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Low Emission Optimised tyres and road surfaces
for electric and hybrid vehicles

State-of-the-Art Report

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1 OBJECTIVE

The objective of the State-of-the-Art Report is to perform review of electric and hybrid passenger vehicles and delivery vans recently and currently participating in road traffic in Poland and Norway and to perform analysis of required properties related to vehicle tyres and road surfaces.

2 INTRODUCTION

Road traffic transportation has a major negative impact on the environment in both Poland and Norway as well in other developed countries. Of special concern is the emission of greenhouse gases such as CO_2 and road traffic noise.

In Norway, passenger cars, heavy trucks and motorcycles are responsible for about 20 % of the total CO_2 produced each year (about 10 million tons of CO_2). Passenger cars and delivery vans contribute to about 70 % of the amount of CO_2 from the road transportation. In Poland, the contribution of road transportation to the total emission of carbon dioxide is about 15 %. That means production of almost 45 million tons of CO_2 every year. Passenger cars and vans are responsible for 63 % of that production, heavy trucks and buses - for 34 % of that amount. Remaining 3 % is produced mainly by agricultural tractors (contribution of motorcycles and mopeds is less than 0.5 %).

One of the possibilities to reduce the emission of greenhouse gases caused by road transportation is to increase the contribution of zero and low emission vehicles in total volume of road traffic. There are a number of different concepts of utilizing an electric engine in a vehicle and, depending on this, they can be classified in two main categories: pure electric vehicles (EV, PEV), using one or more electric motors for propulsion, and hybrid electric vehicles (HEV, PHEV) - driven by a different combinations of an electric motor and a conventional internal combustion engine with three subcategories (parallel, series and power-split).

Besides the benefit of reducing the emission of greenhouse gases, zero and low emission vehicles are assumed in general to be very quiet vehicles especially when driving with low speeds. Road traffic is the source of about 80 % of the total noise annoyance in Norway. By increasing the fleet of electric and hybrid electric vehicles there is a great possibility to reduce the noise pollution affecting people especially in a city areas. The Norwegian Government has an ambition to reduce this annoyance by 10 % within 2020.

Unfortunately, those vehicles are still much more expensive than comparable vehicles powered with traditional internal combustion engine. They have also some technical limitations (e.g. smaller driving range, limited number of charging stations). In several counties, including Norway, a wide range of economical and technical incentives have been introduced by the governments to encourage vehicle owners to pay extra money for environmental friendly vehicle.

3 HISTORICAL REVIEW

The invention of the first electric vehicle took place in early 19^{th} century. In the years of 1832-1839, in Scotland, Robert Anderson build the first prototype of electric-powered carriage. In 1834 in the United States Thomas Davenport invented and installed the first direct current electrical motor in a car that was operated on a circular electrified track. It is now difficult to indicate who was the truly first inventor as various people were developing their constructions at that time. All the first electric vehicles were experimental only. The rechargeable lead-acid batteries were invented in 1859 by French physicist Gaston Planté. They were significantly improved (their capacity greatly increased) in 1881 by another French scientist Camille Alphonse Faure. The same year batteries were started to be manufactured on an industrial scale what contributed in development of electric vehicles.

The first production electric car was built by British inventor Thomas Parker in 1884 and by the year of 1890 there were a number of electric car makers around the world. Nearly at the same time, in 1885, the first vehicle powered by internal combustion engine were invented by German inventor Karl Benz. 25 years later, in 1911, the first gasoline-electric hybrid vehicle was released by the Woods Motor Vehicle Company of Chicago but its production was ceased just after two years (vehicle turned out to be too slow for its price and too difficult to service).

The golden age for motor vehicle was in the late 1890s and early 1900s. In 1900 the electricity-powered cars become the top-selling road vehicles in the United States, capturing 28 % of the market. Electric vehicles had a number of advantages in comparison to dirty, noisy and full of shakes and rattles gasoline vehicles. They were much quiet, did not have the vibrations and gasoline smell. They did not require a manual effort to start, as did gasoline vehicles which required a dangerous and leading to many injuries hand crank to start the engine. Also changing gears on gasoline cars was one of the most difficult parts of driving - the electric vehicles did not require shifting gears, were easy of operation and more reliable. Internal combustion vehicles were faster. The limited range of operation was comparable for both types with slight predominance of gasoline one. It was easier to refuel the gasoline vehicle but a real problem occurred when fuel was not readily available. Due to all the properties, the electric vehicles were used mainly as city cars. In London, Paris and New York they served as city taxis.

The First World War (1914 – 1918) was crucial for electric vehicles popularity. New roads between cities were being built what enabled longer distance travelling required vehicles with a greater range than that offered by electric cars. Service stations and fuel pumps were appearing along those roads as well as in the cities. Fuel was significantly cheaper due to worldwide discoveries of large petroleum reserves. Gasoline vehicles became more and more reliable. Invention of electric automobile starter in 1912 (by Charles Kettering) eliminated the inconvenience and danger related to hand crank for starting a gasoline engine. Wide usage of mufflers (invented in 1897 by Hiram Percy Maxim) caused that the noise emitted by internal combustion engines became more bearable. Because of the mass production of Ford Model T at the first modern assembly line that started in 1913, gasoline vehicles were far cheaper than electric ones. Dead years started for electric vehicle development and for their use as a personal transportation. Almost all electric vehicles had disappeared by about 1935. Stagnation lasted until the end of 1960s.

The fuel crises in the early 1970s revived the interest of vehicle manufacturers in electric vehicles. Numerous experimenters and entrepreneurs began work on electric vehicles all over the world. The concept development phase of prototype electric vehicles and propulsion systems lasted until late of 1980s, early 1990s and then a test phase began.

At the beginning of the 1990s in the United States of America, in response to requirements of California's governmental agency for more fuel-efficient, lower-emissions vehicles, with the ultimate goal being a move to zero emission vehicles, vehicle manufacturers present at the American market developed special electric models (like Chrysler TEVan, Ford Ranger EV pickup truck, GM EV1 and S10 EV pickup, Honda EV Plus hatchback, Nissan Altra EV miniwagon and Toyota RAV4 EV) to sell them in California only for "political reasons". Almost all production of those electric cars were withdrawn from the market by their manufacturers a few years later. Large vehicle manufacturers were not interested in introducing electric vehicles to the market at that time. As opposed, small companies had began to design and marketing electric cars for the public.

One of them was a Danish electric vehicle Kewet launched in 1991, then replaced by Buddy in 2008. Those two cars were very popular especially in Norway constituting 20 % of electric cars in this country. Through October 2013 the total number of about 1500 vehicles have been sold.

Also in 1991 the first Norwegian developed electric vehicle Think was launched. Followed with a new version named Think City, started in 2008, it was sold worldwide total in 2500 units until October 2010. The Think City in 2011 was one of only five crash-tested, mass-produced electric cars in the world (together with Tesla Roadster, Mitsubishi i-MiEV, Nissan Leaf and Smart ED). Its production had stopped in March of 2011 due to financial difficulties reaching the volume of 1045 units sold.

In 1997 in Japan the Toyota Prius, the first mass-produced hybrid gasoline-electric vehicle, was launched. It was introduced worldwide in 2000 and 2001. A total number of over 4.2 million units have been sold worldwide in three generations of this car until the end of 2013.

In 2001, after seven years of research and development, an all-electric small micro car the REVAi (known also as the G-Wiz in the United Kingdom) made by India was launched. When London authorities introduced in 2004 the entrance fee for cars entering the city in a daytime (with exemption for electric vehicles) G-Wiz began very popular in London. Additionally charging points were installed in car parks and on streets. The REVA vehicles were sold worldwide in more than 4000 units by March 2011 (production ended in 2012).

The global economic recession in the late 2000s speed up launching of new models of electric and hybrid electric vehicles. Small vehicles, hybrid electric vehicles and pure electric vehicle became more and more desired instead of fuel-inefficient SUVs. Major world vehicle manufacturers started mass production of electric and/or hybrid car models. And the market is expanding very fast - many new vehicle models are coming soon.

4 ECONOMIC AND USER INCENTIVES FOR ELECTRIC VEHICLES

4.1 Incentives in Norway

Almost 100 % of electricity in Norway comes from hydropower plants, what means that the electric energy is “very clean” with almost zero pollution to the environment. That means that all electric devices, including the traction motors in electric vehicles, are the real zeroemission devices not only in the place of their operation (common situation in many other countries) but also in a global scale.

Already in the year of 2000 the Norwegian Government has decided that within 2020, the average level of the CO_2 emission of new passenger cars shall be below 85 g/km. To fulfil those requirements the share of electric and hybrid electric vehicles in total road traffic should increase significantly. The target was set to reach the amount of 50 000 registered electric vehicles until 2018. A number of both economic and user friendly incentives have been introduced in Norway:

- no purchase taxes (extremely high for ordinary cars - about 80-100 % of a car value)
- exemption from 25% VAT on purchase
- low annual vehicle tax (52 EUR compared to 360-420 EUR for conventional vehicles)
- no charges on toll roads
- national ferries free or with reduced rates
- free municipal parking
- free access to bus/taxi lanes
- free charging stations (4587 points by December 31, 2013)

It was decided and approved by all political parties in the Norwegian Parliament that these incentives are in effect until 2018 or until the 50 000 units of EV target is achieved, whatever comes first.

In Norway the non recurring fees regarding cars are based on vehicle weight, engine power and CO_2 emissions level. Plug-in hybrid electric vehicles are not eligible for the same government incentives enacted for electric cars. In principle, PHEVs are also more expensive than equivalent internal combustion cars due to a higher weight (and higher tax values due to the additional weight) related with possessing of battery pack and accompanying electric components. However, the government approved a tax reduction for plug-in hybrids (the existing weight allowance for conventional hybrids and plug-in hybrids of 10 % was increased to 15 % for PHEVs). The PHEVs have been also allowed to use the parking places with charging possibilities originally reserved only for EVs. This incentive took effect from July 1st, 2013. It was assumed that a PHEV will reduce the CO_2 emission with approximately 44-68 % compared to a normal car with combustion engine (it is based on an assumption that the PHEV is running in pure electric mode in a percentage equal to this range).

However, there is already now a concern that there are so many EVs using the bus/taxi lanes coming into Oslo from the western areas (a rich area!) at the moment, that they may delay the buses. There may be a ban to use this lane on this specific road before 2017, which may cause a massive protest from EV drivers using this road. An environmental NGO has proposed that instead of using the bus lane, zero (or low) emission vehicles may have a separate lane reserved for themselves.

4.2 Incentives in Poland

Unfortunately, quite opposite is in the case of Poland. In this country 94.4 % of electricity comes from fossil-fuel power stations (coal, lignite, gas) and only remaining 5.6 % from renewable sources (wind, hydroelectricity). It means, that electric energy in not as clean as in Norway and environmental pollution related to energy production exists. Nevertheless the air pollution in city centers caused by road traffic is at a high level and it would be worth and necessary to move the emission out of agglomerations. This could be done increasing the population of electric vehicles. Some measures have been taken a long time ago, mainly for public transportation. In three cities in Poland, namely Gdynia, Lublin and Tychy, the public transport is based on trolley buses (over 200 those electric vehicles are in operation). In many other Polish cities tramways are a significant part of this system. Also there are first attempts to introduce electric buses instead of regular – the combustion ones. In Cracow (a city in southern Poland dealing with great air pollution and smog), after performed successful tests, the first bus line operated by electric buses only is going to function since August 2014. Few other cities are currently during tests of single electric buses.

Electric cars are not very popular in Poland yet. The Polish government did not introduced any economic nor user friendly incentives to promote zero or low emission vehicles. The prices of electric or hybrid cars are much higher than corresponding models with combustion engine. There aren't any financial bonuses when buying EV or PHEV in Poland. This is most probably related with the global economy as well as with developing economy of Poland (opposite to rich Norwegian economy).

But some user incentives at a local level were proposed by authorities of particular cities:

- Warsaw: lower annual vehicle tax - 33 % reduction
  (heavy trucks and buses only)
- Lublin: lower annual vehicle tax
  (heavy trucks and buses only)
- Gdańsk: free municipal parking places in selected areas
  (EVs and PHEVs)
- Katowice: free parking on municipal parking areas and street parking
  (EVs and PHEVs)
- Szczecin: highly reduced parking yearly rate (2,50 EUR instead of 360,00 EUR)
  on municipal parking areas and street parking
  (EVs and PHEVs with CO_2 emission below 100 g/km)
- Tarnów: highly reduced parking yearly rate (5,00 EUR instead of 340,00 EUR)
  on municipal parking areas and street parking
  (EVs and PHEVs with CO_2 emission below 100 g/km)
- Toruń: free parking on municipal parking areas and street parking
  (EVs and PHEVs)
- Tychy: free parking on municipal parking areas and street parking
  (EVs and PHEVs with CO_2 emission below 100 g/km)

Another disincentive to buy an electric or hybrid electric vehicle is very popular in Poland LPG fuel, half cheaper than petrol. The conversion of a car engine to LPG is also very popular and inexpensive. The infrastructure to refuel a car with LPG is fully satisfied (over 5500 points) even in small places and villages. In comparison there are only 40 public charging stations in Poland (all paid). Majority of them are located in two cities: Warsaw and Wrocław.

5 POWERTRAIN CONCEPTS OF ZERO AND LOW EMISSION VEHICLES

Zero emission vehicle is a motor vehicle which produce no emissions from the on-board source of power. Usually it is a vehicle, called Battery Electric Vehicle (BEV) or Electric Vehicle (EV) or Plug-in Electric Vehicle (PEV), that is equipped in electric motor and run on electricity stored in batteries.

A wide range of battery types utilized in electric vehicles was developed during the last decades: Lead-Acid Battery (Pb-Gel), ZEBRA – "Zero Emission Battery Research Activities" ($Na\text{-}NiCl_2$), Nickel Metal Hydride Battery (NiMH), Lithium-Ion Battery (Li-Ion). There are also some new, very promising battery types still under development like Lithium Silicon Battery or Lithium Air Battery. To improve the performance and durability of batteries of an electric vehicle a Battery Management System (BMS) is always applied and is responsible mainly for supervising charging and discharging of cells, controlling heating and cooling of cells and balancing of cells usage as well as for identification of degree of charging, estimation of available range and documentation of cell history.

In principle, electric vehicles can also be run on electricity produced in Fuel Cells (reaction of hydrogen and oxygen in a cell produces an electric potential of about 1 V and water vapour to the environment) but the production and especially the storage of hydrogen are very complex and this solution is still in development phase. Another concept of zeroemission vehicle based on utilizing a hydrogen combustion engine is also unpopular due to this reason and due to rather low efficiency of such an engine.

Electric motor can be directly integrated into vehicle wheels bringing the power directly from the electric motors to the vehicle wheels. This concept is nowadays mainly used in electric scooters, electric bicycles but it is/was also considered by main vehicle manufacturers like Mitsubishi, Peugeot, Ford, Volvo and tyre manufacturers (Michelin, Continental).

Currently, the most popular powertrain concept of an electric vehicle is when electric motor is connected to the wheel by a reducer gearbox and driveshafts. This concept is used in all mass-produced electric vehicles available on the market (e.g.: Citroen C-zero, Mitsubishi i-MIEV, Peugeot iOn, Nissan Leaf, Fiat e500, Ford Focus EV, BMW i3, Tesla, Renault Kangoo ZE, VW e-up!).

A variant of the previous powertrain concept is when two electric motors are used to power a vehicle, one for each axis, enabling four wheel drive. Mitsubishi Outlander PHEV is an existing example of that solution. This hybrid vehicle can be driving in pure electric mode and, when this condition is fulfilled, it can be treated as zero emission vehicle. When a hybrid car is driving using its internal combustion engine as a generator of electricity for electric motors (series-hybrid drive mode), then it is "only" a low emission vehicle. The low emission vehicle is a motor vehicle that produces relatively low levels of motor vehicle emissions. According to the California Air Resources Board (CARB) the tailpipe emissions of such vehicle must be below a specified level, as determined by regulations and test procedures specified by CARB.

Another variant of the most popular powertrain concept was adopted in hybrid vehicles when the electric motor through reducer gearbox and driveshafts drives one axle of a vehicle and the internal combustion engine with its gearbox and driveshafts drives the other one. When both engines are in operation the vehicle became a four wheel drive. This solution was implemented e.g. in Peugeot 3008 HYbrid4.

Hybrid vehicles are the vehicles combining two or more different power sources in the drivetrain. Only the hybrids equipped with internal combustion engine and electric motor, so called gasoline-electric hybrids, are currently commercially available. When considering the way in which power is supplied to the wheels three main types of hybrid powertrain system can be distinguished:

- **Parallel hybrid system** - the internal combustion engine and the electric motor are both connected to the gearbox and can simultaneously transmit power via driveshafts to the wheels. The internal combustion engine in this system usually can also act as a generator for supplemental recharging of batteries. The batteries can be also recharged during regenerative braking of a vehicle. Vehicles produced by Honda, namely Insight, Civic Hybrid and Accord Hybrid, are the examples of hybrids equipped with the parallel system. Peugeot 3008 HYbrid4 is equipped with a variant of the parallel hybrid system – when a conventional drivetrain with internal combustion engine and traditional gearbox powers one axle and an electric motor or motors driving the other one. Currently commercially available parallel hybrids are very popular but they are unable to provide only electric propulsion (only few of them are able to drive in pure electric mode but only for short distances). They are designed in majority with a full size internal combustion engine and rather small electric motor with small batteries supplementing the main engine especially during urban stop-and-go conditions and during highway driving.

- **Series hybrid system** - only the electric motor(s) is(are) connected to the wheel. The internal combustion engine, petrol or diesel, usually much smaller than in case of parallel hybrids, works as a generator producing electric power for the electric motor(s) or to recharge the batteries. Series hybrids are designed to be run mostly in pure electric mode and because of this usually have a larger battery pack than parallel hybrids. Regenerative braking mechanism to recharge the batteries is also common. Internal combustion engine running at a constant and efficient speed independently of the vehicle speed changes, can extend the limited range when driving only by electric traction. Because of this, series hybrids are also called extended-range electric vehicles (EREV) or range-extended electric vehicles (REEV), but this description is sometimes also used regarding the power-split hybrid vehicles. Chevrolet Volt and Opel Ampera are the representatives of series hybrids.

- **Power-split (series-parallel) hybrid system** - a combination of series and parallel systems when vehicle wheels can be driven either by internal combustion engine or by electric motor. The IC engine can also act as a generator to recharge batteries or to power the electric engine. Power-split hybrids are more efficient overall, because they use series hybrid mode at lower speeds when it tend to be more efficient (electric motor exhibits maximum torque at standstill and is well-suited to complement the engine's torque deficiency at low RPMs) and parallel mode at high speeds when this mode tend to be more efficient (a smaller, less flexible, and highly efficient internal combustion engine can be used when parallel supplemented by electric motor). The most popular example of power-split hybrid are Toyota Prius and Mitsubishi Outlander PHEV.

The powertrain structure is not the only classification criterion of hybrids. Hybrid vehicles are also categorized depending upon the degree of hybridization.

- **Full hybrid** – it is a vehicle which can drive using just the electric motor powered by batteries, just the internal combustion engine, or using combination of both power sources.

- **Mild hybrid** - it is a vehicle which cannot be driven solely on its electric motor, because the rather small electric motor does not have enough power to propel the vehicle on its own.

- **Plug-in Hybrid** - it is a vehicle which utilizes rechargeable batteries, or another energy storage device, that can be charged from external energy source (usually a normal electric wall socket, but also a special charging station with a grid connection).

6 ELECTRIC AND HYBRID ELECTRIC VEHICLES CURRENTLY AVAILABLE ON THE MARKET IN NORWAY AND POLAND

According to the latest available data [1], there were over 380 000 all-electric (EV) and plug-in hybrid electric (PHEV) passenger cars and delivery vans sold and registered worldwide by the end of December 2013. During only one year, since the end of 2012 when 180 000 such vehicles were present on the roads, the increase of 111% was observed. The number of EVs and PHEVs present at the global market at the end of the year of 2011 was only 50 000 vehicles. It is predicted by a Navigant Research [2] that the amount of EVs and PHEVs by the end of 2014 will grow by 86 % reaching the number of more than 700 000 vehicles.

Only six countries, namely the United States, Japan, China, the Netherlands, France and Norway, account for over 353 000 such vehicles, what is 93 % of the total number of worldwide sold and registered EVs and PHEVs by the end of 2013. Norway is placed at 6th position in this ranking, but it is now the largest of all market for EVs related to the total vehicle fleet and population. The development in population of electric and plug-in electric hybrid vehicles since 2008 on the background of all passenger cars and delivery vans in Norway was presented in Table 1.

Table 1. Population vehicles in Norway 2008 - 2013 [3],[4],[5]

Model	2008	2009	2010	2011	2012	2013
Electric vehicles (EV)	2 419	2 748	3 347	5 381	9 565	18 343
Hybrid vehicles (HV)	n/a	n/a	n/a	13 772	19 465	28 579
Plug-in Hybrid vehicles (PHEV)	1	1	4	6	340	696
Total of EVs and PHEVs	2 420	2 749	3 351	5 387	9 905	19 039
Passenger cars and delivery vans	2 576 482	2 631 585	2 705 827	2 787 156	2 867 598	2 934 901
Share of EVs and PHEVs in stock	0,09%	0,10%	0,12%	0,19%	0,35%	0,65%

Detailed number of new registered EVs (by car make) in Norway in the last 3 years was shown in Table 2. One can observe almost doubled year to year volume of new registered EVs in the given last years.

In November 2013, a total of 12079 new passenger cars were sold and registered in Norway [8]. Of these, the number of new EVs were 1434, a market share of 11.9 %. If imported used EVs are included, the number is 1683. This is an increase of over 357 % since November 2012. In the same month 849 new HVs were sold, with a marked share of 8.9 %. The marked share of EVs in December was 11.2 % (1273 new passenger cars, plus 175 new delivery vans, plus 181 imported used passenger cars).

Table 2. Registrations of new electric vehicles in Norway 2011 - 2013 [6],[7],[8]

Model	2011	2012	2013	Total
Nissan Leaf	381 (18,8%)	2298 (58,2%)	4604 (58,4%)	**7283 (52,6%)**
Tesla Model S	0 (0%)	0 (0%)	1983 (25,2%)	**1983 (14,3%)**
Tesla Roadster	34 (1,7%)	32 (0,8%)	3 (0%)	**69 (0,5%)**
Volkswagen e-up!	0 (0%)	0 (0%)	580 (7,4%)	**580 (4,2%)**
Mitsubishi i-MiEV	1050 (51,9%)	665 (16,8%)	367 (4,7%)	**2082 (15,0%)**
Citroen C-Zero	210 (10,4%)	513 (13,0%)	95 (1,2%)	**818 (5,9%)**
Peugeot iOn	217 (10,7%)	407 (10,3%)	88 (1,1%)	**712 (5,1%)**
Ford Focus	0 (0%)	0 (0%)	83 (1,1%)	**83 (0,6%)**
BMW i3	0 (0%)	0 (0%)	51 (0,6%)	**51 (0,4%)**
Volvo C30	0 (0%)	0 (0%)	10 (0,1%)	**10 (0,1%)**
Think City	133 (6,6%)	17 (0,4%)	8 (0,1%)	**158 (1,1%)**
Think Think	0 (0%)	1 (0%)	0 (0%)	**1 (0%)**
Mia VE79	0 (0%)	8 (0,2%)	5 (0,1%)	**13 (0,1%)**
Smart For Two	0 (0%)	0 (0%)	2 (0%)	**2 (0%)**
Mercedes-Benz SLS AMG	0 (0%)	0 (0%)	2 (0%)	**2 (0%)**
Tazzari Zero	0 (0%)	0 (0%)	1 (0%)	**1 (0%)**
Fiat Fiorino	0 (0%)	4 (0,1%)	0 (0%)	**4 (0%)**
Fiat 500	0 (0%)	3 (0,1%)	0 (0%)	**3 (0%)**
Total	2025 (100%)	3948 (100%)	7882 (100%)	**13855 (100%)**

In Poland electric vehicles are still not very common. In September 2011 it was estimated that at about 500 EVs were registered. But among them there were 203 trolley buses. Many of registered EVs were former ICE vehicles then self-modified to electricity powered. Also numerous low-speed, small electric vehicles class L6e and L7e are included in the given total number.

Official records of electric vehicle registrations are dated back only to 2011. According to the records (CEPiK), 102 new vehicles were registered in Poland during the last three years [9]. Detailed information was presented in Table 3.

Table 3. Registrations of new electric vehicles in Poland in years of 2011 - 2013 [9]

Model	2011	2012	2013	Total
BMW i3	0 (0%)	0 (0%)	4 (12,5%)	**4 (3,9%)**
Citroën C-Zero	1 (2,9%)	2 (5,6%)	0 (0%)	**3 (2,9%)**
Fiat Panda EV*	2 (5,9%)	0 (0%)	0 (0%)	**2 (2,0%)**
Ford Mondeo EV*	0 (0%)	5 (13,9%)	0 (0%)	**5 (4,9%)**
Mitsubishi i-MiEV	22 (64,7%)	2 (5,6%)	0 (0%)	**24 (23,5%)**
Nissan Leaf	0 (0%)	1 (2,8%)	15 (46,8%)	**16 (15,7%)**
Peugeot iOn	7 (20,6%)	11 (30,6%)	0 (0%)	**18 (17,6%)**
Peugeot Electric Partner Origin Venturi	0 (0%)	3 (8,3%)	0 (0%)	**3 (2,9%)**
Renault Fluence Z.E.	0 (0%)	6 (16,7%)	0 (0%)	**6 (5,9%)**
Renault Kangoo Z.E.	0 (0%)	6 (16,7%)	6 (18,8%)	**12 (11,8%)**
Renault Zoe	0 (0%)	0 (0%)	2 (6,3%)	**2 (2,0%)**
smart fortwo electric drive	2 (5,9%)	0 (0%)	1 (3,1%)	**3 (2,9%)**
Tesla Model S	0 (0%)	0 (0%)	4 (12,5%)	**4 (3,9%)**
Total	34 (100%)	36 (100%)	32 (100%)	**102 (100%)**

The hybrid vehicles are more popular in Poland than electric ones. About 300 vehicles per year were registered in years 2007 – 2009 (less than 1000 in total) [10]. In 2010 the yearly amount was doubled - 628 vehicles were registered that year. In 2011 the number of registered hybrids increased to 897, then decreased to 752 in 2012 [11].

Due to the globalization, the same models of vehicles are offered by main car manufacturers on the European market independently on a country. Available car models may differ slightly in trim levels and accessories. Bigger differences are between vehicles intended for the U.S., European or Far Eastern markets. The same applies to the EVs and PHEVs sold on the global market. The same models are commercially available both in Norway and Poland as well as in other European countries. Review of EV and PHEV models currently available was presented in Table 4 (passenger cars – class M1), Table 5 (delivery vans – class N1) and Table 6 (quadricycles – class L7e). Current retail prices in Norway and Poland of the basic model in standard trim version (lowest price in NOK, PLN and EUR, rounded to the nearest 100 based on the ECB Euro foreign exchange reference rate dated December 31, 2013) were also shown.

Table 4. EV and PHEV models of passenger cars (class M1) currently available on the European market

	Vehicle:	**Citroën C-Zero**
	Type:	Passenger car, class M1, A-segment mini cars
	Body style:	Hatchback 5-door
	Powertrain:	BEV
	Electric motor:	47 kW (64 KM) 180 Nm
	Max range:	130 km
	Max speed:	130 km/h
	Dimentions (LxBxH):	3475 x 1475 x 1608 mm
	Curb weight:	1120 kg
	Loading capacity:	330 kg
	Tires front:	145/65 R15
	Tires rear:	175/55 R15
	Price in Norway:	159 900 NOK (19 100 EUR)
	Price in Poland:	121 770 PLN (29 300 EUR)
	Vehicle:	**Mitsubishi i-MiEV**
	Type:	Passenger car, class M1, A-segment mini cars
	Body style:	Hatchback 5-door
	Powertrain:	BEV
	Electric motor:	49 kW (67 KM) 180 Nm
	Max range:	150 km
	Max speed:	130 km/h
	Dimentions (LxBxH):	3475 x 1475 x 1610 mm
	Curb weight:	1110 kg
	Loading capacity:	340 kg
	Tires front:	145/65 R15
	Tires rear:	175/55 R15
	Price in Norway:	174 200 NOK (20 800 EUR)
	Price in Poland:	112 914 PLN (27 200 EUR)

Table 4. EV and PHEV models of passenger cars (class M1) currently available on the European market (continuation)

Vehicle:	Peugeot iOn
Type:	Passenger car, class M1, A-segment mini cars
Body style:	Hatchback 5-door
Powertrain:	BEV
Electric motor:	49 kW (67 KM) 180 Nm
Max range:	150 km
Max speed:	130 km/h
Dimentions (LxBxH):	3474 x 1475 x 1608 mm
Curb weight:	1120 kg
Loading capacity:	330 kg
Tires front:	145/65 R15
Tires rear:	175/55 R15
Price in Norway:	177 800 NOK (21 300 EUR)
Price in Poland:	121 770 PLN (29 300 EUR)

Vehicle:	Smart fortwo electric drive
Type:	Passenger car, class M1, A-segment mini cars
Body style:	Hatchback 3-door
Powertrain:	BEV
Electric motor:	55 kW (74 KM) 130 Nm
Max range:	145 km
Max speed:	125 km/h
Dimentions (LxBxH):	2695 x 1559 x 1565 mm
Curb weight:	900 kg
Loading capacity:	250 kg
Tires front:	155/60 R15
Tires rear:	175/55 R15
Price in Norway:	160 000 NOK (19 100 EUR)
Price in Poland:	79 900 PLN (19 200 EUR)

Vehicle:	Volkswagen e-up!
Type:	Passenger car, class M1, A-segment mini cars
Body style:	Hatchback 5-door
Powertrain:	BEV
Electric motor:	60 kW (82 KM) 210 Nm
Max range:	160 km
Max speed:	130 km/h
Dimentions (LxBxH):	3540 x 1645 x 1498 mm
Curb weight:	1139 kg
Loading capacity:	361 kg
Tires front:	165/65 R15
Tires rear:	165/65 R15
Price in Norway:	194 120 NOK (23 200 EUR)
Price in Poland:	n/a

Vehicle:	BMW i3
Type:	Passenger car, class M1, B-segment small cars
Body style:	Hatchback 5-door
Powertrain:	BEV
Electric motor:	125 kW (170 KM) 250 Nm
Max range:	190 km
Max speed:	150 km/h
Dimentions (LxBxH):	3999 x 1775 x 1578 mm
Curb weight:	1195 kg
Loading capacity:	425 kg
Tires front:	155/70 R19
Tires rear:	155/70 R19
Price in Norway:	249 900 NOK (29 900 EUR)
Price in Poland:	140 900 PLN (33 900 EUR)

Table 4. EV and PHEV models of passenger cars (class M1) currently available on the European market (continuation)

Vehicle:	Nissan Leaf
Type:	Passenger car, class M1, C-segment medium cars
Body style:	Hatchback 5-door
Powertrain:	BEV
Electric motor:	80 kW (109 KM) 254 Nm
Max range:	199 km
Max speed:	144 km/h
Dimentions (LxBxH):	4445 x 1770 x 1550 mm
Curb weight:	1474 - 1548 kg (depending on trim level)
Loading capacity:	395 kg
Tires front:	205/55 R16
Tires rear:	205/55 R16
Price in Norway:	228 600 NOK (27 300 EUR)
Price in Poland:	126 080 PLN (30 300 EUR)

Vehicle:	Ford Focus Electric
Type:	Passenger car, class M1, C-segment medium cars
Body style:	Hatchback 5-door
Powertrain:	BEV
Electric motor:	107 kW (143 KM) 250 Nm
Max range:	162 km
Max speed:	137 km/h
Dimentions (LxBxH):	4359 x 2060 x 1466 mm
Curb weight:	1651 kg
Loading capacity:	385 kg
Tires front:	215/50 R17
Tires rear:	215/50 R17
Price in Norway:	268 000 NOK (32 000 EUR)
Price in Poland:	n/a

Vehicle:	Renault Fluence Z.E.
Type:	Passenger car, class M1, C-segment medium cars
Body style:	Sedan 4-door
Powertrain:	BEV
Electric motor:	70 kW (90 KM) 226 Nm
Max range:	185 km
Max speed:	135 km/h
Dimentions (LxBxH):	4748 x 1809 x 1458 mm
Curb weight:	1605 kg
Loading capacity:	418 kg
Tires front:	205/55 R16
Tires rear:	205/55 R16
Price in Norway:	n/a
Price in Poland:	111 100 PLN (26 700 EUR)

Vehicle:	Tesla Model S
Type:	Passenger car, class M1, F-segment luxury cars
Body style:	Liftback 5-door
Powertrain:	BEV
Electric motor:	225-310 kW (302-416 KM) 430-600 Nm
Max range:	375 - 500 km (depending on model)
Max speed:	193 - 210 km/h (depending on model)
Dimentions (LxBxH):	4978 x 1963 x 1435 mm
Curb weight:	2108 kg
Loading capacity:	490 kg
Tires front:	245/45R19 98W
Tires rear:	245/45R19 98W
Price in Norway:	463 800 NOK (55 500 EUR)
Price in Poland:	200 000 PLN (48 100 EUR)

Table 4. EV and PHEV models of passenger cars (class M1) currently available on the European market (continuation)

Vehicle:	Opel Ampera PHEV
Type:	Passenger car, class M1, C-segment medium cars
Body style:	Hatchback 5-door
Powertrain:	PHEV
Electric motor:	111 kW (150 KM) 370 Nm
Combustion engine:	63 kW (86 KM) 126 Nm (electricity generator only)
Total HSD power:	111 kW (150 KM) 370 Nm
Max range:	80 km (only electric mode), 500 km (both modes)
Max speed:	161 km/h (independent on mode)
Dimentions (LxBxH):	4498 x 1787 x 1439 mm
Curb weight:	1732 kg
Loading capacity:	268 kg
Tires front:	215/55 R17
Tires rear:	215/55 R17
Price in Norway:	359 900 NOK (43 000 EUR)
Price in Poland:	158 950 PLN (38 300 EUR)

Vehicle:	Toyota Prius PHEV
Type:	Passenger car, class M1, D-segment large cars
Body style:	Hatchback 5-door
Powertrain:	PHEV
Electric motor:	60 kW (80 KM) 207 Nm
Combustion engine:	73 kW (99 KM) 142 Nm
Total HSD power:	100 kW (136 KM)
Max range:	25 km (only electric mode)
Max speed:	85 km/h (electric mode), 180 km/h (combustion mode)
Dimentions (LxBxH):	4460 x 1745 x 1490 mm
Curb weight:	1425-1450 kg (depending on trim version)
Loading capacity:	390-415 kg (depending on trim version)
Tires front:	195/66 R15
Tires rear:	195/66 R15
Price in Norway:	334 200 NOK (40 000 EUR)
Price in Poland:	144 900 PLN (34 900 EUR)

Vehicle:	Volvo V60 PHEV
Type:	Passenger car, class M1, D-segment large cars
Body style:	Station wagon 5-door
Powertrain:	PHEV
Electric motor:	60 kW (68 KM) 200 Nm
Combustion engine:	158 kW (215 KM) 440 Nm
Total HSD power:	208 kW (283 KM) 640 Nm
Max range:	50 km (only electric mode), 900 km (both modes)
Max speed:	125 km/h (electric mode), 230 km/h (combustion or combined mode)
Dimentions (LxBxH):	4635 x 1865 x 1484 mm
Curb weight:	1955 kg
Loading capacity:	550 kg
Tires front:	235/45 R17
Tires rear:	235/45 R17
Price in Norway:	606 800 NOK (72 600 EUR)
Price in Poland:	n/a

Vehicle:	Mitsubishi Outlander PHEV
Type:	Passenger car, class M1, J-segment sport utility cars
Body style:	Crossover SUV 5-door
Powertrain:	PHEV
Electric motor:	front: 60 kW (82 KM) 137 Nm, rear: 60 kW (82 KM) 195 Nm
Electric generator:	70 kW (95 KM)
Combustion engine:	89 kW (121 KM) 190 Nm
Total HSD power:	149 kW (203 KM) 385 Nm
Max range:	52 km (only electric mode), 880 km (both modes)
Max speed:	120 km/h (electric mode), 170 km/h (combustion or both modes)
Dimentions (LxBxH):	4655 x 1800 x 1680 mm
Curb weight:	1810 kg
Loading capacity:	500 kg
Tires front:	225/55 R18
Tires rear:	225/55 R18
Price in Norway:	439 900 NOK (52 600 EUR)
Price in Poland:	176 990 PLN (42 600 EUR)

Table 5. EV and PHEV models of delivery vans (class N1) currently available on the European market

Vehicle:	Mia Electric
Type:	Passenger (M1) or delivery van (N1), A-segment mini cars
Body style:	1, 2, 3 or 4-seated, 3-door
Powertrain:	BEV
Electric motor:	18 kW (24 KM) 58 Nm
Max range:	125 km
Max speed:	100 km/h
Dimentions (LxBxH):	2870-3190 x 1640 x 1550 mm (depending on model)
Curb weight:	764-850 kg (depending on model)
Loading capacity:	365 kg
Tires front:	155/65 R14
Tires rear:	155/65 R14
Price in Norway:	159 400 NOK (19 100 EUR)
Price in Poland:	n/a

Vehicle:	Peugeot Partner Electric
Type:	Passenger (M1) or delivery van (N1), M-segment multi purpose cars
Body style:	Van 3-door or 4-door
Powertrain:	BEV
Electric motor:	49 kW (67 KM) 200 Nm
Max range:	170 km
Max speed:	110 km/h
Dimentions (LxBxH):	4380/4628 x 2212 x 1784/1812 mm (short/long version)
Curb weight:	1530-1589 kg (short version) 1569-1628 kg (long version)
Loading capacity:	695-636 kg (short version) 552-611 kg (long version)
Tires front:	195/70 R15 C 98T
Tires rear:	195/70 R15 C 98T
Price in Norway:	244 000 NOK (29 200 EUR)
Price in Poland:	n/a

Vehicle:	Renault Kangoo Z.E.
Type:	Passenger (M1) or delivery van (N1), M-segment multi purpose cars
Body style:	Van 2-door or 3-door
Powertrain:	BEV
Electric motor:	44 kW (60 KM) 226 Nm
Max range:	175 km
Max speed:	130 km/h
Dimentions (LxBxH):	4666/4282 x 1829 x 1826/1844 mm (depending on model)
Curb weight:	1553-1426 kg (depending on model and trim version)
Loading capacity:	max 650 kg (depending on trim version)
Tires front:	195/65 R15
Tires rear:	195/65 R15
Price in Norway:	246 900 NOK (29 500 EUR)
Price in Poland:	104 060 PLN (25 000 EUR)

Table 6. EV and PHEV models of quadricycles (class L7e) currently available on the European market

	Vehicle:	Buddy Electric
	Type:	Quadricycle, class L7e, A-segment mini cars
	Body style:	Three-seated, 2-door
	Powertrain:	BEV
	Electric motor:	13 kW (18 KM) n/a Nm
	Max range:	120 km
	Max speed:	80 km/h
	Dimentions (LxBxH):	2430 x 1490 x 1510 mm
	Curb weight:	650 kg
	Loading capacity:	200 kg
	Tires front:	135(145)/80 R13
	Tires rear:	135(145)/80 R13
	Price in Norway:	169 900 NOK (20 300 EUR)
	Price in Poland:	n/a
	Vehicle:	**Renault Twizy**
	Type:	Quadricycle, class L7e, A-segment mini cars
	Body style:	Two-seated, 2-door
	Powertrain:	BEV
	Electric motor:	13 kW (17 KM) 57 Nm
	Max range:	100 km
	Max speed:	80 km/h
	Dimentions (LxBxH):	2338 x 1381 x 1454 mm
	Curb weight:	487 kg
	Loading capacity:	203 kg
	Tires front:	125/80 R13 65M
	Tires rear:	145/80 R13 75M
	Price in Norway:	91 690 NOK (11 000 EUR)
	Price in Poland:	33 900 PLN (8 200 EUR)
	Vehicle:	**Romet 4E**
	Type:	Quadricycle, class L7e, A-segment mini cars
	Body style:	Hatchback 5-door
	Powertrain:	BEV
	Electric motor:	5 kW (7 KM) n/a Nm
	Max range:	180 km
	Max speed:	65 km/h
	Dimentions (LxBxH):	3090 x 1420 x 1480 mm
	Curb weight:	824 kg
	Loading capacity:	n/a
	Tires front:	145/70 R12
	Tires rear:	145/70 R12
	Price in Norway:	n/a
	Price in Poland:	32 000 PLN (7 700 EUR)

Despite of the electric and plug-in hybrid electric vehicles listed in the tables above a numerous models of other hybrid vehicles (usually parallel hybrids) are currently available on European market. At least one model, in few cases several, are already offered by major vehicle manufacturers like Audi, BMW, Citroen, Ford, Honda, Infiniti, Lexus, Mercedes, Mitsubishi, Nissan, Peugeot, Porsche, Toyota, Volkswagen, Volvo. Other manufacturers are hard working on them and launch of theirs hybrid models is expected in 2014 or the following year.

Those hybrids were designed in a way which does not allow them for electric propulsion only with some exceptions. A few of them are able to drive in pure electric mode but only for short distances (up to 50 km with low speed but usually no more than 5-10 km). Those hybrid cars are equipped in majority with a full size internal combustion engine and with additional, rather small electric motor (or two motors one per axle) and small battery pack supplementing the main engine especially during urban stop-and-go conditions and during highway driving decreasing the fuel consumption and CO_2 emission.

Among electric vehicles available on the market, mini cars from the segment A dominate with Citroen C-zero, Peugeot iOn, Mitsubishi i-MiEV, Volkswagen e-up! and Smart fortwo. The three popular quadricycles (class L7e) are from the same segment. But the most popular EV in Norway, in the meaning of number of registered cars, is a medium car Nissan Leaf from segment C. This electric car is also popular in Poland. To the same C-segment belong also Ford Focus, Renault Fluence and Opel Ampera (PHEV). There is only one representative of segment B - small cars - BMW i3. Segment D - large cars is represented by two PHEVs, namely Toyota Prius and Volvo V60. Very popular in Norway and much less popular in Poland Tesla Model S belongs to segment F - luxury cars. Peugeot Partner and Renault Kangoo, representing segment M - multi purpose cars, and mini car Mia Electric can be homologated as a passenger cars or a delivery vans depending on customer requirements (transportation of people or goods).

7 ENERGY CONSUMPTION AND CO_2 EMISSION OF ELECTRIC AND HYBRID VEHICLES

The vehicle energy consumption and CO_2 emission depend, on one hand, on the type of powertrain and its efficiency and, on the other hand, on the values of resistive forces acting on a moving car. The resistive forces depend on the weight of vehicle (rolling resistance force, inertia force and grade force), its frontal area and drag coefficient (drag force), tyres and inflation pressure (rolling resistance force), moving speed (drag force), acceleration (inertia force) and some other parameters not related to the car but also very important (road surface characteristics and slope, air density, temperature, rainfall, snow). Resistive forces play a very important role in case of electric and hybrid electric vehicles. Rolling resistance, related mainly to vehicle tyres and road surface, is responsible for the majority of resistive forces of a car moving with constant low speed. For the driving speed of 30 km/h, 10 % decrease of rolling resistance coefficient may reduce the energy consumption up to 8 % (and may increase driving range of vehicle by the same value). For higher speeds, of about 70-90 km/h, the reduction may be up to 3-4 % [12].

According to the “Global electric vehicle survey” [13] performed by the Deloitte Touche Tohmatsu Limited Global Manufacturing Industry group in 2011 the typical driving distance per weekday is less than 80 km in vast majority of cases (80 % of responders) and less than 40 km in case of 56 % of responders. According to the “Accenture end-consumer survey on the electrification of private transport” [14] done by Accenture Research in 2011, for 90 % from over 7000 responders from 13 countries the daily driving distance is less than 100 km, for 80 % - less than 80 km, for 73 % - less than 60 km, for 51 % - less than 40 km and 28% of responders drives less than 20 km per weekday. The average daily driving distance for all responders is 52 km. According to the Renault press release [15] in Europe 87 % of daily routes is shorter than 60 km.

Concluding the information above, the electric and hybrid electric vehicles should be, and they really are, intended mainly for urban and suburban driving. Thus the operating range (driving distance) at one charge of batteries of current electric and hybrid vehicles, longer for all vehicle categories than 100 km, should be fully satisfactory even taking into account that the real distance, dependent on many external factors like outside temperature, rainfall, snow, driving behavior (speed, acceleration), slope of a road, is usually much shorter than maximal range given in vehicle specifications. Having this in mind, a hard work should continue leading to minimization and optimization of the energy consumption and resistive forces of those vehicles.

Selected car related parameters influencing energy consumption, depending on vehicle class, were presented in Table 7. The parameters presented in this table were averaged for each vehicle segment on the basis of the gathered specifications of 24 electric and plug-in electric hybrid vehicle models currently available in Norway and Poland. In case of PHEVs only the data of electric propulsion were considered.

Table 7. Vehicle related parameters influencing energy consumption and CO_2 emission of electric and hybrid electric vehicles currently available on the European market

Segment (class)	Number of averaged models			Electric motor:		Electric mode		Dimentions			Frontal area	Weights			Tires width
				Power	Torque	Max range	Max speed	Length	Breadth	Height		Curb	Load	Total	
	EV	PHEV		[kW]	[Nm]	[km]	[km/h]	[mm]	[mm]	[mm]	[m2]	[kg]	[kg]	[kg]	[mm]
A (L7e)			min	5	57	100	65	2338	1381	1454	2,01	487	200	687	125
			max	13	57	180	80	3090	1490	1510	2,25	824	203	1027	145
A (L7e)	**3**	**-**	**aver**	**10,3**	**57,0**	**133,3**	**75,0**	**2619,3**	**1430,3**	**1481,3**	**2,12**	**653,7**	**201,5**	**855,2**	
A (M1)			min	18	58	125	100	2695	1475	1498	2,21	764	250	1014	145
			max	60	210	160	130	3540	1645	1610	2,65	1139	365	1504	175
A (M1)	**7**	**-**	**aver**	**42,3**	**142,3**	**140,7**	**120,7**	**3245,6**	**1558,4**	**1569,9**	**2,45**	**1000,4**	**334,4**	**1334,9**	
B (M1)			min	125	250	190	150	3999	1775	1578	2,80	1195	425	1620	155
			max	125	250	190	150	3999	1775	1578	2,80	1195	425	1620	155
B (M1)	**1**	**-**	**aver**	**125,0**	**250,0**	**190,0**	**150,0**	**3999,0**	**1775,0**	**1578,0**	**2,80**	**1195,0**	**425,0**	**1620,0**	
C (M1)			min	70	226	80	135	4359	1770	1439	2,55	1474	268	1742	205
			max	111	370	199	161	4748	2060	1550	3,19	1732	418	2150	215
C (M1)	**3**	**1**	**aver**	**92,0**	**275,0**	**156,5**	**144,3**	**4512,5**	**1856,5**	**1478,3**	**2,74**	**1602,0**	**372,2**	**1974,2**	
D (M1)			min	60	200	25	85	4460	1745	1484	2,59	1425	390	1815	195
			max	60	207	50	125	4635	1865	1490	2,78	1955	550	2505	235
D (M1)	**-**	**2**	**aver**	**60,0**	**203,5**	**37,5**	**105,0**	**4547,5**	**1805,0**	**1487,0**	**2,68**	**1610,0**	**451,7**	**2061,7**	
M (M1, N1)			min	44	200	170	110	4282	1829	1784	3,26	1426	611	2037	195
			max	49	226	175	130	4666	2212	1844	4,08	1628	695	2323	195
M (M1, N1)	**4**	**-**	**aver**	**46,5**	**213,0**	**172,5**	**120,0**	**4489,0**	**2020,5**	**1816,5**	**3,67**	**1534,3**	**651,5**	**2185,8**	
F (M1)			min	225	430	375	193	4978	1963	1435	2,82	2108	490	2598	245
			max	310	600	500	210	4978	1963	1435	2,82	2108	490	2598	245
F (M1)	**2**	**-**	**aver**	**267,5**	**515,0**	**437,5**	**201,5**	**4978,0**	**1963,0**	**1435,0**	**2,82**	**2108,0**	**490,0**	**2598,0**	
J (M1)			min	60	195	52	120	4655	1800	1680	3,02	1810	500	2310	225
			max	60	195	52	120	4655	1800	1680	3,02	1810	500	2310	225
J (M1)	**-**	**1**	**aver**	**60,0**	**195,0**	**52,0**	**120,0**	**4655,0**	**1800,0**	**1680,0**	**3,02**	**1810,0**	**500,0**	**2310,0**	

Simulations of energy consumption and CO_2 emission can be performed for selected classes of electricity powered vehicles according to the data collected in Table 7 as well as for particular vehicles listed in previous tables. The necessary data regarding tyres used on particular cars are given in the next paragraph. Also a theoretical vehicle models, based on the calculated averaged values of parameters, can be used in those simulations.

8 TYRES USED ON ELECTRIC AND HYBRID VEHICLES

Tyres are characterised by a number of parameters which are interrelated. Improving of one parameter, e.g. rolling resistance, may lead to worsening of other parameters like wet grip or external rolling noise or both. Improving wet grip may have an adverse impact on external rolling noise and vice versa. Tyre manufacturers still have potential to optimise all the parameters. Many of them is closely collaborating with electric and hybrid vehicle manufacturers.

As it was mentioned before, regarding the vehicle and aside from all other parameters not related directly to its construction, the tyres used on a car, have the major influence on energy consumption and CO_2 emission as well as on external noise emission of a moving car. Tyres, mainly because of their rolling resistance, account for 20 % to 30 % of the fuel consumption of vehicles [16]. A reduction of rolling resistance of tyres may therefore contribute significantly to the energy efficiency of zero and low emission vehicles and respectively to the reduction of CO_2 emissions. Thus the proper selection of energy saving (and quiet at the same time) vehicle tyres is extremely important.

Tyre relating parameters influencing rolling resistance and the relation of impact are as follow [12]:

- increase of tyre outside diameter has a positive influence
- increase of tyre width has unknown influence (still to be tested)
- decrease of aspect ratio has unknown influence (still to be tested)
- increase of tyre rubber hardness has a positive influence
- increase of rubber hysteresis has a negative influence
- increase of tread pattern grooving has a positive influence
- increase of belt stiffness has a positive influence
- decrease of tread depth (wear of tyre) has a positive influence

On 1st November 2012, the European Union Regulation (EC) No. 1222/2009 on labelling of tyres came into effect. The aims of labelling are to provide clear and relevant information about the quality of the tyre regarding to its three parameters: fuel efficiency, wet grip and external rolling noise. Labels provide this information through pictograms. Tyres available on market are ranked on a scale from the green class A (best) to the red class G (bad) in case of fuel efficiency and wet grip. In case of external rolling noise tyres are ranked on a three class scale related to future limit values according to the Regulation (EC) No 661/2009. The first class, marked with 3 black bars, means that the tyre external rolling noise is above the future European mandatory limit value (noisier tyre), the second class, marked with 2 black bars – is between the future limit value and 3 dB below (average tyre) and the third class, marked with 1 black bar – is more than 3 dB below the limit (low noise tyre). Additionally to the pictogram the noise value in decibels, measured and calculated in accordance with UNECE Regulation No 117, is given on the label. Sample tyre label was presented in Figure 1.

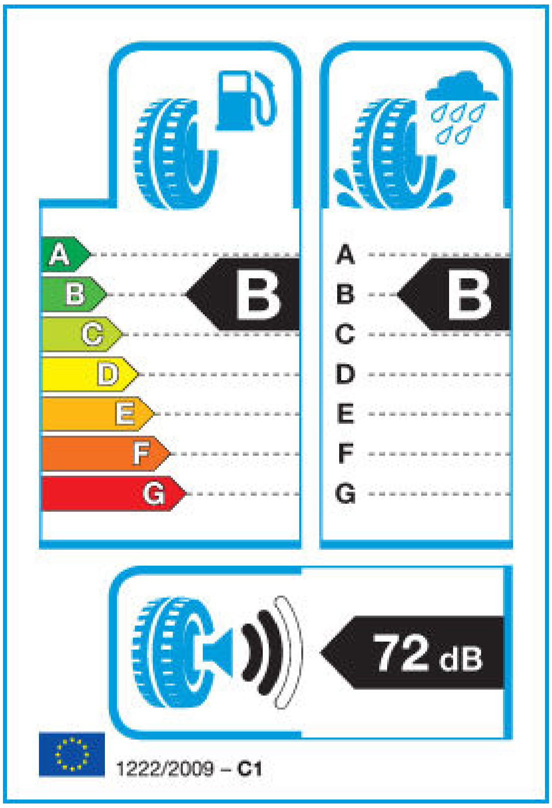

Figure 1. The sample European Union Energy label for tyres

Currently all the major tyre manufacturers have or are about to introduce tyres specially developed for electric and hybrid vehicles. They focus on developing tyres with low rolling resistance in order to reduce the overall energy consumption for zero and low emission vehicles and as such reduce the CO_2 production. Since many models of these vehicles are mainly developed and designed for urban traffic, and thus for speed ranges below 80-100 km/h, there is a great potential for making these tyres also more silent. Normal passenger cars tyres often have to meet maximum speeds of more than 200 km/h, and this sets serious limitations on the design of tyres and their noise characteristics, as the tyres need more weight, increased rubber hardness, low profile ratios, etc.

Recently launched electric and hybrid electric vehicles have been usually equipped with tyres especially designed for them in close cooperation between car and tyre manufacturers. The examples are BMW i3 equipped with Bridgestone Ecopia tyres, Renault Fluence Z.E. with Goodyear EfficientGrip tyres, Renault Twizzy with Continental Conti.eContact or coming soon Renault ZOE with Michelin E-V tyres. Also the Continental developed a ContiSportContact 5 special tyres in the size of 245/35 R21 XL 96W for Tesla Model S full electric car. But this rule is not always applicable. Currently is some cases, and previously in most of the cases tyres were selected just from the ones available on those days at the market. Also now and in the future electric and hybrid car users will be selecting tyres form the market when original tyres are worn and a change is necessary. Thus, when analyzing current market of vehicle tyres, not only the tyres especially designed for the EVs and HVs were in focus of interest but also other tyres with good performance in fuel efficiency (class A). The review of those tyres currently available on the European market or announced to be launched in 2014 was presented in Table 8.

Table 8. Tyres specially developed for electric and hybrid electric vehicles and tyres class-A labeled in case of fuel efficiency currently available on the European market

Bridgestone – Ecopia EP001S

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season				Noise level
195	65	15	91	H	Summer	A	A	)	69 dB
205	55	16	91	V	Summer	A	A	)	70 dB

Bridgestone – Ecopia EP500

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season				Noise level
155	60	20	80	Q	Summer	C	B	)	69 dB
155	70	19	84	Q	Summer	C	B	)	69 dB
175	55	20	85	Q	Summer	B	B	)	69 dB
175	60	19	86	Q	Summer	B	B	)	69 dB

Bridgestone – Blizzak LM-500

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season				Noise level
155	70	19	84	Q	Winter	C	B	)	69 dB

Dunlop – Sport BlueResponse AA

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season				Noise level
205	55	16	94 XL	V	Summer	A	A	)	70 dB
215	55	16	97 XL	V	Summer	A	A	)	70 dB
225	55	16	99 XL	V	Summer	A	A	)	70 dB
225	55	17	101 XL	V	Summer	A	A	)	70 dB

Table 8. Tyres specially developed for electric and hybrid electric vehicles and tyres class-A labeled in case of fuel efficiency currently available on the European market (contd.)

Continental – Conti.eContact

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	Fuel efficiency	Wet grip	Road noise	Noise level
125	80	13	65	M	Summer	E	E	))	70 dB
145	80	13	75	M	Summer	E	B	))	70 dB
165	65	15	81	T	Summer	A	n/a	n/a	n/a
185	60	15	84	T	Summer	A	n/a	n/a	n/a
205	55	16	91	T	Summer	A	n/a	n/a	n/a
195	55	20	91	T	Summer	A	B	))	72 dB

Continental – Conti.eContact Winter

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	Fuel efficiency	Wet grip	Road noise	Noise level
195	55	20	91	T	Winter	A	B	))	72 dB

Goodyear – EfficientGrip

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	Fuel efficiency	Wet grip	Road noise	Noise level
205	55	16	91	V	Summer	A	C	)	67 dB

Goodyear – EfficientGrip AA Edition

Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	Fuel efficiency	Wet grip	Road noise	Noise level
205	55	16	94 XL	V	Summer	A	A	)	69 dB
205	55	16	94 XL	W	Summer	A	A	)	69 dB
215	55	16	97 XL	V	Summer	A	A	)	69 dB
225	55	16	99 XL	V	Summer	A	A	)	69 dB
225	55	17	101 XL	V	Summer	A	A	))	71 dB
225	55	17	101 XL	W	Summer	A	A	))	70 dB

Table 8. Tyres specially developed for electric and hybrid electric vehicles and tyres class-A labeled in case of fuel efficiency currently available on the European market (contd.)

Michelin	Energy E-V	Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	FUEL EFFICIENCY	WET GRIP	ROAD NOISE	Noise level
		185	65	15	88	Q	Summer	A	A	))	70 dB
		195	55	16	91 XL	Q	Summer	A	A	))	70 dB

Nokian	eLine	Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	FUEL EFFICIENCY	WET GRIP	ROAD NOISE	Noise level
		185	65	15	92 XL	T	Summer	A	A	))	71 dB
		195	65	15	95 XL	T	Summer	A	A	))	72 dB
		195	65	15	95 XL	H	Summer	A	A	))	72 dB
		185	60	15	88 XL	T	Summer	A	A	))	71 dB
		205	55	16	94 XL	T	Summer	A	A	))	72 dB
		205	55	16	94 XL	H	Summer	A	A	))	72 dB

Pirelli	Cinturaro P7 Blue	Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	FUEL EFFICIENCY	WET GRIP	ROAD NOISE	Noise level
		215	55	16	97 XL	W	Summer	A	A	))	72 dB
		225	55	16	99 XL	W	Summer	A	A	))	72 dB
		235	45	17	97 XL	W	Summer	A	A	))	72 dB

Yokohama	BLUEARTH-1	Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	FUEL EFFICIENCY	WET GRIP	ROAD NOISE	Noise level
		185	65	15	88	H	Summer	A	C	))	69 dB
		195	65	15	91	H	Summer	A	C	))	69 dB
		205	55	16	91	V	Summer	A	C	))	70 dB
		215	60	16	95	H	Summer	A	C	))	70 dB
		215	45	17	91 XL	W	Summer	A	C	))	70 dB

Table 8. Tyres specially developed for electric and hybrid electric vehicles and tyres class-A labeled in case of fuel efficiency currently available on the European market (contd.)

Toyo	NanoEnergy 1	Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	Fuel efficiency	Wet grip	Road noise	Noise level
		195	65	15	91	H	Summer	A	B	)	68 dB
Toyo	**NanoEnergy 2**	Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Season	Fuel efficiency	Wet grip	Road noise	Noise level
		175	65	14	82	H	Summer	A	C	))	70 dB
		175	65	15	84	H	Summer	A	C	))	70 dB
		185	65	15	88	H	Summer	A	C	))	70 dB
		185	60	15	88 XL	H	Summer	A	C	))	70 dB
		185	55	15	82	V	Summer	A	C	))	70 dB
		195	65	15	91	V	Summer	A	C	))	70 dB
		195	65	15	91	H	Summer	A	C	))	70 dB
		195	60	15	88	H	Summer	A	C	))	70 dB
		205	65	15	94	H	Summer	A	C	))	70 dB
		195	60	16	89	H	Summer	A	C	))	70 dB
		195	55	16	87	V	Summer	A	C	))	70 dB
		195	50	16	88 XL	V	Summer	A	C	))	70 dB
		205	65	16	95	H	Summer	A	C	))	70 dB
		205	60	16	92	H	Summer	A	C	))	70 dB
		205	60	16	96 XL	V	Summer	A	C	))	70 dB
		205	55	16	91	V	Summer	A	C	))	70 dB
		215	60	16	95	H	Summer	A	C	))	70 dB
		215	55	17	98 XL	V	Summer	A	C	))	70 dB
		215	50	17	95 XL	V	Summer	A	C	))	70 dB
		215	45	17	91 XL	W	Summer	A	C	))	70 dB
		225	55	17	101 XL	V	Summer	A	C	))	70 dB
		225	50	17	98 XL	V	Summer	A	C	))	70 dB
		225	45	17	94 XL	W	Summer	A	C	))	72 dB
		215	45	18	93 XL	W	Summer	A	C	))	70 dB
		215	40	18	89	W	Summer	A	C	))	70 dB
		225	45	18	95	W	Summer	A	C	))	70 dB
		225	40	18	92 XL	W	Summer	A	C	))	70 dB

As it can be observed when analyzing data collected in Table 8, not only the tyres with highest fuel efficiency label (class A) are mounted by cars manufacturers on new sold electric and hybrid electric vehicles. Those findings have been confirmed by visual inspection of such cars performed recently for the purpose of this project at car dealers in Trondheim, Norway. The inspection results were presented in Table 9. During inspection it was impossible to find out what specific tyre units were fitted on a car if a few varieties of efficiency classes for the same tyre brand, model, size, load index and speed rating exist and the tyre EU label is inaccessible. Thus, all the varieties were presented in the table.

Table 9. Tyres fitted on selected electric and hybrid and plug-in hybrid electric vehicles in Trondheim, Norway in 2013

Car model	Type	Tyres	Section width	Aspect ratio	Rim diameter	Load index	Speed rating	Tyre position	FUEL EFFICIENCY	WET GRIP	ROAD NOISE	Noise level
Nissan Leaf	EV	Bridgestone Ecopia EP150	205	55	16	91	V	All	B	B	))	69 dB
									B	C	))	69 dB
									C	C	))	71 dB
									C	C	)))	72 dB
Nissan Leaf	EV	Michelin Energy Saver	205	55	16	91	V	All	B	B	))	70 dB
									C	A	))	70 dB
									E	B	))	70 dB
Nissan Leaf	EV	Dunlop ENASAVE EC300	215	50	17	91	V	All	B	C	))	70 dB
Mitsubishi i-MIEV	EV	Dunlop ENASAVE 2030	145	65	15	72	S	Front	C	E	))	69 dB
Mitsubishi i MIEV	EV	Dunlop ENASAVE 2030	175	55	15	77	V	Rear	C	E	))	69 dB
Tesla Model S	EV	Michelin Pilot Sport	245	35	21	95 XL	Y	All	E	A	))	70 dB
BMW i3	EV	Bridgestone Ecopia EP500	155	70	19	84	Q	Front	C	B	))	69 dB
BMW i3	EV	Bridgestone Ecopia EP500	175	60	19	86	Q	Rear	B	B	))	69 dB
Toyota Auris Hybrid	HV	Dunlop SP FastResponse	225	45	17	91	W	All	E	B	))	69 dB
									E	B	))	70 dB
Toyota Prius 7+	HV	Bridgestone Turanza ER33	205	60	16	92	V	All	C	C	))	69 dB
Toyota Prius 7+	HV	Yokohama Advan dB V551	205	60	16	92	V	All	C	B	))	71 dB
Toyota Prius	HV	Michelin Primacy HP	215	45	17	87	W	All	E	A	))	70 dB
Lexus CT200h	HV	ContiSportContact3	215	45	17	87	V	All	F	B	)))	72 dB
Opel Ampera	PHEV	Michelin Energy Saver	215	55	17	94	H	All	B	B	))	71 dB

The performed inspection can be concluded that electric (with exception of BMW i3) and hybrid vehicles are not equipped with special designed for EVs or with the most energy efficient tyres, and that they do not have any special tyres at all, but use normal summer tyres that can also be found on cars with internal combustion engines only. Thus there is still a large potential to reduce the energy consumption and CO_2 emission of electric and hybrid electric vehicles when fitting them with fuel efficient tyres. There is also a technological potential to develop tyres with lower energy consumption than currently available on the market.

Similar conclusions can be drawn with regard to the noise emission of electric and hybrid electric vehicles. Analysing the noise properties of all tyres presented in tables above it can be concluded that the majority of them are "average" from the noise point of view. Only six tyres of those wide selection were labelled with "1 bar" (low noise tyre) in the external noise ranking. Among them only one tyre has been labelled with 67 dB and one with 68 dB. Remaining tyres were characterized with higher noise emission levels. Few of them were classified with "3 bars" what means high noise tyres. All the tyres presented above were selected from currently market available according to the low fuel efficiency criterion. This means that it is still a great potential to develop tyres with both low fuel efficiency and low noise emission. But first tyres with both low noise rating and satisfactory fuel efficiency (e.g. class B if class A is unavailable) should be selected for electric and hybrid electric vehicles. There are a selection of such tyres available on the market.

9 NOISE EMITTED BY ELECTRIC AND HYBRID VEHICLES

Noise is emitted by each moving vehicle independently if it has an internal combustion engine propulsion or if it is powered by an electric motor. Regardless of a type of vehicle three main categories of noise sources of can be defined [17]. The first category, called the powertrain noise or power unit noise, is related to the combustion engine or electric motor together with its accessories, vehicle transmission, and intake and exhaust system in case of ICE and hybrid vehicles driven not in pure electric mode. The second category is the tyre/road noise, that is related to the rolling of the vehicle tyres on the road surface and is dependant both on vehicle tyres as well as on road surface. Third category, namely the aerodynamic noise, is related to the turbulent airflow around the vehicle and also partly through the vehicle. Aerodynamic noise generally has a minor influence on the total noise emitted by a vehicle in all traffic conditions except driving with a very high speeds (usually over 130 km/h) and for vehicles with very poor aerodynamic design. Depending on road traffic conditions, mainly the vehicle speed, acceleration, cruising with constant speed, coast-down or braking, tyres used on vehicle and road surface the vehicle is driving on, powertrain noise or tyre/road noise can dominate over the other. In case of modern internal combustion vehicles, in a typical road traffic conditions, when a vehicle moves with a constant speed within the range from about 30-40 km/h up to about 130 km/h, the tyre/road noise dominates, and it also may dominate when an IC vehicle is coasting with a speed below that specified range. Of course some exceptions from those general dependence may occur.

The powertrain noise source of electric and hybrid electric vehicles in pure electric mode is very quiet, although some high-frequency noise from the electric systems may be audible. As it was already proved above, the electric and hybrid vehicles are in majority fitted with normal tyres, that are also used on conventional vehicles. Thus, in this case the trans-over speed, when tyre/road noise starts to dominate, is much lower.

9.1 Literature survey

An extensive literature survey have been performed to find out what is the difference in noise emission between electric or hybrid electric vehicle and conventional vehicle with internal combustion engine. There are a numerous researches performed in this field all over the world. They differ in the main purpose they had been performed, in used methodology, in selected distances between tested vehicles and microphone, in selected vehicles, in tyres fitted on them, in road surfaces, the test vehicles were driving on. In numerous cases there wasn't any information about the road surface type, on which the measurements were carried out, nor about tyres, which were fitted on a test vehicles. In some cases also information about vehicles selected and used in tests was very poor. The findings of the particular researches are as follow.

The results of experiment performed in 2001 by researchers of the former French National Institute for Transport and Safety Research INRETS [18] show that at very low speeds (below 30 km/h) the noise emission difference between combustion and hybrid or electric vehicle can be up to about 15 dB (when 1st gear is engaged) and about 5 dB (for 2nd gear), but at the speeds above 50 km/h the difference is negligible. As expected, no difference between electric and hybrid car when driving in pure electric mode was observed.

Researches performed in Austria in 2009 [19] were based on measurements of the total vehicle noise of 20 different electric and combustion cars with both petrol and diesel engines. They were concluded that the decrease of noise levels of electric vehicles was about 4 dB at 30 km/h and 3 dB at 50 km/h. No measurements were performed for the speeds above 50 km/h.

Japanese researchers performed measurements of noise emission of a small electric vehicle and a much larger hybrid vehicle [20] and compared the results to the noise values of a conventional average car are taken from the Japanese traffic noise prediction model. They found out that the electric and hybrid cars were about 3 dB quieter for constant speed driving independently on the speed, and from 20 dB (for 10 km/h) down to 15 dB (20 km/h), 10 dB (30 km/h) and finally to about 3 dB for the speed of 50 km/h and above, when accelerating. The 3 dB difference for constant speed might be due to quieter tyres on the electrified vehicles than on the average cars.

Also in Japan in the same year of 2009 noise measurements of hybrid car driven in electric mode, and of two combustion cars for comparison, were conducted by Japanese Automobile Standards Internationalization Center JASIC [21] (also reported in [22]) with the speed range from 0 to 30 km/h. The purpose of those tests was to estimate whether electric and hybrid electric vehicles may cause a safety risk to pedestrians (especial visually impaired people) due to their low noise level. Obtained results showed that the hybrid vehicle electrically powered was quieter only at speeds below 20 km/h (about 10 dB at 5 km/h, 6 dB at 10 km/h and 3-4 dB at 15 km/h). For the speeds from 20 to 30 km/h differences in noise emission were below 3 dB and they may be caused by differences in fitted tyres (not specified) on tested vehicles. For stationary conditions, when combustion cars were idling, the difference was the highest and it was about 20 dB.

The JASIC study was continued and in 2011 comparative measurements of noise emission of two electric, one hybrid and two conventional cars were performed [23]. Two test speeds were selected: 10 km/h and 20 km/h. It was found out that the difference in measured noise levels of electrically powered (two EVs and one HV) and two combustion cars was from 6 to 9 dB at the speed of 10 km/h. At 20 km/h only one electric car was about 5 dB quieter than conventional cars, for other cars there were no apparent difference (less than 2 dB).

Researchers from the University of Perugia, Italy, in 2009 performed tests of post quadricycles in the purpose of improvements in noise mitigation of postal delivery service [24]. They compared noise emission of hybrid, electric and conventional versions of those vehicles at the speed of 35 km/h. The construction of hybrid quadricycle disables its driving in pure electric mode. Results revealed that the most quiet, as expected, was the electric vehicle. The hybrid quadricycle was 4 dB louder and the most noisy conventional quadricycle was about 14 dB louder than electric and 10 dB louder than the hybrid one.

Belgian Road Research Centre BRRC tested in 2010 a hybrid electric vehicle together with five other combustion cars with diesel and petrol engines at the speeds around 20 km/h [25]. Different driving conditions were used: constant speed at 20 km/h on the 2nd gear, and with engine idling for conventional cars, additionally electric and combustion mode for hybrid vehicle. One of the findings was that there was almost no difference for the hybrid car between its two operating modes at that speed, even though its tyres seemed to be exceptionally quiet. Therefore, it was concluded that in both the electric and the combustion mode, at 20 km/h, the hybrid electric vehicle emits mainly tyre/road noise. Other finding was that for two cars, one medium-sized and one large, the coasting condition, which should have given only tyre/road noise, was only about 1 dB quieter than the constant speed condition on the 2nd gear. Thus the conclusion was that for the two combustion cars, engine noise at constant speed is far below tyre/road noise at 20 km/h (1 dB of difference for the two cars corresponds to 6 dB of difference between tyre/road noise and engine noise for remaining three cars) and would be almost inaudible.

Measurements comparing the noise emission of hybrid vehicles with noise emission of the same vehicle models but equipped in internal combustion engine were performed in 2010 by the National Highway Traffic Safety Administration in the USA [26]. Tests were conducted for three pairs of so-called “twins” with the speeds form 6 to 40 mph (from about 10 to 65 km/h). Additional tests were performed for reversing at 5 mph (8 km/h), acceleration from 0 to 20 mph (32 km/h), and deceleration from 20 mph (32 km/h) down to 10 mph (16 km/h). The results showed that differences in emitted noise when cruising are negligible for two “twins” for the speed of 10 mph and above, and for the remaining one from 20 mph. The sound levels for hybrids cruising at a constant speed of 6 mph were 1 to 9 dB lower than for their combustion “twins”. In case of reversing at 5 mph hybrid vehicles were 7 to 10 dB quieter than the combustion ones. When accelerating, in case of two “twins” there were almost no difference in measured noise levels, the remaining hybrid surprisingly was 2 dB louder than its “twin”. This vehicle was also 2 dB louder when decelerating while other hybrids were 1 to 2 dB quieter than their “twins”.

Another vehicle noise comparable measurements were conducted by Institute for Public Health and the Environment RIVM in 2010 and reported in [27]. Two mini cars of A-segment, but not the same models, were selected, one electric and one conventional car with diesel engine and tests were performed for three speeds: 10, 30 and 50 km/h. The findings were that the electric car was quieter by, respectively for test speeds, about 10, 6 and 3 dB than the conventional combustion car. According to the researchers, the reduction effect may be overestimated due to differences in sizes of selected vehicles. Although both were from the same segment, the electric car was much lighter than rather heavy diesel car.

The Dutch consulting company M+P Engineers in 2011 performed some measurements of the noise from electric vehicles and combustion vehicles for comparison [28]. It appeared that there is almost no difference for the speeds above 40 km/h. For lower speeds differences up to 7 dB were observed.

In 2011 a research study was conducted to find out the differences in noise emission of the same mini car (A-segment) in two versions: conventional with internal combustion engine and converted to electricity with electric motor on board [29]. Measurements were performed when driving within the speed range from 10 to 80 km/h and also for cost-down (engine switched-off) in the same speed range. The results showed unexpectedly, that the electrified version is not quieter than the conventional at any speed, and at high speeds it is even noisier (up to 4 dB). Tyre/road noise dominates in the whole speed range in cases of both vehicles.

Within the CityHush “Acoustically Green Road Vehicles and CityAreas” - the EU project aiming in reducing transport noise, especially in urban areas, comparative noise measurements of five small and one medium-size electric cars were performed [30]. Obtained results were compared with noise data of different combustion vehicles. Concluding, a difference of 7.5 dB at the constant speed of 50 km/h and 5 dB at full acceleration from this speed was found in noise emission between electric and combustion cars.

In 2012 American researchers from the Resource Systems Group Inc. and from the Noise Pollution Clearinghouse reported the results from performed noise emission tests of a mid-size passenger hybrid electric car [31]. Measurements were conducted for the speed range from 5 mph (8 km/h) up to 70 mph (113 km/h). The vehicle was both cruising with constant speed and fully accelerated. The obtained results were compared to the calculated noise values of a standard combustion car according to the American road noise prediction method. The research can be concluded that there is a difference at a constant speeds below 15 mph (24 km/h). As expected, the maximum is for the lowest measured speed of 5 mph and it is about 10 dB. In the range starting from 15 mph there is no noticeable difference until 50 mph. Then, unexpectedly, the hybrid electric vehicle is up to 2 dB louder than the standard car in the higher speed range. When fully accelerating, the max. difference of about 7 dB is for the lowest test speed of 5 mph, then it decreases and from 20 mph almost no difference was noted.

Researchers from the University Duisburg-Essen (Germany) in 2011 had tested three electric vehicles and four comparable conventional cars when driving with a constant speed of 30 km/h [32]. Among the tested vehicles, three of them were triplets (the same car model with electric, petrol and diesel engine) and following two may be called twins (electric and petrol). It was found that the electric cars were quietest of all, diesel car was the loudest. The differences in noise emission between “triplets” were respectively 3.5 dB (electric vs. petrol) and 4.5 dB (electric vs. diesel). Difference between “twins” was 2 dB. The noise level differences within electric cars were less than 1 dB, while the combustion cars noise levels differed up to 3.5 dB, including the diesel car, and up to 2.5 dB excluding it.

The literature survey can be concluded, that it has been proven by the vast majority of performed experiments by independent researchers all over the world, with consistent results, that only at speeds below approximately 30 km/h for cars, there is a significant difference in noise emission from combustion vehicles and electric and hybrid electric vehicles driven in pure electric mode. It has been demonstrated that the difference in noise emission is between 10 dB and 20 dB. The only exception to this rule is when a vehicle is reversing, e.g. backing out from a parking lot. In this case the electrically driven vehicles are louder than combustion cars.

The other finding from the literature survey is that at more commonly used speeds in urban conditions, within the range of 30 to 50 km/h as well as above, the tyre/road noise is dominating, so electric and hybrid electric vehicles emit similar noise like vehicles with internal combustion engines. It would therefore be a great benefit if the tyres and road surfaces can be optimized to reduce the noise as well as reduced CO_2 under urban conditions.

9.2 Tyre related parameters influencing noise emission

Vehicle tyre can be characterized by many parameters such as its width and other dimensions, inner structure, rubber hardness and other material properties, tread pattern and tread air/rubber ratio (grooving), condition (wear and ageing). All of them influence or may influence the tyre noise emission.

The list of parameters and the relation of impact was presented below according to [17] and [34]:

- decrease of tyre width has a positive influence
- increase of tyre outside diameter has a positive influence
- decrease of aspect ratio has unknown influence (still to be tested)
- increase of belt stiffness has a positive influence
- increase of tyre rubber hardness has a negative influence
- increase of tread pattern grooving has a negative influence
- decrease of tread depth (wear of tyre) has a negative influence

Each of the mentioned parameters can influence the tyre/road noise by a few decibels. Of course, tuning the parameters to decrease tyre noise emission may worsen other tyre properties like rolling resistance or friction. Thus the optimisation of the parameters is necessary to obtain satisfactory both noise emission level and energy efficiency as well as other tyre properties. Of course further development of tyres is still necessary and there is still technological potential for tyre improvement.

9.3 Future wheel concepts

In order to decrease the vehicle noise emission in the future, both of electric and combustion propelled vehicles, a substantial reduction of the tyre/road noise (more than 10 dB) is necessary. It is therefore crucial to develop functional noise reducing measures for tyre/road noise, such as the composite wheel, Michelin Tweel or DualQ tyre concept proposed within QCity and continued in CityHush projects.

The composite wheel was designed by the Swedish inventor Hans-Erik Hansson already in the late 1980s [33] (referred also in [17]). Several generation of that wheel with numerous modifications and improvements as well as many trials were performed since that time. The composite wheel version of the year of 2001 was presented in Figure 2.

Figure 2. The composite wheel in 2001 and its inventor – Hans-Erik Hansson (upper photo) and the version of 2006 (lower photos)

The wheel consists of a circular belt made of glass fiber or carbon fiber reinforced plastic, supported by a rim with carbon fiber spokes. Thanks to the non-pneumatic wheel concept and the material selection, the belt could be designed with ventilation holes that reduce both the sound radiation from the vibrations, as well as the amplification by the horn effect. Those holes are additionally advantageous for removing water from the contact patch and hence, reducing the risk of aquaplaning. Another great advantage, from an acoustical point of view, is the open design, with no sidewalls which effectively reduces the noise radiation. The wheel during tests was up to 10 dB quieter than comparable pneumatic tyre [17]. Also the rolling resistance coefficient of this wheel was significantly about 40% lower.

The same idea was used for a non-pneumatic tyre invented and patented by Michelin [35]. It consists of a rubber tread attached to the hub by flexible spokes (Figure 3). Rolling resistance of this wheel is lower than for pneumatic tyre. The latest prototype of this wheel is rather noisy, especially at high speeds, due to vibration of spokes. But this concept have a potential to reduce emitted noise.

Figure 3. The Michelin Tweel concept [35]

Different wheel concept was developed within the QCity EU Project [36] and has been tested within the CityHush EU Project [37]. The DualQ tyre consists of two narrow tyres with small crown radius mounted on the same rim with a spatial separation between them (Figure 4). This spatial separation is preventing the two tyres to interact acoustically, which ensure that the horn amplification is not re-established. Four prototype tyres were developed and manufactured.

Figure 4. The DualQ tyre concept (dimentions in mm) [36] and prototype mounted on a car [37]

Performed measurements showed noise reduction of about 6 to 8 dB in relation to standard tyre when measured on CPX test trailer and about 4 to 6 dB reduction when tested on passenger car [37]. It can be estimated that the overall noise reduction for the combination DualQ tyres/low noise road surface is likely to be at least 10 dB relative to the combination standard car tyres/standard road surface.

Concluding, it is still a technological potential to design tyres which would be quieter than currently available. The existing European Union Regulation No 661/2009 sets out the minimum requirements of external noise emission of tyres. Technological development makes it possible to significantly reduce external rolling noise beyond those minimum requirements.

10 PAVEMENT INFLUENCE ON ROLLING RESISTANCE AND NOISE EMISSION

Road surface is characterized by many parameters and properties such as skid resistance (both in dry and in wet condition), tyre wear, surface wear, durability, visual guidance, drainage, splash and spray generation, emission of particulates, rolling resistance and noise generation. It follows that the parameters of particular interest in this report, i.e. rolling resistance and noise characteristics, are just two of many parameters which should be taken into account when selecting and constructing a pavement. One should remember that different pavements change their characteristics with time and wear in different ways. It means that a pavement which is very good in new condition might be not so good or even poor after a few years of operation.

Road surface, on which a vehicle is moving, significantly influences both the vehicle fuel consumption and its noise emission. This is due to the substantial effect of road surface characteristic on rolling resistance and noise emission of vehicle tyres interacting with the surface.

10.1 Influence on rolling resistance

Extensive research on the pavement influence on tyre rolling resistance were performed within the MIRIAM Project [38]. The project aim was the possible reducing the energy consumption due to the tyre/road interaction by selection of pavements with lower rolling resistance, and hence lowering CO_2 emissions and increasing energy efficiency of vehicles using the surface. Findings of performed research related to road surface were presented in the project deliverable [39]. It can be concluded, based on the recently conducted measurements (during the last few years), that the range in rolling resistance between the best and the worst pavements tested in the several European countries is 50 %, what means that the worst pavement (very rough) is characterized by the rolling resistance coefficient 50 % higher than the best one (smooth). Although the common pavements exposed to high road traffic show a spread of 20 to 25 % in rolling resistance. Pavement macrotexture, represented by the parameter MPD, is the major factor influencing rolling resistance.

Part of the measurements reported in the MIRIAM deliverable, mentioned above, were performed at the Kloosterzande test track in the Netherlands, where 40 test sections in new condition were located [40]. The values of rolling resistance coefficients for tested pavements were presented in Figure 5.

In April of 2013 a measurement campaign was conducted by the Technical University of Gdańsk, Poland and M+P Consulting Engineers, the Netherlands to investigate the variation in rolling resistance of different road surface types on the Dutch primary (highways) and secondary (provincial) roads [41]. The rolling resistance and texture of 69 road sections varying both in surface type and age (maintenance condition) were measured. The values of rolling resistance coefficients were presented in Figure 6.

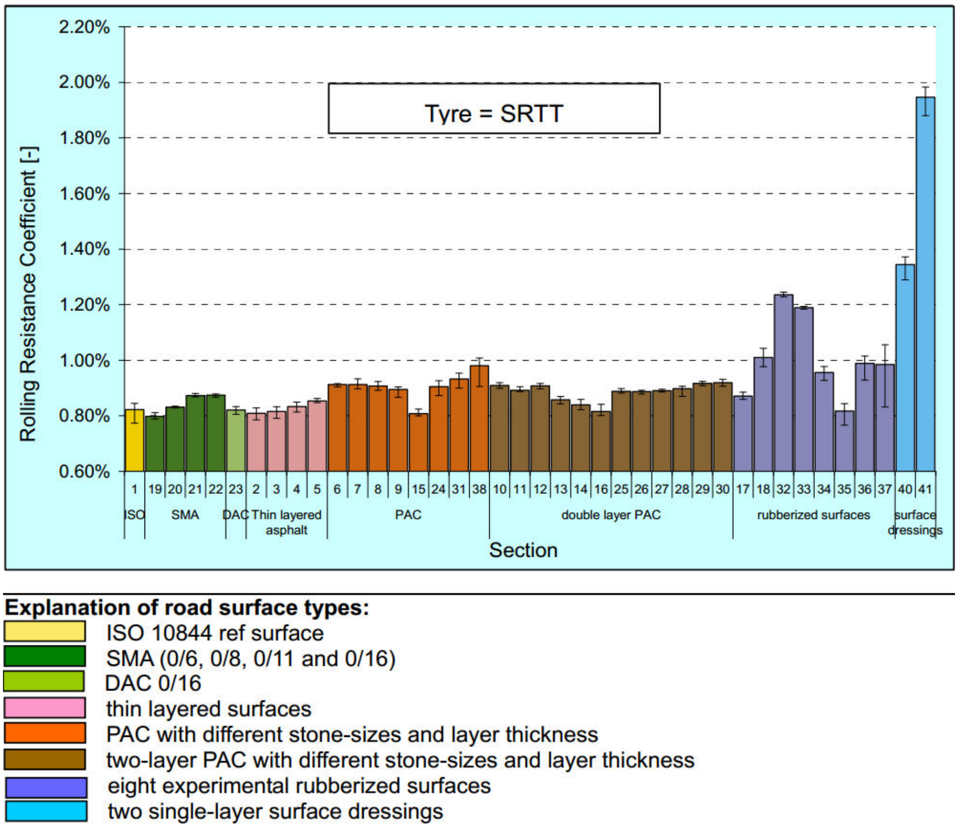

Figure 5. Results of measurements of the rolling resistance coefficient on 40 test sections at Kloosterzande test track in the Netherlands [40]

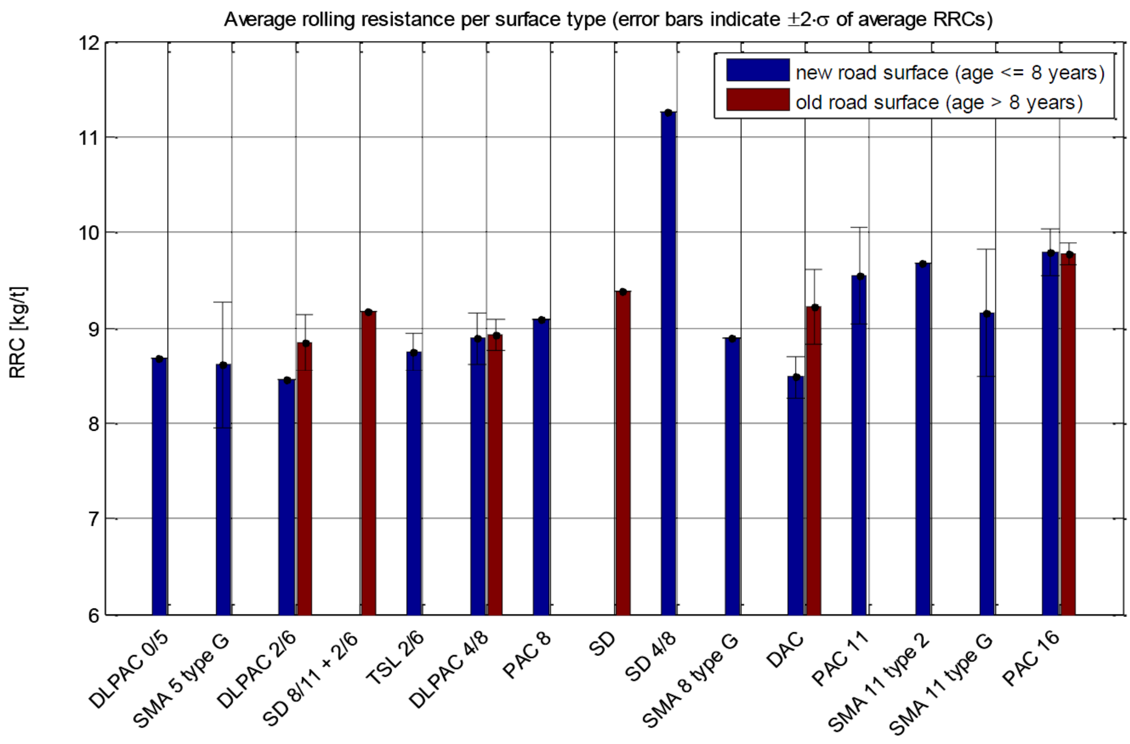

Figure 6. Results of rolling resistance measurements obtained during M+P and TUG joined measurement campaign in the Netherlands in 2013 [41]

The values of rolling resistance coefficient obtained during the 2013 measurement campaign correspond to the measurements results reported in MIRIAM project. The spread of RRC values is similar and again the surface dressing was the worst and protruding pavement.

Concluding, the proper selection of low rolling resistance pavement may lead to significant reduction of energy consumption and hence to decreasing of CO_2 emission of vehicles using the road. But all road surface parameters, also functional, should be taking into account when selecting pavement type for particular road e.g. to avoid porous pavements in city streets where traffic speeds are very low as extensive clogging of the pavement may be present in such case.

10.2 Influence on noise emission

Road surface has also a substantial influence on the noise emission of moving vehicles. It was already proved, that tyre/road noise dominate in majority of traffic conditions. In case of electric and hybrid electric vehicles this influence is even greater due to the lower speed at which significantly quieter electric propulsion becomes negligible and tyre/road noise prevails. Noise reduction features of road surface become very important. The acoustic properties of low-noise pavements have been or are being investigated in European projects like SILVIA, SILENCE or PERSUADE, among others.

In recent years such pavements have become more and more popular and accepted as an effective means of road traffic noise abatement, which has some key advantages over other options like noise barriers. Low-noise pavements reduce tyre/road noise at the source and significant and beneficial noise reduction up to 10 dB(A) can be achieved, just due to the proper pavement characteristics. Many countries have been part of the development of low-noise pavements such as double layer porous asphalt, noise reducing optimized thin layers and rubberized asphalt, among others. The pavement which has been proven to have the highest noise reducing potential is a poroelastic road surface. This surface, beside its porosity, has a relatively high proportion of rubber granulate from scrap tyres. Currently, there is a large European project running, PERSUADE, to develop and evaluate such surfaces [42].

It is not the aim of this project to develop a new low-noise pavement nor to improve a pavement in some way to obtain higher noise emission reduction of interacting vehicle tyres. This project aims only to demonstrate the state-of-the-art technology for tyres developed for zero or low emission vehicles, which are optimized for low rolling resistance and may have a potential for reduction of tyre/road noise. Since the vehicle energy consumption and noise emission levels are very much related to a pavement, the investigation of selection of an optimized low-noise pavement is also included in the project.

There is a wide literature selection dealing with noise aspects of pavements e.g. [17], [43], [44]. According to recent, most comprehensive study covering all aspects relevant to the project [44], the following types of pavements can be specified in respect to tyre/road noise emission criterion. The most common pavement in most of European countries including Norway and Poland, namely the SMA 0/11 (or DAC 0/11) was the reference - neutral pavement in this specification and a given below in some cases potential noise reduction refer to this pavement. Listed pavements are ranked from the most noisy to the most quiet one.

- Paving setts (extremely higher noise than reference)
- Transversely tined cement concrete TTCC (much higher noise than reference)
- Brushed cement concrete BRCC (much higher noise than reference)
- Hot rolled asphalt HRA (much higher noise than reference)
- Surface dressing with large chippings (much higher noise than reference)
- Very smooth dense surfaces (higher noise than reference)
- SMA and DAC with large chippings, above 13 mm (higher noise than reference)

- SMA and DAC with medium chippings (reference pavement)
- Diamond grinding (potential noise reduction: 1-2 dB)
- Exposed aggregate cement concrete EACC (potential noise reduction: 1-2 dB)
- Small-aggregate surface dressings (potential noise reduction: 1-5 dB)
- Thin layers (potential noise reduction: 3-7 dB) Thin surfacings are most useful on low- or medium-speed roads and streets. Noise reduction properties gradually reduced with time.
- Asphalt rubber friction course ARFC (potential noise reduction: 2-5 dB) The noise reduction effect seems to deteriorate somewhat with time.
- Single-layer porous surfaces (potential noise reduction: 1-7 dB) The problem is the reduced efficiency due to clogging. The pores are "self-cleaned" in the wheel tracks for high-speed traffic in wet conditions. Noise reduction propertied diminishing by about 1 dB per year; but faster on low-speed roads.
- Double-layer porous surfaces (potential noise reduction: 4-8 dB)
- Poroelastic surface (potential noise reduction: 7-12 dB)

Classification of pavement types regarding to their noise properties was proposed in [45]. According to this classification, pavements are categorized into five groups (see Table 10).

Table 10. The proposed classification of pavements regarding to their noise properties

Pavement category	Noise level CPXI (80 km/h) [dB(A)]	Sample pavements
Low noise	< 93.5	Single layer PAC with chippings size ≤ 10 mm
		Double layer PAC
		Poroelastic pavement
Reduced noise	93.5 ÷ 96.4	SMA and AC with chipping size ≤ 10 mm
		BBTM with chipping size ≤ 10 mm
		Single layer PAC with chippings size > 10 mm
Normal noise	96.5 ÷ 99.5	SMA with chipping size > 10 mm
		BBTM with chipping size 10 - 16 mm
		AC with chippings size 10 - 16 mm
		CC with optimal texture
Increased noise	99.6 ÷ 102.5	SD
		SMA with enhanced friction
		AC with chippings size > 16 mm
		CC
		Concrete blocks with optimal pattern
High noise	> 102.5	CC transversely brushed
		Concrete blocks without optimalization
		Paving stones

Concluding, differences in tyre/road noise levels between various types of pavement may reach 16 dB, but usually do not exceed 5-8 dB when the extremely noisy pavements are excluded. Anyway, it is a great potential for decreasing noise emission of passing vehicles when selecting proper pavement for a road. In case of electric and hybrid electric vehicles a very noisy pavement can mean that the tyre/road noise is more dominant at lower speeds than it would be on a low-noise pavement and there can therefore be a difference in how great a noise reduction can be obtained. The same is also true for the tyres on the vehicles.

11 CONCLUSIONS

Electric and hybrid electric vehicles become more and more popular in many European countries, especially in Norway, where the increase in electric vehicle fleet in the last few years is really incredible - almost doubled year to year volume of new registered electric cars. In Poland electric vehicles are still not very common. Significantly more popular are hybrid electric cars but still they constitute only a small percentage of the total volume of vehicle fleet. It is expected that the use of zero and low emission vehicles in European countries will consist a significant part of the vehicle fleet in 10-20 years time.

Electric and hybrid electric vehicles are characterized by a number of advantages in comparison to vehicles equipped with an internal combustion engine. One of them is recuperation, in which part of consumed energy is recovered when braking and batteries are charged in this process. Electric powertrain is much more effective in comparison with conventional one (93-99 % vs. 25-35 %). Whereas combustion engines are only able to deliver torque when idle speed is reached, electric motors deliver torque from the very beginning. Hence clutch and gearbox are not necessary for them what save also maintenance costs. Electric vehicles are powered by electricity delivered by power plants located out of city centers, thus the vehicle's environmental pollutions connected with energy production, if any when it comes from renewable energy sources, are moved out of agglomerations. Another advantage is that electric vehicles are also less noisy at low speeds dominating in typical urban driving conditions.

On the other hand the main "disadvantage" of electric and hybrid vehicles is that they are still much more expensive than comparable conventional combustion vehicles. Other minor disadvantages are smaller driving range or limited number of charging stations. Due to this, electric and hybrid electric vehicles are intended mainly for urban and suburban driving. Besides, to compensate their disadvantages, in several counties, including Norway, a wide range of economical and technical incentives have been introduced by the governments.

Currently all the major tyre manufacturers have or are about to introduce tyres specially developed for electric and hybrid vehicles. They focus on developing tyres with low rolling resistance in order to reduce the overall energy consumption for zero- and low- emission vehicles and as such reduce the CO_2 production. The tyre/road noise reduction is also a focus of interest. In parallel, road pavement manufacturers are developing wearing courses with significant noise reduction properties. It seems that there is an unexploited potential for a combined technology that reduces energy consumption and road traffic noise. Unexpectedly, not only the tyres with highest fuel efficiency class A labeled are mounted by cars manufacturers on new sold electric and hybrid electric vehicles, they usually fit the cars with normal summer tyres. Similar conclusions can be drown regarding OEM tyre selection for those vehicles. Only few of them were labelled with "1 bar" (low noise tyre) and in only one case the tyre has been labelled with 67 dB. Remaining tyres were characterized with higher noise emission levels. Thus there is still a large potential to reduce the energy consumption and CO_2 emission as well as noise emission when using both energy efficient and low noise tyres.

The performed literature survey dealing with noise emission of vehicles driven in an electric mode can be concluded, that only at speeds below approximately 30 km/h there is a significant difference of about 10-20 dB in noise emission comparing to combustion vehicles. The only exception to this rule is when a electric vehicle is reversing and in this case it is more noisy. The other finding from the literature survey is, that at more commonly used speeds in urban conditions (30 to 50 km/h and above) the tyre/road noise is dominating, so electric and hybrid electric vehicles emit similar noise like vehicles with internal combustion engines. It would therefore be a great benefit if the tyres and road surfaces can be optimized to reduce the noise, as well as reduced CO_2, under urban conditions. Technological development make it possible.

Road surface, on which a vehicle is moving, significantly influences both the vehicle energy consumption (hence CO_2 emission) and its noise emission. This is due to the substantial effect of its characteristic on rolling resistance and noise emission of vehicle tyres interacting with the surface. In case of electric and hybrid electric vehicles this influence on noise emission is even greater, comparing to conventional cars, due to the lower speed at which significantly quieter electric propulsion becomes negligible and tire/road noise prevails.

Recently low noise pavements have become more and more popular and accepted as an effective means of road traffic noise abatement. Reducing the traffic noise at the source is clearly a more cost effective measure compared to more conventional methods such as road barriers or facade insulation. Significant and beneficial noise reduction up to 10 dB(A) can be achieved, just due to the proper pavement characteristics. Differences in tyre/road noise levels between various types of pavements may reach 16 dB, but usually do not exceed 5-8 dB when the extremely noisy pavements are excluded. Anyway it is a great potential for decreasing noise emission of passing vehicles.

It was presented in this report, that the proper selection of low rolling resistance pavement may lead to significant reduction of both energy consumption and noise emission of vehicles using the road. But all pavement parameters, also functional, should be taking into account when selecting pavement type for particular road. One should also remember that different pavements change their characteristics with time and wear.

Concluding, the occurrence of electric driven vehicles and their significant volume increase in current traffic fleet promises a unique breakthrough in reduction of urban community noise as well as in reduction in environmental pollutions.

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