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Chapter 3

ENERGY EFFICIENCY OF ROAD VEHICLES – TRENDS AND CHALLENGES

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ABSTRACT

Improved energy efficiency is one of society's most important instruments for mitigating climate change. This Chapter deals with assessment of the energy efficiency attainable in road vehicles with various powertrains. Current situation, short-term and long-term trends, and the most important challenges are surveyed and analyzed in this chapter. The scope of technologies that are reviewed includes: conventional powertrains based on internal combustion engines (ICE), powertrains of hybrid electric, battery electric and fuel cell vehicles. Moreover, we discuss a potential increase in energy efficiency of ICE by introduction of advanced technologies, such as: engine downsizing, variable valve actuation, cylinder deactivation, variable compression ratio, homogenous charge compression ignition, etc. A comparison of energy efficiency of powertrains using different energy sources is carried out by application of the "well-to-wheel" (primary) energy use approach. We find that an internal combustion engine is far from reaching its maximal potential. Further development of ICE can lead to significant improvement of its energy efficiency and substantial reduction of pollutant emissions to the “zero-impact” level. It is shown that life cycle emissions of electric vehicles (EVs) differ considerably between regions, depending on the carbon intensity of the power generation mix. Compared with EVs, hybrid vehicles have a capability to benefit from the latest advancements both in ICE technology and in electric propulsion technology. This provides a potential for hybrid vehicles to become a widespread measure of energy consumption and GHG emissions reduction.

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1. INTRODUCTION

Transport activity is an integral part of a country's economic development. Economic growth and the parallel improvement in the welfare of its population are leading inevitably to an increase in the demand for transportation. One of the best examples of this tradeoff is displayed in the data on car sales in China. Registration of passenger vehicles has increased from 6.3 million in 1999 to 45.9 million in 2009, with an annual growth rate of 22% [1]. According to the predictions in [1], car registrations in China would reach 91, 203 and 464 million in 2020, 2030 and 2050, respectively. By 2035, the global fleet of cars is projected to hold 1.7 billion cars (today there are approximately 1 billion cars worldwide [2]).

It is important to note that transportation is responsible for a large part of the energy consumption worldwide. According to International Energy Agency (IEA) data [3], about 26% of all energy-related CO_2 emissions in 2007 were caused by transportation. It is likely to account for a higher share in the future, unless special measures are taken. Following the recommendation of the United Nations Intergovernmental Panel on Climate Change (IPCC), annual global greenhouse gas (GHG) emissions must be reduced by 50 - 85% by 2050 in comparison with the emissions level in 2000. This will result in limiting the long-term global heating to 2.0 - 2.4^{o}C and avoiding the most destructive impacts of climate change [4]. More recent studies have indicated that climate change occurs faster than previously expected and that even a 50% reduction in global GHG emissions by 2050 may not be enough [5].

Road transportation was responsible for about three quarters of total energy consumption in the transportation segment in 2006 [6]. In Europe, this number is even higher and has reached 82.5% in 2009 [7]. Among road transport modes, energy consumption of light-duty vehicles (LDV) accounted for the major share, with about 50-60% [8, 9]. Nowadays, road transportation is almost entirely dependent on crude oil (about 95% [10]). Therefore, in order to meet GHG emission targets, as well as to decrease oil dependency, overall energy consumption of road vehicles must be reduced significantly. The major challenge in reaching this goal is that the necessary reductions in the carbon emissions by vehicles must be achieved without disruptions in transportation patterns and population mobility. Accordingly, IEA has performed several predictions of GHG emissions (in CO_2 equivalent) by 2050 for a number of different scenarios [3] as presented below:

- Baseline. This scenario assumes that no new energy and climate policies are introduced, total vehicle travel mileage more than doubles by 2050 and fuel economy of new vehicles is improved by 25-30% compared with 2007.
- High baseline. The difference between this scenario and the baseline is that the total vehicle travel triples by 2050, together with an increase of approximately 20% in fuel demand. In result, this will probably require a much greater use of high-carbon and more expensive fossil fuels such as unconventional oil and synthetic fuels as coal-to-liquid (CTL) and gas-to-liquid (GTL) fuels.
- BLUE map. This scenario reflects the uptake of new technologies and alternative fuels across transport modes. Novel powertrain technologies such as hybrids, plug-in hybrids (PHEV), electric vehicles (EV) and fuel cell vehicles (FCV) penetrate the LDV and truck markets, resulting in significantly improved energy efficiency for all modes. This scenario assumes that very low greenhouse-gas

alternative fuels such as hydrogen, electricity and advanced biofuels achieve large market shares.
- BLUE shifts. This scenario presumes that travel is shifted towards more efficient modes and that total travel growth is restrained by better land use, a denser development of metropolitan areas, a greater use of non-motorized modes of travel and the substitution of travel by telecommunication technologies. No advanced technology deployment is assumed in this scenario.
- BLUE map/shifts. This scenario combines both BLUE map and BLUE shifts, and therefore is the benchmark scenario for the maximal reduction of GHG emission.

The results of GHG emission projections made in accordance with these scenarios are shown in Fig.1 [3]. If no new energy and climate policies are introduced, the energy consumed by transport is projected to double by 2050 with more than doubling the amount of GHG emissions to 16-20 Gt for baseline and high baseline scenarios, respectively. This increase of GHG emissions is projected despite the anticipated improvement in the fuel economy of vehicles by 25-30%. In order to achieve the GHG emission reduction suggested by IPCC of 50-85% by 2050, much more aggressive strategies of GHG intensity reduction have to be introduced. Very optimistic BLUE map/shifts scenario estimates that about 18% of the projected GHG emission mitigation may be achieved by modal shifting, 35% - by introduction of alternative fuels and electricity decarbonization and 47% - by improvement of vehicle efficiency. Taking into account that LDV are responsible for the majority of energy usage by road transportation, the most significant improvement in energy efficiency should be achieved in the LDV sector, as presented in Fig.2 [3]. Well-to-Wheel (WTW) GHG intensity of LDVs should be reduced from about 180 g CO_2-eq/passenger km by a factor of about 4.5, thus imposing a great technological challenge. IEA's BLUE map scenario projects that this target could be accomplished by a large scale penetration of hybrid, electric and fuel cell vehicles to the market, as presented in Fig.3 [3].

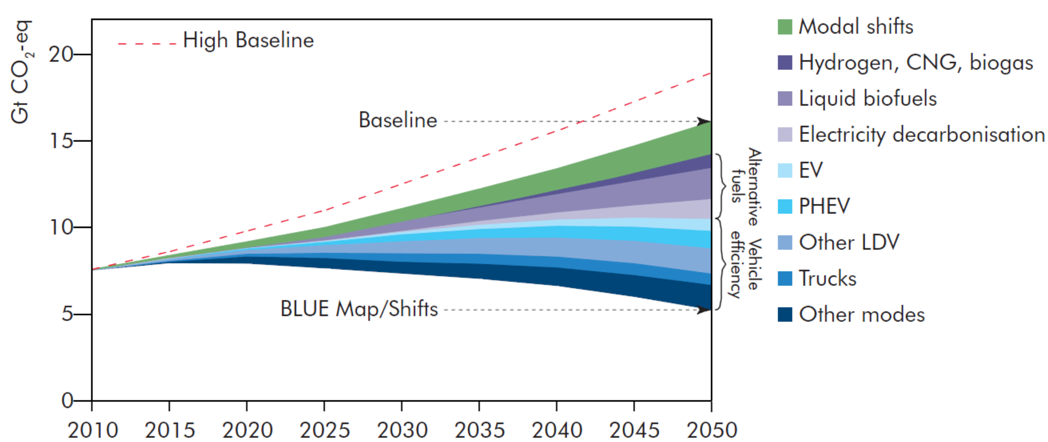

Figure 1. IEA prediction of GHG emissions reduction [3]. Energy Technology perspectives © OECD/IEA, 2010.

According to the baseline scenario, about 80% of LDV sales in 2050 will be combined of conventional gasoline fueled and diesel fueled vehicles. Conversely, according to the BLUE map scenario, hybrid, electric and fuel cell vehicles will dominate the market in 2050 and reach as high as 80% of LDV sales. Furthermore, it is important to note that this scenario projects a market share of approximately 45% for FCVs and EVs. Other studies, e.g. [11], also show that a multi-strategy approach is required to reach significant reductions in transport GHG emissions.

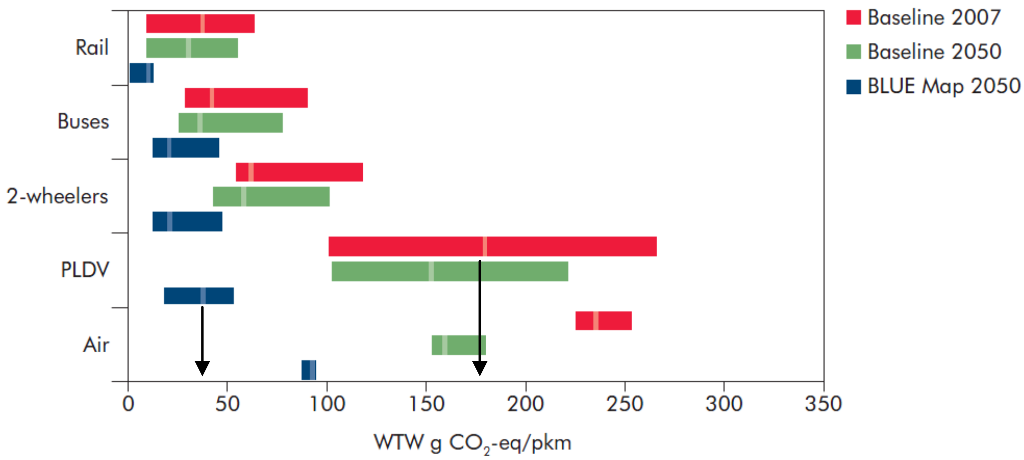

Figure 2. Evolution of the GHG intensity of the passenger transport modes [3]. The clear line indicates world's average, the bar presents regional differences. PLDV – passenger light duty vehicle. Energy Technology perspectives © OECD/IEA, 2010.

In the following chapter we will try to assess the potential improvement in the energy efficiency of vehicles (focusing mainly on light-duty vehicles) allowed by the implementation of various technologies.

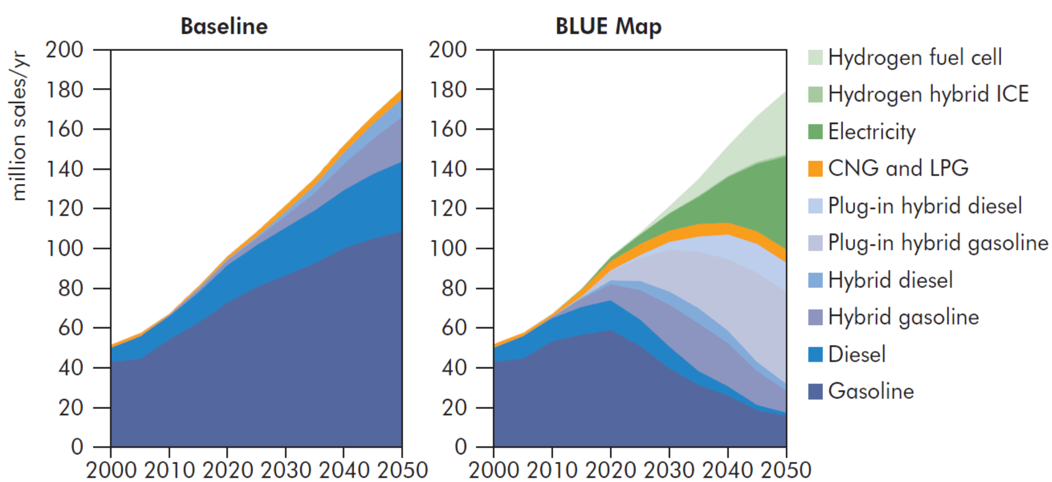

Figure 3. LDV sales by technology type in the Baseline and BLUE Map scenarios [3]. Energy Technology perspectives © OECD/IEA, 2010.

2. FACTORS AFFECTING VEHICLE GHG INTENSITY

According to WBSCD [12], vehicle's GHG intensity is determined by the following factors:

1) Amount of energy required by the average vehicle to perform a given amount of transport activity in each transportation mode. This factor depends on the energy consumption of the vehicle.
2) Carbon content of the fuel used and its production and distribution methods.
3) Total volume of transportation activity, which is dependent on the number of vehicles operated, their usage patterns, and is a function of consumer demand.
4) Modal composition of transportation activity, which is dependent on consumer choice, mode pricing and fiscal measures that influence mode selection.

The first two modes have the biggest impact on vehicle's GHG intensity. More than 80% of the reduction in GHG emissions is accounted by IEA in the BLUE map scenario as a result of an improvement in energy efficiency of vehicles and fuel decarbonization. Energy efficiency of vehicles is determined by their powertrain and other technological advancements, as well as by owner dependent factors. The most common non-propulsion technologies that were found to have an influence on the energy efficiency of vehicles are outlined briefly below:

- Construction materials have a major influence on the weight of the vehicle, which affects the amount of energy required to overcome its inertia and therefore, altering its dynamic performance. Rolling resistance is a measure of the forces between the tires of the vehicle and the road. It is directly proportional to the weight of the vehicle. In order to reduce the weight of a vehicle, lightweight technologies and alternate part designs could be utilized [12, 13]. A 5-7% reduction in rolling resistance of passenger cars leads to an improvement of approximately 1% in their energy efficiency [13]. Some examples of lightweight materials that are applicable for vehicles are aluminum, magnesium, various plastics and composite materials. The latter have a very high weight reduction potential up to 60% [13]. Nevertheless, their use in vehicles is still limited due to cost considerations.
- Tire technology. The treads of the tires are the main factor influencing tire wear and the major component of the tire contributing to rolling resistance. Reductions in tread thickness, volume and mass are among the means available to reduce rolling resistance. Even so, they may be undesirable, if lead to shorter tire life and an increase in the number of scrap tires [14, 15].
- The shape of the vehicle determines its aerodynamic drag, which is directly proportional to the square of the vehicle's velocity. At highway speeds, more than 50 percent of fuel consumption is used to overcome the aerodynamic drag. It is important to note that drag is only one of the aerodynamic forces working on a moving vehicle. The others are the lift and the side forces. These forces and the moments associated with their axes (rolling, yawing and pitching) are

dependent on the square of the velocity of the vehicle relative to the air stream and on some geometric aspects of the vehicle itself. They influence a vehicle's behavior on wet roads and in crosswinds and therefore cannot be neglected during the design stages [16]. Aerodynamic drag may be decreased by reducing a vehicle's frontal area, smoothing out body surfaces, covering the vehicle's under-floor and taking other measures, which help to prevent air stagnation zones [13, 17, 18]. The average modern passenger car achieves a drag coefficient C_d of between 0.30 and 0.35. However, there are some concept cars that have attained C_d values below 0.15 [19], thus demonstrating the existing potential of improvement in energy efficiency.

- Braking losses recuperation. In a vehicle equipped by mechanical brakes, during braking events, the energy devoted to overcome inertia is dissipated to heat. Conversely, in a vehicle equipped by an energy storage device (e.g. battery) and an electric generator, part of this kinetic energy can be recuperated by a regenerative braking system. The system, which is a standard feature in hybrid and electric vehicles, may significantly reduce their energy consumption - by up to 50% [20]. The largest reduction is achieved during urban driving, when most of the energy is consumed during vehicle acceleration and can be partially recaptured during deceleration. Another way to recover a vehicle's kinetic energy is the flywheel technology. Flywheels are almost twice more efficient over a full regenerative cycle as compared with a battery based regenerative braking systems, because of their lower number of energy transformation events [21].
- Advanced driver assistant systems (ADAS). The ADAS systems are usually based on various sensor and communication technologies, which contribute to safer traffic and smoother vehicle movement in a traffic flow, therefore, leading to improved energy efficiency of vehicles and more efficient usage of infrastructure. The vehicle's x-by-wire technology developments have made the spread of the ADAS systems possible [12].
- Vehicle accessories. The technology of various accessory systems driven from the engine, such as air conditioning (A/C), power steering and others affects their energy consumption and thus influences the energy efficiency of a vehicle. A/C is considered to be the main auxiliary load on a vehicle's engine when it is operating. The impact of A/C usage is largest in urban driving, because additional energy is consumed during vehicle stops. EV energy consumption is most sensitive to A/C usage that may increase energy consumption by over 70% in urban driving conditions [10]. Thus, significant energy savings can be achieved by operating A/C system smartly, e.g. with aid of intelligent energy management systems [22]. These systems are intended to reduce the energy consumption of vehicles accommodated with A/C and improve their efficiency by using the look-ahead approach, analyzing inputs from several information systems to make optimal decisions. Intelligent energy management systems predict road power demand by using look-ahead control of vehicle systems and an intelligent control strategy to manage the operation of the A/C system components. They can save up to 12% of the energy consumed by a conventional A/C system [22].

3. POWERTRAIN TECHNOLOGIES – DEVELOPMENT TRENDS

3.1 Internal Combustion Engines

Results of recent studies suggest that there is a big potential for improvement in the further development of internal combustion engine (ICE) technologies. The immediate impact of these improvements on global environment and economics is considered to be much more significant than the effect attainable by the introduction of completely new technologies, which suffer from shortcomings in production, infrastructure, recycling, in-depth understanding of health effects and public acceptance [23].

ICE converts chemical energy of combusted fuel into mechanical work. Today, an average conventional vehicle with spark ignition (SI) engine is driven in urban conditions with an efficiency of about 15% [13]. 85% of fuel energy is wasted due to engine and driveline losses, and engine idling at vehicle stops. The energy loss inside the engine occurs due to internal friction, pumping work, incomplete combustion and waste heat. Therefore, ICE technological advancements are focused on mitigation of these losses. The following advanced engine technologies are considered and sometimes already implemented to increase engine usage efficiency:

- Downsizing accompanied by engine boosting;
- Accessories electrification;
- Variable valve train;
- Direct injection in SI engine;
- Advanced fuel injection strategies;
- Variable compression ratio;
- Engine idle stop;
- Low temperature combustion concepts;
- Waste heat recovery;
- Adaptive control of engine flexible sub-systems;
- Improved materials

All these advancements focused on improvement of the energy efficiency of ICE are and will be developed under severe legislation aimed at achievement of zero-impact pollutant emissions. In a long-term perspective, the differences between SI and compression ignition (diesel) processes will diminish. A future ICE will probably be a highly flexible multi-fuel combustion engine with variable adaptive sub-systems controlled by a sophisticated powertrain management system.

Engine downsizing is a technology that has successfully penetrated the market in the last years. Downsizing has several effects. Firstly, it reduces pumping work by shifting engine operating regimes to higher load factors, and secondly, it produces reductions in frictional losses, thus contributing to improvement in the energy efficiency. Engine displacement can be reduced by about 20% (according to [23] – up to 40%) with the level of torque required for aggressive acceleration provided by engine boosting (turbocharging or/and supercharging), whenever this level of performance is required. Downsizing technology benefits from the high level of consumer acceptance because the improvement in energy efficiency is usually accompanied by better dynamic performance of the vehicle. The latter effect is achieved as a result of the beneficial engine torque curve that is provided by the boosting systems. Improved design of the gearbox can assist as well in the process of engine downsizing by transferring the requirements to higher engine loads [24]. Arnold et al. [25], Petitjean et al. [26], Heywood [27], and Leduc et al. [28] have studied downsizing of gasoline engines with turbocharging. It has been shown that vehicles of the same weight, powered by downsized turbocharged gasoline engines yield fuel savings of up to 20 percent. The average expected benefit in energy efficiency is in the range of 8-10% [29].

Downsizing can be achieved also by cylinders deactivation, known also as multiple displacements, displacement-on-demand and variable cylinder management [30]. Whereby, whenever low power is required, some cylinders do not participate in the four-stroke cycle due to advanced control of the engine [24]. Cylinder deactivation leads to an average savings in fuel consumption of about 7.5% [30].

Recent studies on ICE boosting technologies [31, 32] deal mainly with the problems of surge at low speed, transient performance, energy utilization of a highly pulsating flow exiting engine and turbocharger operation at extremely high speeds. The progress achieved will allow engine operation at very high values of brake mean effective pressure [33] together with non-compromised load acceptance. Energy efficiency increase that can be assigned to turbochargers improvement is estimated in the range of 2-7 % [13].

Electrification of engine accessories is a broadly accepted way of saving several percent of fuel consumption. This trend includes the replacement of mechanical and hydraulic systems by electrical equipment with on-demand operation, thus reducing parasitic losses. In addition, continuous high-efficiency generators reduce the losses in existing electrical equipment, while higher voltage-systems in conventional vehicles increase the possibilities of regenerative braking, and extend auxiliary systems electrification [34]. A potential of energy efficiency improvement as a result of accessories electrification is estimated by 1-2 % [30, 34].

Energy efficiency and power output of an ICE can be improved significantly by appropriate optimization of cylinder charging and air/fuel ratio in a wide operation range. Increasing the flexibility of valve train actuation can provide a number of benefits, such as the elimination of throttling losses (will allow fuel savings of 4-6 % [24, 35]), cylinders deactivation and possibility for a Miller cycle realization. For several years, automakers have offered systems to continuously alter valve timing, lift and opening duration. In 2009–2010, BMW launched engines combining compact valve management systems with direct injection and turbocharging [34]. In 2010, FIAT offered a MultiAir variable valve actuation technology with no throttle valve, which according to the company, reduces fuel consumption by up to 10% [36, 37]. Variable valve trains are estimated to reduce energy consumption and GHG emissions up to 20% [23].

The adoption of direct injection technology in SI engines is another way to improve efficiency. However, realization of stratified charge and combustion is more expensive as compared with conventional SI engine, mainly as a result of the need to use advanced injection technology and nitrogen oxides (NOx) aftertreatment [23]. The possible improvement in the fuel consumption of a direct injection SI engine is estimated between 3% and 15% [13]. Advanced fuel injection strategies are also required to attain effective combustion in PFI as well as direct injection SI engines [23, 38], better efficiency together with lower noise, emission formation and better operation of aftertreatment systems in diesel engines. Multi-step injection strategies in diesel engines usually contain pilot, main and post injection phases. Multi-step injection combined with injection rate shaping, pressure modulation and variable nozzle holes size are becoming a noticeable part of advanced diesel engine concepts [39, 40].

Variable compression ratio (VCR) is aimed at achievement of best possible engine thermal efficiency in a wide operation range. A potential for a gain in energy efficiency is highly dependable on the driving pattern of the vehicle and the fuel type used. Therefore, available estimates of fuel savings are ranging widely from 2 to 25% [13, 23, 24, 30, 41]. Engineering solutions that provide VCR are still expensive [24, 30] and further development aimed at cost reduction and reliability improvement is required.

The engine idle stop system often called "micro-hybridization" shuts down the engine when the vehicle is stopped for example at a red light or a traffic jam, and engages the engine (using energy from the battery) when the accelerator pedal is pressed. This system is a standard feature in HEVs and EVs. However, recently it is successfully penetrating to the conventional motor vehicle market and is being offered as an option by almost all vehicle manufacturers. This system is featured by a specially designed, belt driven, 14V integrated starter/generator (ISG), which is installed in place of the conventional alternator. It is important to note that this system does not impose any significant additional weight. Micro-hybridization can also be expanded to additional driving situations, such as the Stop-In-Neutral (SIN) approach [34]. As in the case with the VCR, a potential for a gain in energy efficiency is highly dependable on the driving pattern of the vehicle. It diminishes to negligible values when driving in highway conditions and reaches its maximum at the most congested stop-and-go driving. The range of possible improvement in energy efficiency is estimated to be between 0.5-15 % [13, 30, 34, 42].

The novel concept of low temperature combustion frequently referred to as the homogeneous charge compression ignition (HCCI) or controlled auto ignition (CAI) has been drawing a considerable amount of attention due to its potential of high efficiency, fuel type flexibility and zero-impact emissions of NOx and particulate matter (PM). HCCI is characterized by the premixed fuel and air before the start of combustion [43, 44]. The fuel/air mixture auto-ignites as a result of the temperature increase during the compression stroke. HCCI is the new combustion concept that attempts to combine the benefits of both Otto and Diesel cycles. The fuel/air mixture is premixed and burns very quickly like in the Otto cycle, thus providing better thermal efficiency. Similarly with the Diesel cycle, this mixture auto-ignites and the benefits of a higher compression ratio together with throttle-free operation can be utilized. However, there are still serious challenges preventing this novel concept from being immediately implemented in ICE, giving it a significant push forward in the competition with alternative propulsion concepts. Some of the main problems that should be resolved are the control of the combustion phasing, extension of the HCCI operation range and high hydrocarbons (HC) and carbon monoxide (CO) emissions. In the future, the following technologies should be further developed for the HCCI combustion engine to become practical [43]:

- Fully flexible injection strategies;
- EGR (exhaust gas recirculation) control;
- Closed-loop feedback control;

- Extension of the low temperature combustion mode to higher loads;
- Individual cylinder control to ensure the same combustion phasing.

Most of the developments in the ICE technology that are mentioned in this section, such as: variable valve train actuation, controlled engine boosting, VCR, advanced injection strategies, adaptive control, etc. should be applied in the HCCI combustion engine. The potential of HCCI concept to improve energy efficiency is high. Yang et al. [45] have shown that HCCI engine can have specific fuel consumption, at part load, of 50% that of a port injection SI engine and 30% less than a direct injection SI prototype. The similar result of doubling fuel economy compared with the conventional SI engine is mentioned by Berggren and Magnusson [34].

It is well known that about 30% of fuel energy introduced to ICE is wasted with engine exhaust gases [24, 34, 46]. Its utilization can lead to a significant improvement of ICE energy efficiency. Turbocharging is a widely applied and well known method of the waste heat recovery (WHR). However, at the turbine exit of a conventional turbocharger, a high exergy of exhaust gas is still available. Utilization of the two-stage turbocharging architecture [31] further improves WHR. For some usage patterns the turbo-compounding approach that applies an additional power turbine coupled with the electric generator may be an attractive option [34, 47]. However, economic feasibility of this approach should be always assessed. Energy efficiency improvement due to turbo-compounding is assessed in [48] at about 2 % (from 47.3 to 48.2%). Another, quite well described method of WHR is by using it for the vehicle cabin air heating [46]. Higher amounts of the waste exhaust energy can be utilized in a Rankine cycle [24, 34, 49], where exhaust heat feeds into a steam generator to produce a steam, which is used through the steam turbine/generator system to convert the recovered exhaust waste heat into electrical power. The latter may be used to assist the engine, charge the battery or cover the onboard electrical power demand. It was demonstrated [49, 50] that up to 50% of exhaust gas exergy can be recovered when a Rankine cycle based WHR system is employed. This means that a WHR system based on Rankine cycle can help the engine increase its overall efficiency by more than 10 percent [50]. Fig.4 shows one of the possible configurations of the Rankine cycle WHR system that utilizes also the engine's coolant heat [49].

Several automakers have announced R&D activities in different thermoelectric devices (TE). The latter rely on the Seebeck effect and can directly convert part of the exhaust heat to electric power, without the use of mechanically rotating parts. In addition, they provide some advantages such as completely solid state, no noise, no vibrations, sometimes no moving fluids and a high reliability. Nonetheless, significant system design challenges, such as low conversion efficiency with current technology and the relatively high costs of the thermoelectric semiconductor materials, should be overcome during the development of the TE [51–54]. Latest advances in the semiconductor materials technology have paved the road to further development that could permit the improvement of powertrain efficiency by 5–10 percent [55].

Another way to recover engine's waste heat is by using the energy of exhaust gases to promote endothermic reaction of steam reforming of alcohol [56, 57]. In principle, any renewable fuel may be used, not only alcohol.

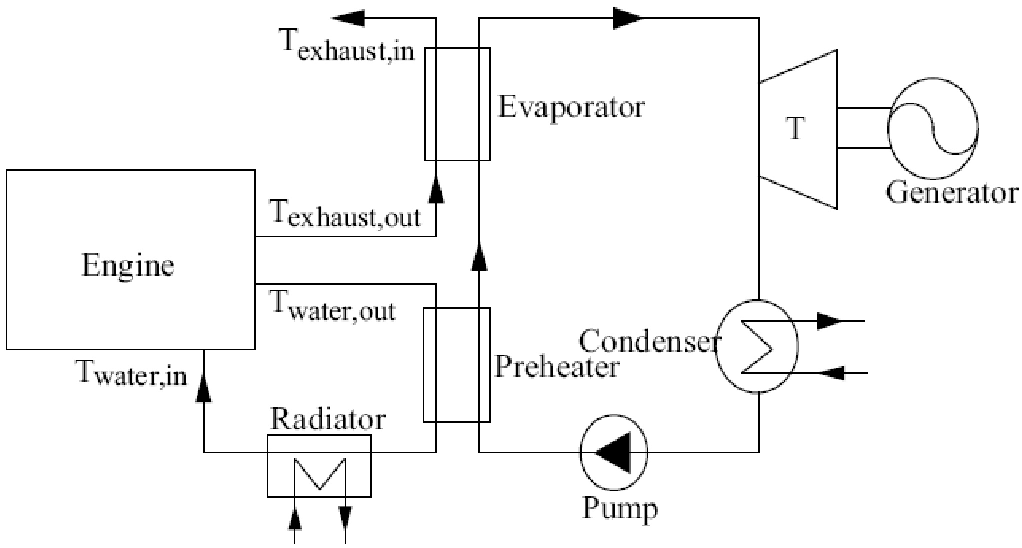

Figure 4. Rankine cycle WHR system with a pre-heater using the engine coolant [49]. Reprinted from Renewable and Sustainable Energy Reviews, vol. 15, issue 6, Tianyou Wang, Yajun Zhang, Zhijun Peng, Gequn Shu, A review of researches on thermal exhaust heat recovery with Rankine cycle, p. 2862-2871, Copyright (2011), with permission from Elsevier.

Fig. 5 shows the steam reforming of ethanol – SRE. ICE in this scheme is fed by the gaseous products of SRE, mainly hydrogen and carbon monoxide, frequently called syngas. The latter has, as a rule, greater heating value than primary liquid fuel and may be more efficiently burned in the engine in comparison to the original fuel. This approach, called thermo-chemical recuperation (TCR) [58, 59], has been receiving renewed interest as one of the possible methods of increasing powertrain efficiency and reducing emissions. It is known that an onboard reformer can't work efficiently in a wide range of engine operation regimes typical for a conventional road vehicle, especially at transient modes and cold-start conditions [60]. In the case of a hybrid propulsion system, which always has an additional energy source, these shortcomings can be successfully overcome. TCR technology for HEV powertrains is at initial stages of R&D, however theoretical potential of energy efficiency improvement is significant – up to 11 percent [56] and justifies further development of the technology. A special research effort is required to guarantee an acceptable transient behavior of TCR systems.

Modern ICE is a complex mechatronic system. The emerging engine technologies, such as advanced engine boosting, variable valve train control, fuel injection strategies, VCR, HCCI, etc., require development of adaptive sophisticated control systems using new sensor and computing technologies [23, 61]. Some examples of mechatronic controls, which are anticipated to become available in the next decade include [24, 61]: advanced adaptive and closed-loop; combustion feedback control and new sensor technologies (e.g. cylinder pressure, ion sensing, position sensors) which lead to single-cycle control strategies, enlarged operation range, improved transient response and development of flexible learning systems for cycle-to-cycle control.

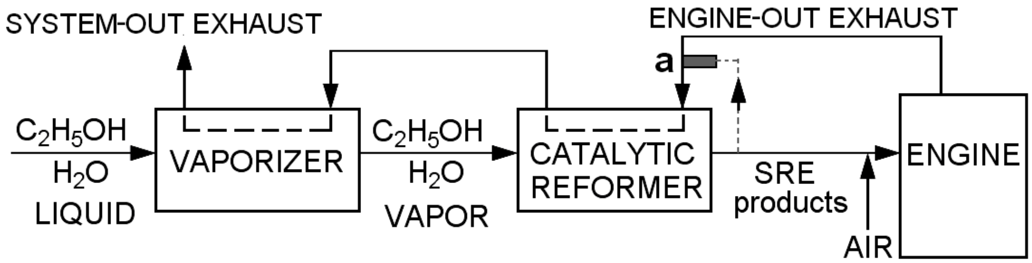

Figure 5. Scheme of the integrated reformer-SI engine TCR system. a – optional SRE products burner [56].

Development trends in ICE technologies include other directions as well, such as advanced lubricants, materials and surface treatments that allow friction reduction inside an engine [62-64]; development of materials that allow engine operation at higher temperatures and pressures and other. Moreover, the development of additional alternative concepts of ICE is continued. A split cycle ICE with promising energy efficiency potential can be mentioned as an example [65]. These and other alternative concepts would usually require massive change to the existing engine manufacturing and service infrastructure. Thus, a technological breakthrough with very significant advantages must be achieved to allow alternative ICE concepts penetrate the market [23]. Table 1 summarizes the potential of various engine technologies to improve energy efficiency. All the technologies are classified on three groups according to their level of readiness to penetrate market:

- production-intent: manufacturing is started or anticipated in next five years
- emerging: manufacturing is anticipated in 10-15 years
- long-term: manufacturing may be anticipated after 2025.

Table 1. Increase of energy efficiency due to various engine technologies

ICE technology	Efficiency increase, %	Readiness to penetrate market
Downsizing	8-10 (potential up to 20)	Production-intent
Friction reduction	1-5	Production-intent
Boosting	2-7	Production-intent
Accessories electrification	1-2	Production-intent
Variable valve train	4-10 (potential up to 20)	Production-intent
Direct injection in SI engine	3-15	Production-intent
Advanced fuel injection strategy	3-5	Production-intent
Engine idle stop	0.5-15	Production-intent
Cylinders deactivation	7.5	Emerging
Waste heat recovery	2-11	Emerging to long-term
Variable compression ratio	2-25	Long-term
Low temperature combustion concepts	Up to 50%	Long-term

Table 1 shows clearly that internal combustion engine is far from realizing its full energy efficiency capabilities and that the technologies that are expected to penetrate the market in a long-term perspective promise the biggest efficiency improvement potential. This overview of ICE-based improvement possibilities raises the question of limits to such efficiency increase. As mentioned by Kobayashi et al. [13] and Taylor [24], a part of these technological benefits are additive when multiple advancements are built into a powertrain, though synergistic effects may reduce the total energy efficiency increase. According to [24], practical limits for mass market vehicles indicate a vast untapped potential: a factor of two in efficiency to be gained for gasoline fueled SI engines (i.e. from about 30% to 60%), and another factor of two in propulsion efficiency of a specified vehicle.

3.2 Electric Drive Technology

Electric-drive vehicles (EDVs) have been gaining increased interest constantly, in the context of growing concerns about energy supply security and climate change aspects associated with road transport. The common feature of EDVs of various types is that the torque is supplied to the wheels by an electric motor that is powered either solely by a battery or other source of electricity, or in combination with an internal combustion engine. This definition covers hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), fuel cell vehicles (FCVs) and also photovoltaic electric vehicles (PVEVs) [66].

Hybrid powertrain. A desire for powertrain efficiency improvement together with an increase of on-board electric power requirements creates a need for hybrid-electric propulsion technology. The biggest advantage of hybrid powertrains is their capability to benefit from the latest advancements in both ICE and electric propulsion technology. This provides hybrid powertrains a potential of becoming a widespread measure for reducing fuel consumption and GHG emissions, especially in urban driving. In HEVs the battery is recharged only by ICE and regenerative braking system, without any possible external charge using the electricity grid. PHEVs, on the other hand, can obtain part of their energy from the grid. However, they require a larger battery and perhaps a larger motor. PHEVs can be seen as an intermediate technology between BEVs and HEVs.

They can indeed be considered as either BEVs supplemented with an internal combustion engine to increase the driving range or as HEVs where the all-electric range (AER) is extended as a result of larger and heavier battery that can be recharged from the grid. HEV and PHEV architecture can be assigned to one of the following schemes: series hybrid, parallel hybrid or their combination, which is sometimes called power-split [67]. In the *series-hybrid* configuration, only the electric motor provides power to drive the wheels. Sources of electrical energy are either the battery (ultra-capacitors may be an option) or a generator powered by ICE. An example of *series PHEV* is the Chevrolet Volt developed by GM [68]. Such vehicles are also called Extended-Range Electric Vehicles. In case of the *parallel hybrid*, both electric motor and thermal engine can provide power in parallel to the same transmission. Power split or series/parallel hybrid configuration combines the advantages of both parallel and series hybrid concepts. This is the architecture implemented in the Toyota Prius HEV [69]. This relatively complex scheme (Fig.6) allows running the vehicle in an optimal way by using the electric motor only, or both the ICE and the electric motor together, depending on the driving conditions.

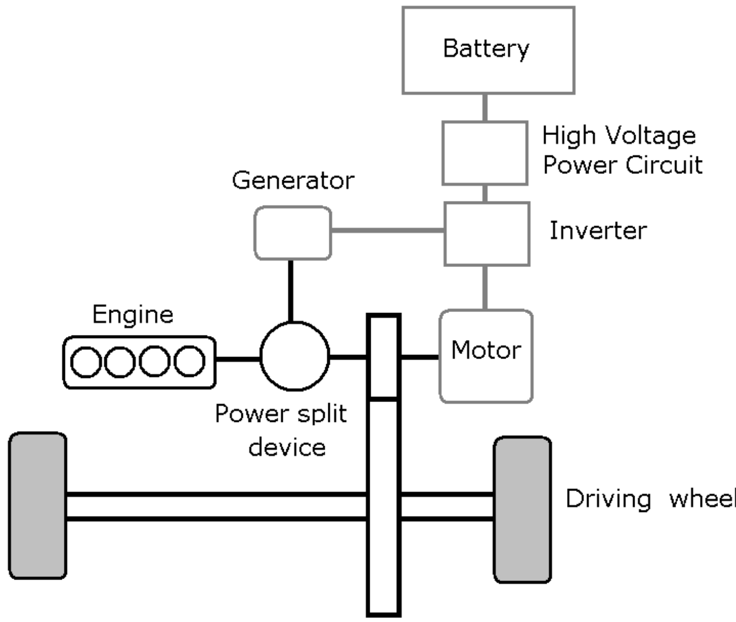

Figure 6. Power split hybrid configuration.

Hybrid powertrain allows energy saving through the following features:

- Engine shut-down at vehicle stops, during braking or coasting;
- Regenerative braking and the use of the electricity generated to recharge the battery/ultra-capacitor;
- Using the electric motor to supply additional power during accelerations, while using downsized ICE with improved energy efficiency. Miller cycle engine used in the Toyota Prius HEV can be a good example for that;
- Using the electric motor instead of ICE at low loads (in some configurations [13]), thus eliminating engine operation at low efficiency regimes;
- Shifting vehicle and engine accessories to a more efficient electric operation.

Energy efficiency improvement by HEV grows up with traffic congestion. HEV, such as Toyota Prius attains about 40-50 percent of fuel economy improvement [13]. Market penetration of PHEV technology will strongly depend on further progress in batteries development. There are many parameters in battery performance, such as: energy density, cycle life duration, safety, recyclability, etc., that still require significant improvement. The energy storage capacity of batteries is of high importance since it will directly determine the distance the vehicle is able to drive on the charge depletion (CD) mode, as well as the mass of the battery pack. For PHEVs, the energy storage requirement that is considered in the literature typically varies from about 6- 9 kWh to 30 kWh depending on the CD range, as compared to 1-2 kWh for HEVs and 30-50 kWh for BEVs [66].

PHEV's potential to mitigate the use of fossil fuels is clear – the energy received (charged) from the grid will replace the fuel. The higher the AER of PHEV, the bigger the amount of fuel that is replaced. However, the potential of PHEV to reduce GHG emissions above that attained by HEV depends on the energy sources used for electricity production [13, 34, 70]. In regions, where low carbon fuels are used for electricity generation, GHG reduction over the PHEV lifecycle will be substantial. In areas that rely on coal in electricity production PHEV lifecycle GHG emissions can be higher in comparison with HEV [13].

Battery electric vehicle. Pure electric vehicles are driven by highly efficient (above 90%) electric motors. However, the small driving range and short battery life, together with high cost have limited the market penetration of BEVs thus far. Fig. 7 demonstrates certain progress attained in the last decades with the improvement of batteries' energy density by using the Li-Ion chemistry. However, it still remains an order of magnitude lower compared with conventional fossil fuels – Fig. 8. Regrettably, at the moment there are no breakthrough developments in the field that may indicate a potential of closing this gap in the foreseeable future [66]. This problem will limit significantly the potential of pure battery electric vehicles to penetrate the market. Another obstacle is the high cost of batteries that has to be reduced significantly if they are to become more widespread [66, 71, 72].

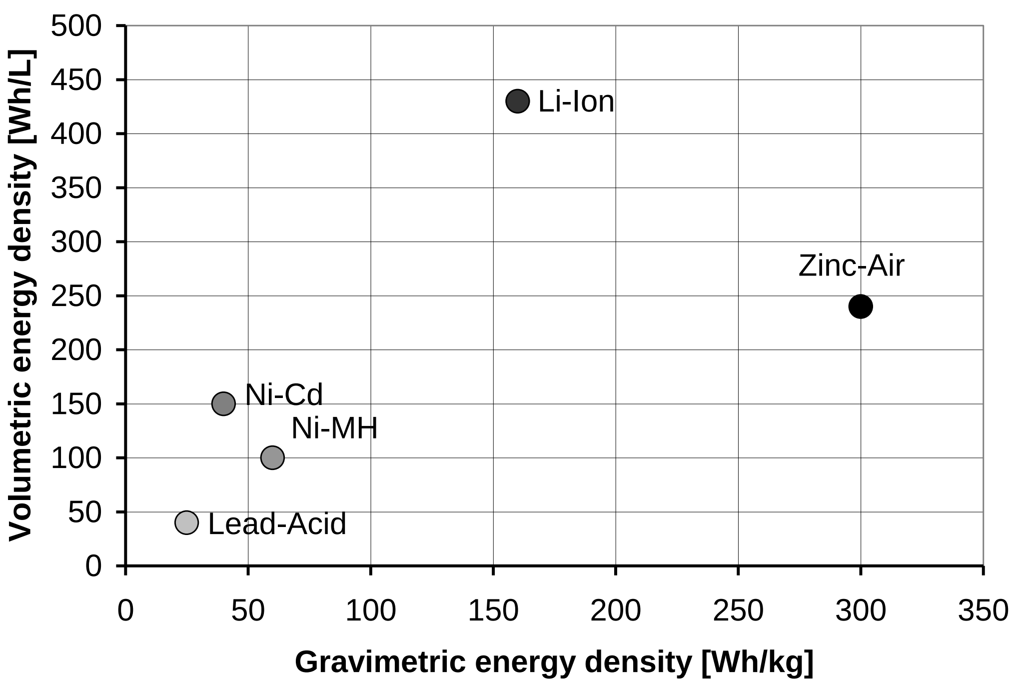

Figure 7. Progress in batteries development.

Nickel Metal Hydride (NiMH) batteries are the current typical batteries used by car manufacturers in mass-produced HEVs. However, NiMH batteries are considered to have reached their maximum potential [66]. For the future, experts do not expect significant new technical improvements and cost reductions [73, 74]. Car makers are moving to Lithium-Ion batteries, especially because they offer a higher energy density than that of NiMH batteries (Fig.7).

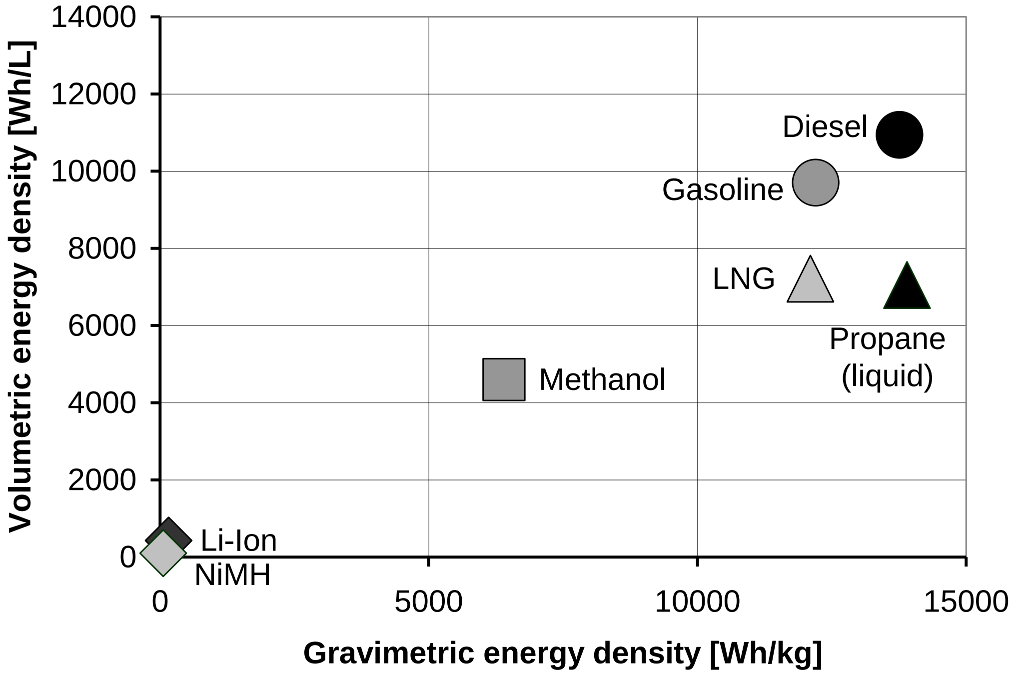

Figure 8. Energy storage density of various sources.

They are considered to be the best currently available option not only for PHEVs, but also for BEVs and HEVs, at least in the short to medium term. Li-ion batteries offer a wide field of new developments and have not yet achieved the same maturity level as the NiMH batteries have [66]. They have been tested intensively worldwide and are already used in many PHEV and BEV prototypes [75]. For large-scale production of battery resources, e.g. noble metals and chemicals, recycling infrastructure has to be ensured. Furthermore, health and safety aspects resulting from normal BEV operation, such as gaseous emissions during recharging, high voltage in vehicles, electromagnetic fields surrounding the vehicle and its crash behavior are significant for the customer acceptance of this technology [23]. Although BEVs are available nowadays, their high price and low range make them niche products. This image problem has to be faced. Although the BEV's potential of GHG reduction strongly depends on the electricity production mix, well-to-wheel emissions of GHG can be reduced by more than 50 percent compared to conventional vehicle with gasoline powered ICE [13].

There is a widespread consensus that a prerequisite for the development of new transportation systems is their sustainability. This means “development that meets the needs of the present without compromising the ability of future to meet their own needs" [76].

Sustainability includes vehicle and engine technology aimed towards zero environmental impact, and introduction of transport systems that are operated to provide mobility with optimized energy management and minimal emissions. Here there is an important role of Intelligent Transportation Systems (ITS) and in particular, urban Cybernetic Transportation Systems (CTS) [77, 78], which is a system of road vehicles with automated driving capabilities (either fully or partially). Its vehicle fleet is used for moving passengers or goods on a network of roads, and is under control of a computerized management system. CTS vehicles mostly consist of BEVs that have indeed zero tailpipe emissions, but for being truly sustainable, the energy sources used for the electricity production should be renewable. In the meanwhile, if the used energy sources are not renewable, the care should be taken in a decision-making on implementation of CTS based on sociological and environmental parameters. A viable approach for providing sustainable transportation to a city is, indeed, based on co-modal systems. This means specially-designed systems that combine the use of the individual car and the collective (public) transportation management system. If these are controlled to operate efficiently, they offer the combined advantages (e.g. comfort) of the former with those of providing sustainable overall mobility by the latter. CTS, which is clearly an Intelligent Transportation System is the promising example of such co-modal system [79]. Several CTS types have started to appear in the last years of the 20th century. Some have been or are now under construction in various European locations, while others have been deployed in demonstrations, during R&D work in the field.

Fuel cell vehicle, as the name suggests, uses fuel cells as its primary source of power. Fuel cell technology utilizes hydrogen as the primary fuel to generate electricity. Therefore, all known problems of hydrogen production, infrastructure establishment, storage on-board a vehicle, etc. are relevant for FCVs and should be resolved, in addition to inherent FCV technology challenges, to allow market penetration of fuel cell vehicles. Renewable fuels, such as methanol, ethanol, as well as natural gas can be used for their on-board conversion into hydrogen through adequate reforming steps [80, 81]. However, in this case the FCV will no longer be a zero-emission vehicle, because of CO_2 emissions accompanying the reforming process. Special caution is required also to eliminate formation of CO, which is a poison for fuel cells [81]. This complicates the system and reduces its overall efficiency. Compared with the strict requirement for high-purity hydrogen for fuel cells, ICE is much more flexible and can effectively burn different mixtures of hydrogen, carbon monoxide and other gases. This characteristic greatly reduces the cost of energy obtained from renewable fuels [57]. Oxygen is used in a fuel cell as the main oxidant. If pure hydrogen is used as a fuel, FCV is a really zero-emission vehicle. The only product emitted from the vehicle's tailpipe is water. Fuel cells produce electric power through an electrochemical process, in which hydrogen energy is converted into electricity. Several different liquid and solid media can be used to facilitate the fuel cells electrochemical reactions. These media are phosphoric acid (PA), molten carbonate (MC), solid oxide (SO), and polymer electrolyte membrane (PEM). Each medium consists of a distinct fuel cell technology and unique performance characteristics. In an ideal case, the efficiency of a fuel cell comes out to be as high as 83%. However, the overall efficiency of fuel cells is impacted by the ratio of the parasitic power that is consumed by the auxiliary components to the stack power. For example, the electrical efficiencies of PEM fuel cells are in the range of 23- 40 %, [82]. However, there are more losses to be considered. Typically, automotive PEM fuel cells consume more of the rated stack power output to provide power to pumps, blowers, controllers, etc. Depending on the chosen drive train technology, the DC power is converted to frequency modulated AC or to voltage adjusted DC, before motors can provide motion for wheels. Energy is always lost in the electric system between fuel cell and wheels. Fuel cells today are much more expensive than an equivalently sized ICE.

4. OWNER DEPENDENT EFFECTS

The most impressive technological advances may be diminished, if appropriate owner dependent measures are not taken to ensure the highest possible energy efficiency and lowest emissions of a vehicle in the process of its real-world usage. It is well known that a vehicle's speed strongly affects its fuel consumption. The increase of the average speed in urban driving by 5 km/h could reduce fuel consumption by about 10 % – Fig.9 [83]. Similar data are published by Kobayashi et al. [13]. The increase in the average speed during urban driving may be attained by various measures, such as: infrastructure development, ITS implementation, driver information systems, etc.

Driving style has also a significant influence on a vehicle's operating energy efficiency. As can be seen from Fig.9, a reduction of up to 50% in the energy consumption can be reached when the driving style is changed from aggressive (sharp accelerations and sudden brakes) to calm (priority set forth). Similar results were obtained by Lohse-Busch [10] with an additional important observation that electric vehicle energy consumption is most sensitive to driving aggressiveness. Numerous studies conducted worldwide confirm effectiveness of eco-driving (a term used to describe energy efficient use of vehicles [84]) as an important tool of energy efficiency improvement [13].

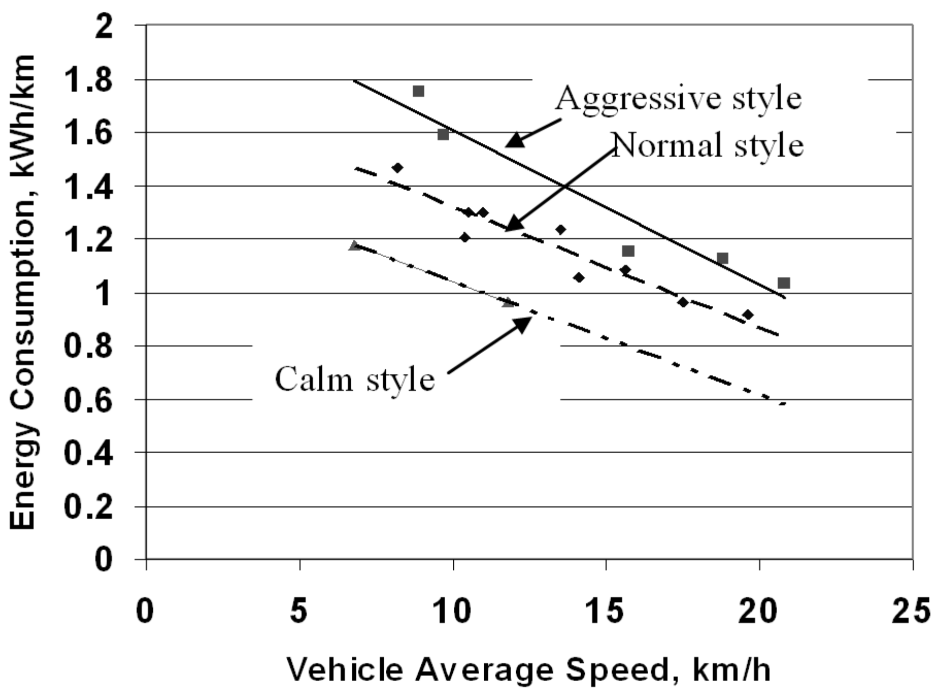

Figure 9. Energy consumption of BEV in urban driving – effects of average speed and driving style. BEV - converted electric van, GVW=4.5 ton, battery – Zn-Air [83].

Keeping a vehicle in a proper technical condition is another important tool of improving its operating energy efficiency. It was shown that for public buses [85] and LDVs [86] efficiency was improved by about 3-4 % after maintenance measures were applied. In addition, a small, but still sensible improvement in fuel economy can be realized by keeping a vehicle's tires properly inflated. According to [86], drop of each 7 kPa in the pressure for all four tires leads to increase in fuel consumption by 0.3 %. Some additional improvement of energy efficiency can be achieved by using high quality lubricants, especially those containing advanced friction modifiers.

5. COMPARISON OF DIFFERENT POWERTRAIN TECHNOLOGIES

It was discussed in section 3 that more than 80% of GHG emission reduction is accounted by IEA in the BLUE map scenario as a result of vehicle energy efficiency improvement and fuel decarbonization. Attaining the ambitious goal of 50-85 percent GHG emission reduction by 2050 will be impossible without a revolution in the energy sources market. Introduction of alternative renewable fuels will allow further enhancement of benefits in energy efficiency brought by newly developed technologies.

The primary energy efficiency is usually used as a measure for comparison between vehicles using different energy carriers. Primary energy efficiency takes into account all energy “from the well to the wheel” (WTW approach). This type of assessments should consider energy losses during fuel production and distribution, vehicle production, etc., in addition to “tank to wheel” losses [11, 70, 87]. These predictions, especially aimed towards the assessment of energy efficiency 40 years ahead, are based on a large number of assumptions and featured by a high degree of uncertainty. Nevertheless, basic findings are consistent in various studies [11, 13, 34, 70, 87-89]:

- A multi-strategy portfolio approach is needed to make deep reductions in road transport GHG emissions.
- An internal combustion engine is far from reaching its maximal potential. As demonstrated above, further development of ICE can lead to significant improvement in its energy efficiency and substantial reduction of pollutant emissions to the “zero-impact” level. Availability of low-carbon alternative fuels will further enhance the benefits of novel low-temperature combustion processes, which are under intensive development nowadays.
- Due to the fact that no breakthrough developments in the energy density of batteries for electric vehicles have been accomplished, it still remains significantly lower compared with conventional fossil fuels. This and other technical hurdles should be overcome to allow wide market penetration of pure battery electric vehicles.
- There is a potential to double the primary (WTW) energy efficiency using electric drivetrains in vehicles, such as BEVs and PHEVs, compared with present ICE vehicles. No significant differences amongst BEVs and PHEVs could be identified from a primary energy efficiency point of view.
- Hybrid vehicles have a capability to benefit from the latest advancements both in ICE and in electric propulsion technology. They provide a potential to become a widespread measure for reducing energy consumption and GHG emissions.

- Life cycle emissions for electric vehicles differ considerably between regions depending on the carbon intensity of the power generation mix. By simulating the performance of equivalently specified BEVs, PHEVs and ICE-vehicles, Doucette and McCulloch [90, 91] have found that in countries with a power generation mix of low carbon intensity, electric vehicles were immensely superior in terms of emissions. However, in the US with its heavy use of coal as feedstock for electric power generation, EVs were only slightly better. In countries, such as China and India, with very high carbon intensity of their power production, the overall emissions of the most efficient diesel cars were equal or lower than those of corresponding electric vehicles.

The environmental impact of road transportation system is a function not only of the emissions level, but also of the number of people that are exposed to the polluted air and therefore exposed to health damage. Here major differences are possible between BEVs and ICE vehicles. To account for this fact, we propose to introduce an environmental impact factor (EIF) to evaluate a vehicle's environmental impact and to allow comparison between different transportation modes. The dimensionless *EIF* value is calculated as: $EIF = TEI \cdot D_s$, where D_s is the receptor density in the site of consideration and *TEI* is the total emission indicator, defined similarly as in [92]. Receptor density is calculated as the population per km^2 of the site area. Since it is usually impossible to distinct between various pollution sources that were involved in the additional electricity production due to EV activity, the uniform background approach was suggested by Curtiss and Rabl [93]. The approach is applied to calculate *EIF* values for EV based transportation modes. Had the world been homogeneous, the receptor density would have been uniform, D_u. Receptor density D_s depends on the site. The relative receptor density *f* can be defined as $f= D_s/ D_u$. Dependence of *EIF* on *f* can be used to analyze the environmental impact of different transportation modes. The example of this analysis is shown in Fig.10 with comparison of *EIFs* calculated for CTS (based entirely on BEVs), Euro 5 and Euro 6 diesel buses depending on relative receptor density *f* and in two very distinct electricity production scenarios: The Israeli scenario – where more than three quarters of electricity is still generated by combustion of coal; and the French scenario – where about 90% of electricity is generated with nuclear energy, hydraulic and other renewable sources. D_u values for Israel and France (358 and 114 person per km^2, respectively) were calculated using the published data from Israel Ministry of Foreign Affairs [94] and from US Department of State [95].

As can be seen, the EIF_{CTS} value for the fuel mix in Israel is becoming lower than *EIF* values of Euro 5 and Euro 6 diesel buses at relative receptor densities of 1.5 and 6.8, respectively. This means that for the considered case of CTS application it will be environmentally beneficial over the conventional Euro 6 diesel bus, if implemented at sites with the receptor density of 2430 person per km^2 or higher. The results show that for France fuel mix, EIF_{CTS} is always lower than that for the Euro 6 diesel bus in any receptor density. The difference between them becomes larger along with an increase in the relative receptor density.

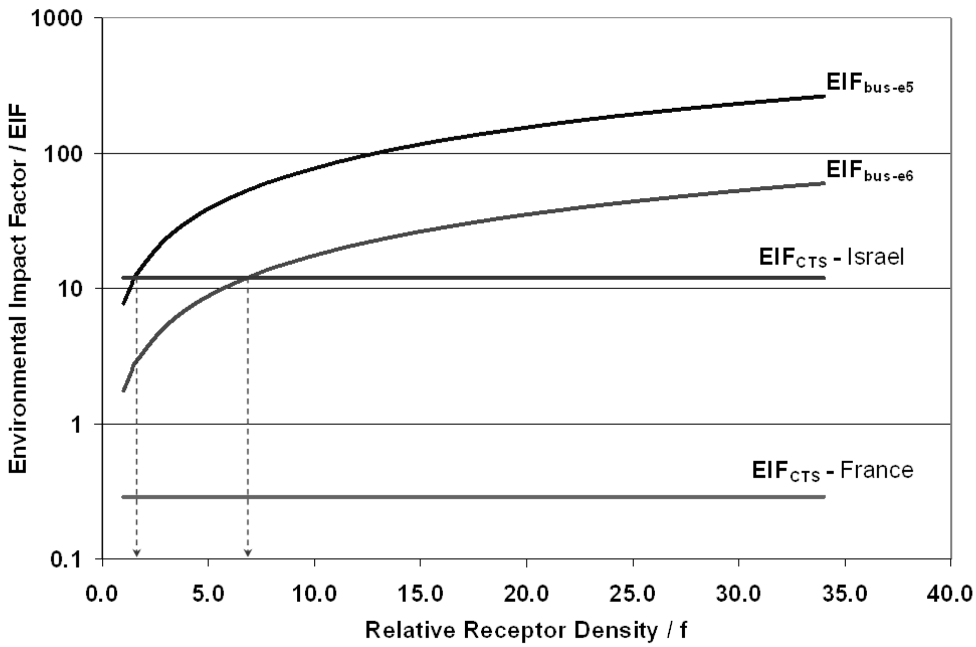

Figure 10. Effect of relative receptor density on environmental impact factor for different transportation modes.

The analysis of powertrain technology development trends makes it hard to believe that attaining the BLUE map scenario with massive penetration to market of FCVs and BEVs (about 45% of total LDV sales – Fig.3) by 2050 may be realized unless breakthrough developments occur. The projection of [96] for US concludes that the desirable 50% reduction of GHG by 2050 may be attained with an aid of wide spreading PHEVs and HEVs. Pure electric and fuel cell vehicles are considered to remain niche products, with market share of about 10-12% also by 2050 – Fig.11.

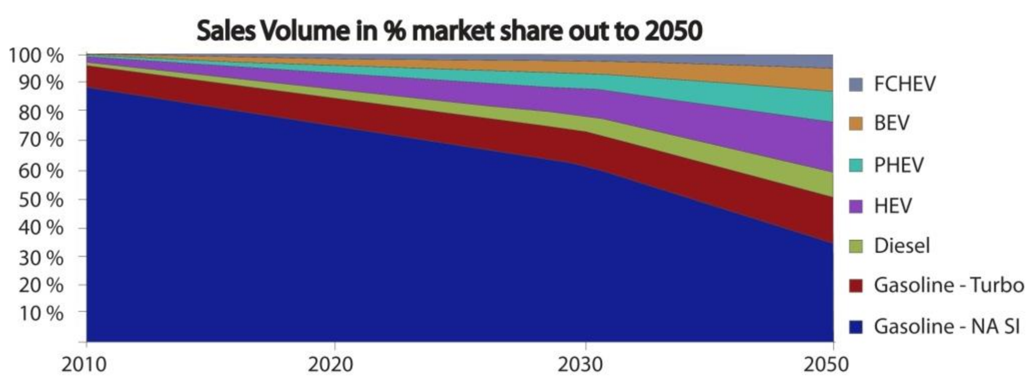

Figure 11. Sales volume in % market share out to 2050 – projection of [96] for US. Reprinted from Transportation Research Part A: Policy and Practice, vol. 46, issue 3, Parisa Bastani, John B. Heywood, Chris Hope, The effect of uncertainty on US transport-related GHG emissions and fuel consumption out to 2050, p.517-548, Copyright (2012), with permission from Elsevier.

CONCLUSION

In order to prevent destructive influence of global heating, GHG emissions must be reduced by 50 - 85% by 2050 as compared with their levels in 2000. This will limit the long-term global heating to 2.0 - 2.4°C and avoid the most destructive impacts of climate change. To meet GHG emission targets, as well as to decrease oil dependency, overall energy consumption of road vehicles should be reduced significantly. The challenge is that vehicle carbon emission reductions must be achieved without disruptions in transportation patterns and population mobility. Attaining the ambitious goal of 50-85 % GHG emission reduction by 2050 will be impossible without a revolution in the energy sources market and the introduction of alternative renewable fuels that will allow further enhancement of benefits in energy efficiency brought by newly developed technologies. A multi-strategy portfolio approach is needed to make deep reductions in road transport GHG emissions.

There is a potential to double the primary (WTW) energy efficiency using electric drivetrains in vehicles, such as BEVs and PHEVs, compared with present ICE vehicles. No significant differences amongst BEVs and PHEVs could be identified from a primary energy efficiency point of view. Hybrid vehicles have a capability to benefit from the latest advancements both in ICE and in electric propulsion technology. This provides a potential to become a widespread measure for reducing energy consumption and GHG emissions. Life cycle emissions for EVs differ considerably between regions depending on the carbon intensity of the power generation mix. An internal combustion engine is far from reaching its maximal potential. As demonstrated above, further development of ICE can lead to significant improvement in its energy efficiency and substantial reduction of pollutant emissions to the "zero-impact" level.

Based on the performed analysis of powertrain technology development trends, it is hard to believe that attaining the BLUE map scenario with massive penetration to market of FCVs and BEVs (about 45% of total LDV sales) by 2050 may be realized unless breakthrough developments occur. It seems that BEVs and FCVs will remain niche products also by 2050, whereas hybrid vehicles will massively penetrate the markets.

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