unfccc.int/resource/docs/convkp/kpeng.html

[3] *CO_2 Emissions From Fuel Combustion, Highlights*, *2011 Edition*. IEA – International Energy Agency, OECD/IEA 2011, CO2highlights.xls, www.iea.org/co2highlights/ (Accessed: 2012-10)

[4] Bernstein P. M., Montgomery W. D., Rutherford T. F.: *Global impacts of the Kyoto agreement: results from the MS-MRT model*. Resource and Energy Economics 21 (1999), Elsevier

[5] *A Global Warming Primer*, National Center for Policy Analysis, 2007, ISBN 1-56808-193-6.

[6] Fourier J.-B. J.: *Remarques génerales sur les temperatures du globe terrestre et des espaces planétaires*, Annales de Chimie et de Physique, vol XXVII, 1824, 136-167; translated by R. T. Pierrehumbert, 1 September, 2004, Chicago, IL,USA; English title: *On the Temperatures of the Terrestrial Sphere And Interplanetary Space*; published on the website of the Department of the Geophysical Sciences, The University of Chicago, http://geosci.uchicago.edu/~rtp1/papers/Fourier1827Trans.pdf (Accessed: 2013-05)

[7] Tyndall J.: *Note on the transmission of radiant heat through gaseous bodies*. Proceedings of the Royal Society of London, 1859, 37 – 39.

[8] Arrhenius S.: *On the influence of carbonic acid in the air upon the temperature of the ground*. London, Edinburgh, and Dublin, Philosophical Magazine and Journal of Science, 41 (5), 1896, 237–275.

[9] *Climate Change 2001: Synthesis Report*, edited by: Robert T. Watson (The World Bank). Published for the Intergovernmental Panel on Climate Change: Cambridge University Press, 2001, ISBN 0 521 80770 0 hardback, ISBN 0 521 01507 3 paperback.

[10] Schäfer, F., van Basshuysen, R.: *Schadstoffreduzierung und Kraftstoffverbrauch von Pkw-Verbrennungskraftmotoren*, Neue Folge Band 7. Springer-Verlag, Wien - New York **1993**, ISBN 3-211-82485-5.

[11] *2009 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. AEA for the Department of Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (Defra), Version 2.0, Updated 30/09/2009*. www.defra.gov.uk/environment/business/reporting/conversion-factors.htm (Accessed: 2010-05)

[12] *Međuvladin panel o promjeni klime, Četvrto izvješće o procjeni, Promjena klime 2007.: Zbirno izvješće. Sažetak za donositelje politike*. Meteorological and Hydrological Service of Republic of Croatia, http://klima.hr/razno/priopcenja/IPCC_IVizvj2007.pdf (Accessed: 2010-08)
Climate Change 2007: Synthesis Report, Summary for Policymakers, An Assessment of the Intergovernmental Panel on Climate Change. WMO, UNEP, www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf (Accessed: 2010-08)

[13] *Annex "Full Background Report" - Methodology, Assumptions, Descriptions, Calculations, Results - to the GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study*. L-B-Systemtechnik GmbH, 85521 Ottobrunn, Germany, 27 September 2002. www.lbst.de/gm-wtw (Accessed: 2005-02-01)

[14] Hieb M.: *Global Warming: A closer look at the numbers. Water Vapor Rules the Greenhouse System.* www.geocraft.com/WVFossils/greenhouse_data.html (Accessed: 2012-08)

[15] Gerhard Lee C.: *Introduction to Geological Perspectives of Global Climate Change*. Capitol Hill Seminar, Sponsor: Center for Science and Public Policy, September 20, 2006, published: http://ff.org/centers/csspp/docs/gerhardppt.ppt, http://ff.org/centers/csspp/pdf/gerhardnotes.pdf (Accessed: 2012-08)

[16] *Auto Jahresbericht 2008*. VDA, ISSN 0171-4317, www.vda.de/de/publikationen/publikationen_downloads/detail.php?id=489 (Accessed: 2009-08)

[17] Global Warming Project, www.petitionproject.org/index.php (Accessed: 2012-09)

[18] *CO_2 Emissions From Fuel Combustion, Highlights*, *2009 Edition*. IEA – International Energy Agency, OECD/IEA 2009, www.iea.org/co2highlights/ (Accessed: 2009-12)

[19] Kessel D. G.: *Global warming — facts, assessment, countermeasures*. Elsevier, Journal of Petroleum Science and Engineering 26 (2000), p. 157–168.

[20] *International Energy Outlook 2008*. September 2008, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC 20585, DOE/EIA-0484(2008), http://www.eia.doe.gov/oiaf/ieo/index.html (Accessed: 2009-08)

[21] *Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles*. Official Journal of the European Union, 5.6.2009, L 140/1 – L 140/15.

[22] *Monitoring the CO_2 emissions from new passenger cars in the EU: summary of data for 2010*. European Environment Agency, www.eea.europa.eu/data-and-maps/data/co2-cars-emission, Monitoring_CO2_emissions_from_new_passenger_cars_in_EU27.pdf (Accessed: 2012-10-19)

[23] Chester M. V., Horvath A.: *Environmental assessment of passenger transportation should include infrastructure and supply chains*. Environmental Research Letters, 4 (2009) 024008, http://iopscience.iop.org/1748-9326/4/2/024008/ (Accessed: 2010-05)

[24] Nemry F., Leduc G., Muñoz A.: *Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency*. Technical Note JRC 54699, European Commission, 2009. http://ftp.jrc.es/EURdoc/JRC54699_TN.pdf (Accessed: 2010-01)

[25] Klell M.: *Alternative Kraftstoffe, Wasserstoff, Allgemeines – Erzeugung – Verteilung – Speicherung – Anwendung*. HyCentA Research GmbH, Graz, 2005. www.hycenta.tugraz.at/Image/H2_allg_herstlg_MK_web.pdf (Accessed: 2012-10)

[26] Junker H. K.: *Die Zukunft des Verbrennungsmotors*. ATZ-Extra (125 Jahre Automobil), Nr. 4/2011.

[27] Pischinger S.: *Antriebsentwicklung der Zukunft*. ATZ-Extra (125 Jahre Automobil), Nr. 4/2011.

[28] *How do Hydrogen Fuel Cell Vehicles Compare in Terms of Emissions and Energy Use? A Well-to-Wheel Analysis*, Energy Independence Now. http://www.hydrogenhighway.ca.gov/facts/einwelltowheel.pdf (Accessed: 2012-10)

[29] Markel T., Simpson A.: *Plug-in Hybrid Electric Vehicle - Energy Storage System Design*. Conference Paper NREL/CP-540-39614, presented: Advanced Automotive Battery Conference, May 17-19, 2006, Baltimore, Maryland. www.spinnovation.com/sn/Batteries/Plug-in_Hybrid_Electric_Vehicle_Energy_Storage_System_Design_Conference_Paper.pdf (Accessed: 2008-09)

[30] Shiau C.-S. N.,Samaras C., Hauffe R., Michalek J.: *Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles*. Elsevier, Energy Policy 37 (2009), 2653–2663.

[31] Owen N. J., Gordon R. L.: *"Carbon to Hydrogen" Roadmaps for Passenger Cars: Update the Study for the Department for transport and the Department of Trade and Industry*. Ricardo Consulting Engineers, 2003, RD 03/209501.6

[32] Scherer G. G., Röder A.: *Auswirkungen der Brennstoffzellen-Technologie auf die Entwicklung alternativer Antriebe im Automobilbereich*. ATZ 4/2001, 274-281

[33] Hoepke E.: *30 Mercedes-Benz-Omnibusse mit Brennstoffzelle im Flottenversuch*. ATZ 6/2003, 574-577

[34] Bossel U.: *Alternative Energy Conversion (Sustainable Energy Future)*. FORUM 2008 World Academy of Ceramics, June 5–8, 2008, Chianciano, Italy, published: www.efcf.com/reports/E02_Hydrogen_Economy_Report.pdf (Euroepan Fuel Cell Forum) (Accessed: 2010-03)

[35] Lechner G., Naunheimer H.: *Automotive Transmissions*. Springer-Verlag 1999, ISBN 3-540-65903-X

[36] Wallentowitz H.: *Longitudinal Dynamics of Vehicles*. Institut für Kraftfahrwesen, RWTH Aachen, 2004

[37] *Ford Focus Limousine Greenpower Modellinformationen*. Erdgas Biogas, Switzerland, www.erdgas-fahren.ch/230.html (access: 2009-11)

[38] Perlo P.: *Convergence of Renewable Energy and Electrical Car*. EPoSS, Berlin, 2009, PowerPoint presentation, www.amaa.de/Presentations%202009/D1_SA_P1.pdf (Accessed: 2010-10)

[39] *Handeln für den Klimaschutz – CO_2 Reduktion in der Automobilindustrie, Stand August 2009, 2. überarbeitete Auflage*. VDA, www.vda.de/de/downloads/487/ (Accessed: 2010-10)

Submitted: 11.12.2012

Accepted: 16.5.2013

Zoran Lulić
zoran.lulic@fsb.hr
University of Zagreb
Faculty of Mechanical Engineering and
Naval Architecture
Ivana Lučića 5, 10002 Zagreb, Croatia
Eduard Missoni
University of Zagreb
Faculty of Transport and Traffic Sciences
Vukelićeva 4, 10000 Zagreb, Croatia
Rudolf Tomić
University of Zagreb
Faculty of Mechanical Engineering and
Naval Architecture
Ivana Lučića 5, 10002 Zagreb, Croatia