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Empirical Evaluation of the Replacement of Conventionally Powered Vehicles with Hybrid and Electric Vehicles on the Example of the Poznań Agglomeration

Aleks Jagielski, Andrzej Ziółkowski *, Maciej Bednarek and Maciej Siedlecki

Faculty of Civil Engineering and Transport, Poznan University of Technology, ul. Piotrowo 3, 60-695 Poznan, Poland; aleks.jagielski@doctorate.put.poznan.pl (A.J.); maciej.bednarek@doctorate.put.poznan.pl (M.B.); maciej.siedlecki@put.poznan.pl (M.S.)

* Correspondence: andrzej.j.ziolkowski@put.poznan.pl

Abstract: From the collected data of the Central Register of Vehicles, an average of 15,000 vehicles were registered per month in the Greater Poland region in 2020–2022. It should be borne in mind that most of them were conventionally powered cars-spark-ignition or compression-ignition engines, the daily operation of which negatively affects the environment. Institutions responsible for regulating the homologation of passenger vehicles are introducing increasingly stringent emission standards to reduce the harmful effects of vehicles on the environment. In addition, more and more public campaigns are being conducted on the use of cars equipped with alternative propulsion systems, e.g., electric, full-hybrid or increasingly popular hydrogen-powered vehicles. The publication presents forecasts for the replacement of vehicles equipped with spark-ignition and compression-ignition engines with cars equipped with hybrid propulsion systems or electric systems. Tests of vehicles in real operating conditions were carried out in the Poznań agglomeration in an urban area, where the number of vehicles per area is higher than in the case of a nonurban zone. The research objects were both cars equipped with a conventional drivetrain and a hybrid system. The research made it possible to draw up a hybridization index, which was then applied to the number of vehicles registered over the past few years.

Keywords: combustion engines; RDE; PEMS; HEV; PHEV

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1. Introduction

With the global push to meet growing energy and environmental challenges, including the reduction of greenhouse gas (GHG) emissions from road transportation, there is significant pressure to develop fuel-efficient vehicle technologies [1]. Electric drive vehicles (EDVs), including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), are currently the main powertrain technologies aimed at achieving lower carbon dioxide (CO2) emissions [2–4]. An increasing number of metropolitan areas are introducing limits on the entry of certain groups of vehicles into the inner city, which is also boosting interest in alternatively powered vehicles. In addition, numerous subsidies and concessions are being applied to owners of such cars, such as a free paid parking zone within the city, or the possibility of using bus lanes. Based on data from the Central Statistical Office and Central Register of Vehicles and Drivers [5,6], there are about 420,000 cars and single-track vehicles registered in Poznań, most of which are powered by internal combustion engines. Only about one in three vehicles is equipped with a hybrid or all-electric system, which can be considered as a no-emission system. Based on observations, most EVs are the second vehicle in a household to escrow in an urban area due to the aforementioned concessions and restrictions. The main means of displacement remains the compression-ignition or spark-ignition car due to better refueling infrastructure, longer range and lower purchase, and eventual repair costs [7–11].

As mentioned, BEVs and FCEVs are zero-emission vehicles, while HEVs generate significantly lower emissions compared to conventional vehicles as a direct result of lower fuel consumption. But in the case of electric vehicles, the problem is much more complex, as they require electricity, which in many countries is still produced from fossil fuels. Electricity production generates pollution. An opportunity to improve the balance of pollution is to use electricity from alternative sources, such as wind farms and photovoltaics. Technological progress in this area and market share should gradually increase with the development of the electric vehicle market.

Urban and non-urban areas are the main two areas for which hybrid and electric vehicles are designed. This is due to the fact that in these conditions the described vehicles have the possibility of recovering significant amounts of kinetic energy and its subsequent conversion into electrical energy. If we are talking about hybrid systems equipped with an internal combustion engine, then the use of electric energy significantly reduces fuel consumption and emissions of harmful toxic compounds [12–15]. In the discussed group of vehicles, electric energy is used primarily when starting from a standstill requiring higher torque. In the case of electric vehicles, on the other hand, it is the converted energy that is stored in the batteries that provide the energy needed to drive the electric motors [16]. In the urban cycle, due to the most intense variation in acceleration, the energy recovery process is greatest.

Constant changes in homologation regulations mean that vehicle powertrains are constantly evolving [17]. Significant changes in vehicle testing procedures have emerged in recent years, the largest being real-world real-driving emissions (RDE) measurements. These are performed using portable emission measurement system (PEMS) devices, which allow detailed analysis of engine performance and exhaust emissions. Such apparatus allows testing of vehicles, but also machines and equipment in the non-road category [18–20]. Due to increasing knowledge of the impact of electric vehicles on the environment and increasingly ambitious legislative plans for a zero-emission economy, new sources of powering vehicles and machines are being sought. This is resulting in the significant development of fuel cell electric vehicles. This topic is being taken up by a growing number of researchers [21–23].

An analysis of the literature in question has led to the conclusion that there are many publications, but they mainly focus on vehicles with one type of alternative propulsion system. In order to accurately and critically assess the environmental benefits of replacing conventional vehicles with hybrid vehicles, among others, it is necessary to conduct a comparative analysis of exhaust emissions and energy consumption. A comparison of the exhaust emissions and energy consumption of conventional, electric and hybrid vehicles is presented in [24–29]. An analysis of the literature showed that both hybrid and conventional vehicles had higher fuel consumption during RDE tests compared to those conducted under laboratory conditions. Alternative powertrains, however, had about 23–49% lower fuel requirements in a test conducted according to RDE guidelines [30,31].

With the aim of complementing existing publications on emissions from vehicles equipped with different powertrains and capabilities, the authors of this article decided to conduct tests on conventional and HEV vehicles, and then determine the extent of the reduction in harmful emissions as a result of replacing SI and CI vehicles with HEV/PHEVs and EVs, using the example of the Poznań metropolitan area.

2. Materials and Methods

2.1. Research Objects

As part of the research on replacing conventionally powered vehicles with hybrid and electric vehicles, the authors used test facilities equipped with an internal combustion engine and one with a hybrid system. The HEV is powered by a spark-ignition engine as the main propulsion source, while the electric motor can operate in series and parallel modes. The first one (Figure 1) was equipped with an internal combustion engine with a displacement of 1.2 dm^3 and a useful power of 77 kW. It was equipped with a triple-function catalytic reactor and a lambda probe as exhaust aftertreatment systems.

Figure 1. Vehicle A.

The second test vehicle was equipped with a 2.2 dm^3 compression-ignition engine. Its maximum power was 150 kW and it was additionally equipped with exhaust after-treatment systems such as EGR (exhaust gas recirculation), DPF (diesel particulate system), DOC (oxidation catalyst) and SCR (selective catalytic reduction) (Figure 2).

Figure 2. Vehicle B.

The last test object (Figure 3) is powered by a four-cylinder internal combustion engine with a displacement of 2.5 dm^3 generating 133 kW at 6000 rpm. It is equipped with gasoline direct injection and a DOHC system with four valves per cylinder. The electric motor in this vehicle generates 105 kW, not exceeding 650 volts of voltage. The total power of the entire system is 164 kW.

Figure 3. Vehicle C.

Selected data related to the research facilities are shown in Table 1. The basic indicator describing the dynamics of vehicles is their specific power. This is the quotient of the maximum useful power of the engine and the total weight of the vehicle. Calculating this ratio for vehicle A yielded a value of 0.49 kW/kg; for vehicle B, a value of 0.53 kW/kg; and for vehicle C, a value of 0.73 kW/kg (Table 1).

Table 1. Characteristics of the research objects.

	Vehicle A	**Vehicle B**	**Vehicle C**
Ignition	Spark ignition	Compression ignition	Spark ignition
Displacement	1.2 dm^3	2.2 dm^3	2.5 dm^3
Number and arrangement of cylinders	4 in-line	4 in-line	4 in-line
Maximum power output of combustion engine	77 kW	150 kW	133 kW
Maximum power output of electric engine	-	-	105 kW
Injection system	GDI	Common Rail	GDI
Aftertreatment	TWC with lambda control	EGR, DPF, DOC, SCR	TWC with lambda control
Transmission	Automatic	Automatic	Automatic
External dimensions length/width/height	4.06/1.69/1.45 m	4.82/1.94/1.80 m	4.85/1.84/1.46 m
Unit power output index	0.49 kW/kg	0.53 kW/kg	0.72 kW/kg
Total weight	1 540 kg	2 950 kg	2 235 kg

2.2. Test Route

Emissions were measured under real traffic conditions using road tests referred to as RDE (real-driving emissions). RDE tests allow the determination of real emissions and energy intensity of a vehicle during operation. Traffic is characterized by great variability and randomness depending on road infrastructure such as traffic lights or congestion and other users, so the speed and acceleration profile of a vehicle is highly irregular. In order to compare the results of the tests, they must be conducted in a reproducible manner, so strict conditions have been developed that the selected route must provide during the tests. The driving requirements vary depending on the type of vehicle being tested. For passenger cars, the test route consists of urban driving, extra-urban driving and highway driving. Each of these stages has a specific speed range, with urban driving also to include several stop periods. The total duration of the test should be 90–120 min, and the distance traveled in each driving mode must not be less than 16 km. In the case of replacing conventionally propelled vehicles with hybrid and electric vehicles, only the urban part (Figure 4) of the Poznań agglomeration was taken into account, which was characterized by a length of about 29.50 km, an average speed of 20.65 km/h and a stopping time of 29.67% relative to the entire urban part. The above parameters meet the stringent requirements for the RDE test.

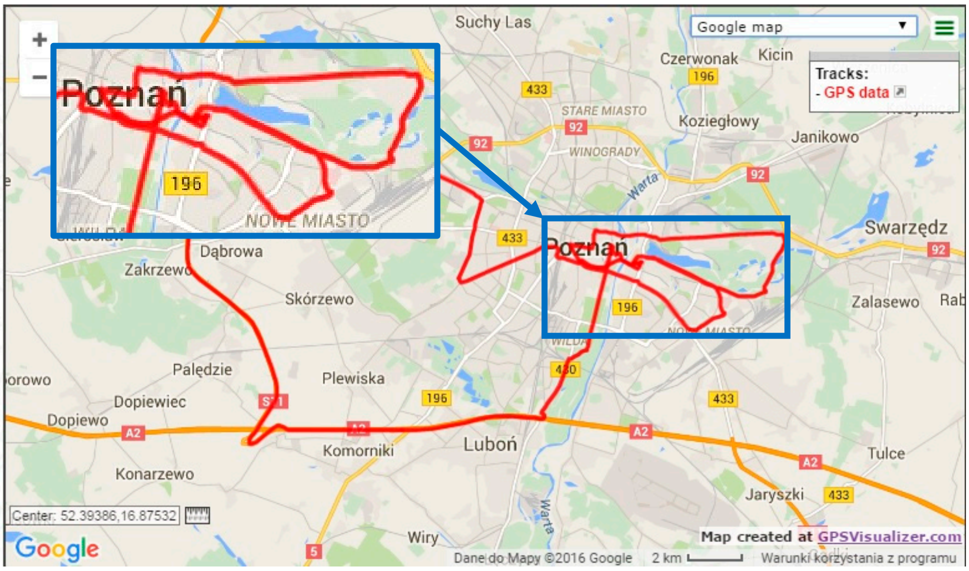

Figure 4. Route of the research road based on GPS data.

2.3. Measurement Equipment

Exhaust emission tests were conducted in accordance with RDE (Real-Driving Emissions) test conditions. For this purpose, it was necessary to use a mobile test apparatus (Figure 5) of the PEMS (portable emission measurement system) type, which must meet strict requirements. The power supply of the PEMS must be external so as not to affect the operation of the engine. The installation and weight of the PEMS must not affect the driving conditions of the vehicle. Prior to the start of the measurements, the measuring apparatus must be heated and calibrated with the appropriate standard gases to ensure the proper conditions and accuracy of the measurement of exhaust gas components. A probe testing the exhaust mass flow rate was also connected to the exhaust system. The measurements were complemented by a connected GPS (global positioning system) module, a module recording the current weather conditions affecting the tested values, and a diagnostic cable connected to the OBD (on-board diagnostic) connector in the car to retrieve data from the ECU (engine control unit) on engine speed, among other things. The devices operated at a measurement frequency of 1 Hz to ensure sufficient measurement accuracy under dynamically changing driving conditions. The Semtech DS analyzer samples the exhaust gas using a Pitot tube-shaped probe placed in the car's exhaust system. The exhaust gas is heated to avoid condensation of hydrocarbons and then filtered to remove particulates. Table 2 shows the methods for measuring the concentration of each compound used in the Semtech DS.

Figure 5. Portable emission measurement system Semtech DS.

Table 2. Semtech DS technical specifications.

Parameter	Measurement Method	Measurement Range	Measurement Accuracy
CO_2	Non-dispresive infrared (NDIR)	0–20%	±3% measurement range
CO	Non-dispresive infrared (NDIR)	0–10 %	±3% measurement range
$NO_X = NO + NO_2$	Non-dispresive ultraviolet (NDUV)	NO: 0–2500 ppm NO_2: 0–500 ppm	±3% measurement range
HC	Flame ionization (FID)	0–1%	±2.5% measurement range
O_2	Electrochemical (EC)	0–20%	±2.5% measurement range
Exhaust gas flow	Mass flow T_{max} up to 700 °C		± 2.5% ± 1% measurement range

The exhaust gas sample first passes through the FID (flame ionization detector) analyzer, where the THC hydrocarbon concentration is measured. The sample is then cooled and directed to NDUV (non-dispersive ultraviolet) and NDIR (non-dispersive infrared) analyzers, which measure the concentration of NO_X (NO + NO_2) oxides of nitrogen, as well as CO_2 carbon dioxide and CO carbon monoxide in turn. Finally, the sample goes to an electrochemical analyzer to measure the concentration of oxygen O_2, from where it is sent to the atmosphere (Figure 6).

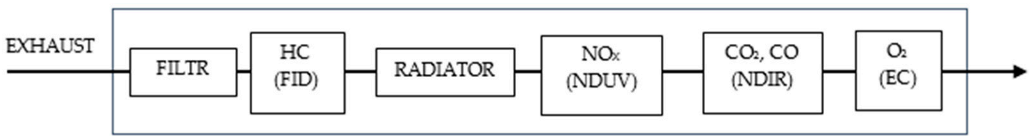

Figure 6. Scheme of measurement with analyzer Semtech DS.

3. Results

To determine the operating conditions of internal combustion engines, the authors used the characteristics of the proportion of operating time in the engine speed and load intervals (Figure 7). In the case of vehicle A, the largest share of 80% occurs for a load not exceeding 40%, with 20% occurring at the lowest speed in the interval (400 rpm; 800 rpm>). The value of the share is close to the value of the share at standstill during the test. In contrast, the share then increases for each speed range to the highest value of about 8% for the speed range (2000 rpm; 2400 rpm). Only 3% of the share represents the area of operation above 2800 rpm, and only 2.5% represents the area above 80% load. The characteristics of vehicle B were less extensive compared to vehicle A. About 20% of the time, the engine operated in the speed range (400; 800>), with a load of (0; 20>%). The values (1200; 1600>) can be taken as the main engine speed ranges, which is a direct result of the characteristics of compression-ignition internal combustion engines (smaller speed range compared to the spark-ignition engine). In the case of vehicle C, the dominant share of electric power was observed, as 58% of the total operating time the internal combustion engine was not used at all. For the remainder, it was registered that the engine operated in the engine speed range of 0–4800 rpm. Within this range, the largest share of engine load came from two ranges (60; 80%>) and (80; 100%>). They accounted for a total of 27% of the total operating time, which is due to the operating characteristics of the hybrid drivetrain.

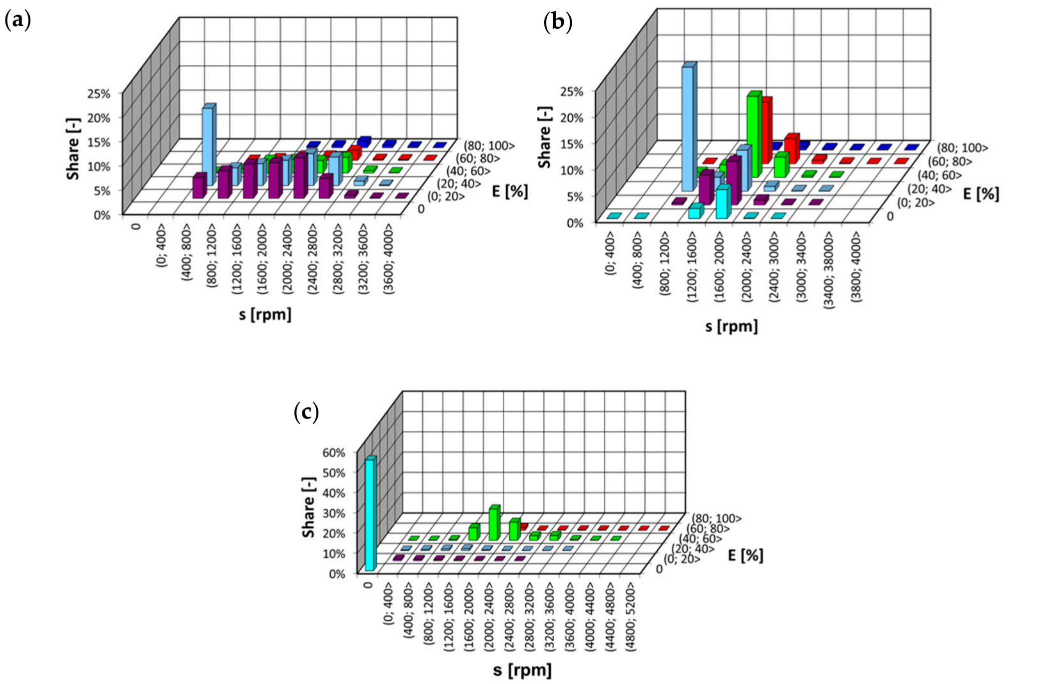

Figure 7. Operating time share characteristics depending on the combustion engine speed and load (**a**) vehicle A, (**b**) vehicle B, (**c**) vehicle C.

In the case of unburned hydrocarbon emissions, it can be seen that the highest values for all three vehicles were recorded at maximum engine speed and a drive unit load ranging from 60% to 100%. Over the entire range of characteristics, for both runs, the emission value increased with increasing speed and load (Figure 8). Compared to vehicles equipped with a spark-ignition engine, test subject B had the highest unburned hydrocarbon emissions. This is due, among other things, to the fact that diesel fuel in its molecular structure contains larger hydrocarbon molecules with a greater number of carbon atoms than gasoline, and the molecules in question have higher boiling points-typically between 150 °C and 370 °C.

A different situation was observed for the intensity of NO_X emissions (Figure 9). Its highest values occurred for vehicle B throughout the test. A trend was observed that the values of these emissions increased with increasing engine speed and load. Vehicles A and C were equipped with spark-ignition internal combustion engines equipped with three-way catalytic converters (TWCs), which have a NO_x conversion rate of 95%, which is significantly higher than the SCR systems used in diesel engines (vehicle B was equipped with such a system). The EGR system used here, whose main task is to feed the exhaust gas into the combustion chamber in order to reduce the global combustion temperature responsible for NO_x formation, did not help either. Vehicles A and B were characterized by similar intensity of the aforementioned exhaust component. This was particularly related to exhaust gas cleaning in both cases. The intensity of CO_2 emissions was similar-the highest values throughout the test were recorded for vehicle B (Figure 10). This was influenced by two parameters. The first was the engine displacement, which was larger compared to vehicle A. Another key parameter was the fact that vehicle C was able to recover energy from the vehicle's braking, thus supporting the electric part of the drivetrain and reducing fuel consumption, which naturally reduces the intensity of CO_2 emissions (in direct proportion to fuel consumption).

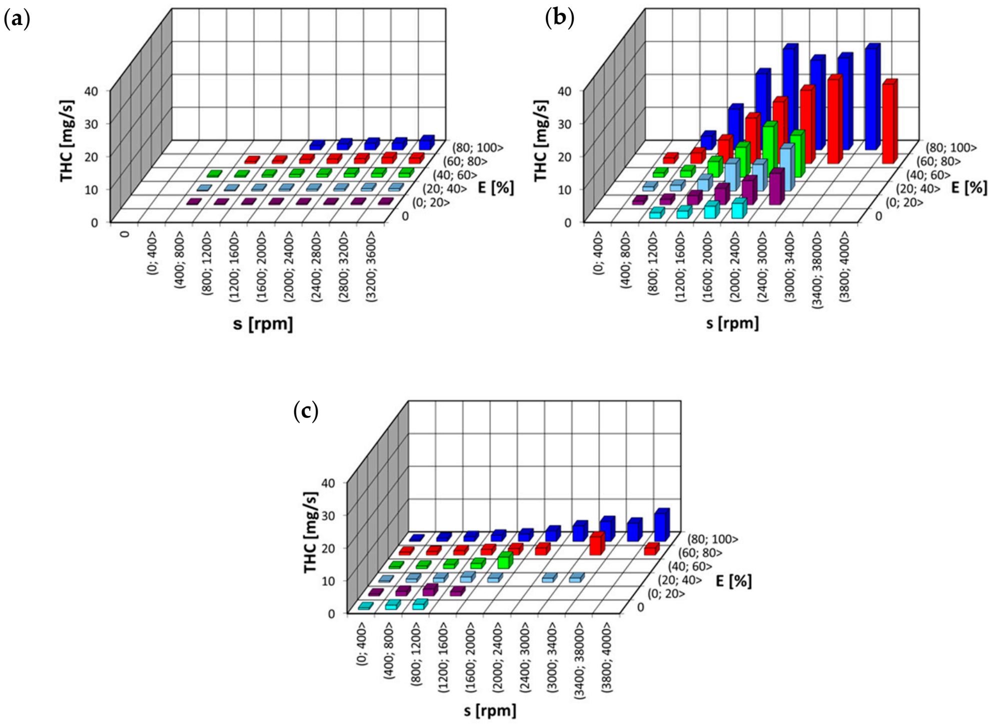

Figure 8. Emission of THC recorded in the RDE cycle: (**a**) vehicle A, (**b**) vehicle B, (**c**) vehicle C.

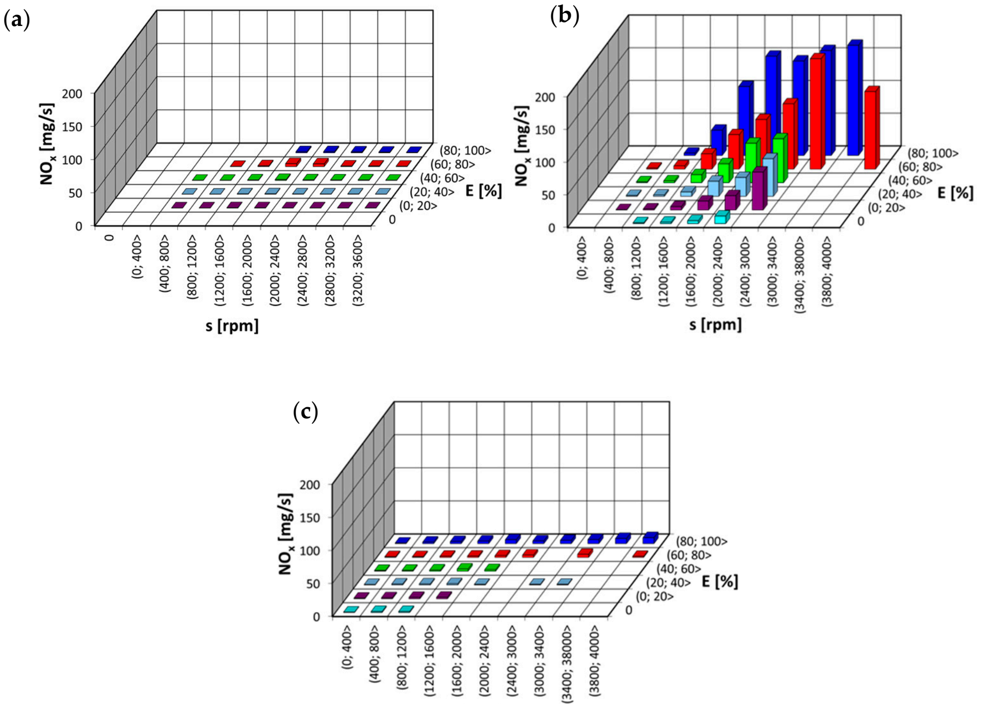

Figure 9. Emission of NO_x recorded in the RDE cycle: (**a**) vehicle A, (**b**) vehicle B, (**c**) vehicle C.

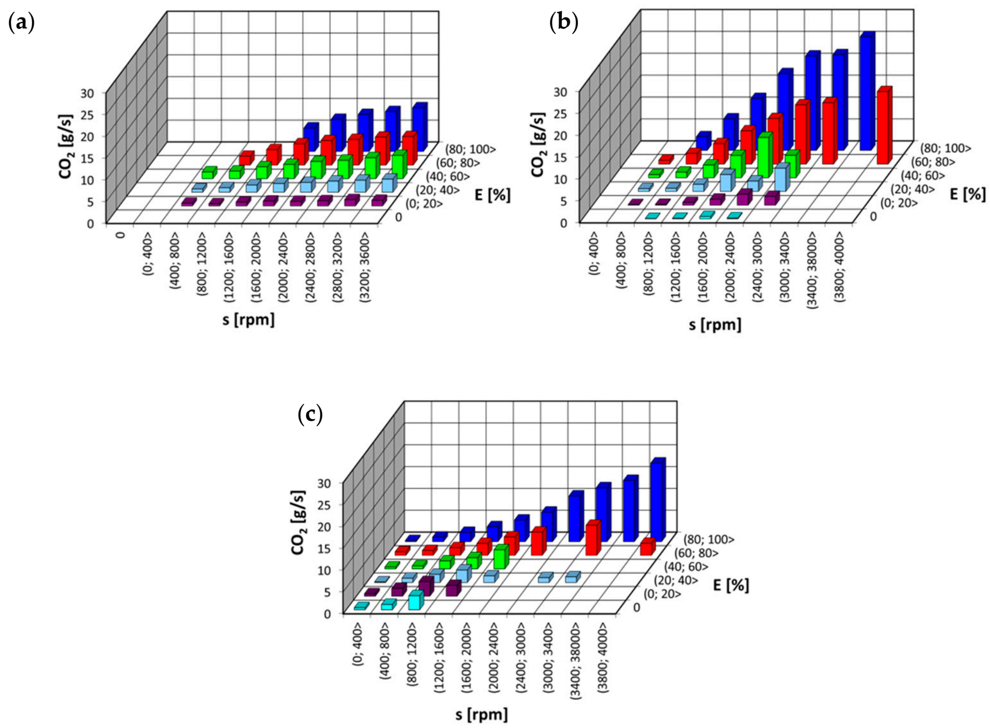

Figure 10. Emission of CO_2 recorded in the RDE cycle: (**a**) vehicle A, (**b**) vehicle B, (**c**) vehicle C.

The next step in analyzing the results obtained in the test was to evaluate the possibility of substitution of spark-ignition and compression-ignition vehicles by BEV and HEV/PHEV vehicles in the city of Poznań. For this purpose, calculations were made of THC, NO_x and CO_2 emissions for all registered cars, the number of which is about 420,000. For this purpose, for each type of propulsion, the value obtained from the tests was taken and multiplied by the number of vehicles in each category; for electric cars, it was assumed that the road emission of individual compounds is 0. Below is shown (Figure 11). the distribution of registered vehicles according to their type of propulsion. About 55% are vehicles equipped with a spark-ignition engine, followed by the HEV/mHEV category. Every tenth car circulating in Poznań is powered by diesel fuel. The least popular groups are PHEV (1%) and EV (3%).

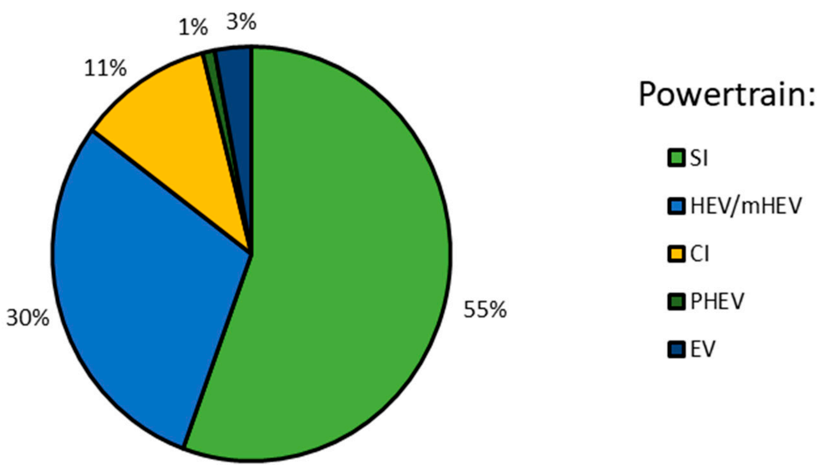

Figure 11. Share of each type of propulsion of passenger vehicles in the Poznań agglomeration [4,5].

The authors then made calculations for four options regarding the feasibility of replacing conventional powertrains. The first concerned the case of 100% replacement by hybrid vehicles, the next concerned electric propulsion only. The third and fourth were related to a 50%/50% and 75%/25% split, with HEV/mHEVs and PHEVs accounting for a larger share in the last one. Each of the assumed variants was characterized by reductions in emissions of individual compounds. The highest values were recorded for NO_x, which is a direct result of the fact that the study included a compression-ignition vehicle, which, as mentioned, is characterized by higher emissions of this compound than in the case of spark-ignition or hybrid cars. The calculated values of THC and CO2 are similar for each other in each variant. The largest decrease in emissions occurred when the conventional powertrain was replaced by an electric system, this is because electric vehicles can be treated as emission-free. For the 100% HEV configuration, the decrease was the lowest, due to the presence of the internal combustion engine as one of the propulsion sources. The 50%/50% and 75%/25% configurations adopted can be qualified as the most likely to occur, given the current trends associated with the promotion of alternative-propulsion vehicles. In the case of the first, the decrease was recorded in the range of 37% to 47%, the second variant was characterized by a lower reduction in emissions and was between 21–33%, this is directly related to the fact that every 4th vehicle considered would be electric. Tables 3–5 provide a summary of the variants described, along with a description of which compound was affected.

Table 3. THC emission scenarios.

	THC	
Configuration	**Emission**	**Decrease/Increase**
presently	39.50 [kg/km]	0%
100% HEV	37.16 [kg/km]	−5.93%
100% EV	11.72 [kg/km]	−70.34%
50%/50% HEV/EV	24.44 [kg/km]	−38.13%
75%/25% HEV/EV	30.80 [kg/km]	−22.03%

Table 4. NO_x emission scenarios.

	NO_x	
Configuration	**Emission**	**Decrease/Increase**
presently	76.66 [kg/km]	0%
100% HEV	61.94 [kg/km]	−19.21%
100% EV	19.53 [kg/km]	−74.52%
50%/50% HEV/EV	40.73 [kg/km]	−46.87%
75%/25% HEV/EV	51.33 [kg/km]	−33.04%

Table 5. CO_2 emission scenarios.

	CO_2	
Configuration	**Emission**	**Decrease/Increase**
presently	72.55 [t/km]	0%
100% HEV	67.42 [t/km]	−7.07%
100% EV	21.26 [t/km]	−70.70%
50%/50% HEV/EV	45.18 [t/km]	−37.72%
75%/25% HEV/EV	57.14 [t/km]	−21.24%

The final step in analyzing the results obtained during the study was to evaluate the fuel consumption of each vehicle. The authors used the carbon balance method, which uses a vehicle's on-road CO, THC and CO_2 emissions and fuel density to determine fuel consumption. The carbon balance method is considered one of the most accurate ways to determine the course of fuel consumption. The method is defined by the formula [32]:

$$FC = \frac{0.1155 * [(0.866\ HC) + (0.429\ \mathrm{CO}) + (0.273\ \mathrm{CO_2})]}{\rho_{fuel}} \quad (1)$$

The average fuel consumption is shown in Figure 12, and from the lowest result, was recorded for vehicle C. This was followed by vehicles A and C, whose fuel consumption was higher in the range of 8–23%. In addition, comparisons of the fuel consumption of conventional and hybrid vehicles were also made by the authors of the paper [31]. Their analysis showed significant fuel savings for a vehicle equipped with an alternative powertrain, which was also confirmed in the work of other researchers [33].

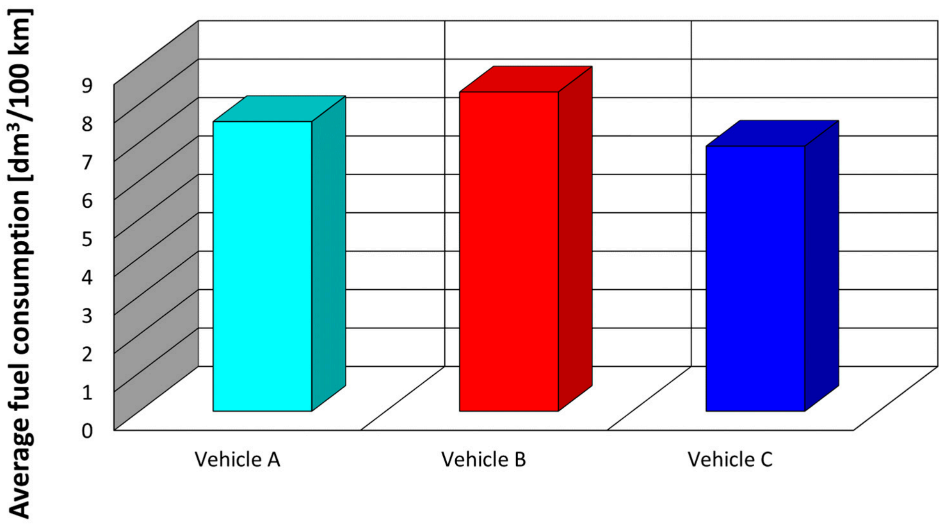

Figure 12. Average fuel consumption from the test.

4. Conclusions

In conclusion, the analysis carried out in terms of the possibility of replacing vehicles equipped with a conventional propulsion system indicates that all configurations for the vehicles used will reduce road emissions in the Poznań agglomeration. The most favorable variant, changing vehicles with ZI and ZS engines to electric cars, and the recorded decrease was about 70–75%. However, it should be borne in mind that this is the most optimistic variant from the point of view of ecological aspects. On the other hand, the realistic configuration is described in variant 4, in which 75% of cars with internal combustion engines are replaced by vehicles with a hybrid system, and 25% by electric vehicles. In this case, there is a decrease in emissions from about 21% to 33%. The studies performed clearly indicate, the legitimacy of using hybrid and electric vehicles relative to vehicles with a conventional internal combustion engine to reduce carbon dioxide emissions into the atmosphere in urban areas. Any benefits applied by state institutions to promote such types of propulsion will increase their popularity over time. However, it is impossible to say with certainty how much more time will be needed to achieve results.

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