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Comparison of the Energy Consumption and Exhaust Emissions between Hybrid and Conventional Vehicles, as Well as Electric Vehicles Fitted with a Range Extender

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Abstract: The introduction of new Euro exhaust emission standards and CO_2 limits has forced carmakers to implement alternative hybrid and electric powertrains. We are observing a dynamic advancement of this sector. The authors' primary motivation was to perform a series of measurements of the exhaust emissions and fuel mileages from vehicles fitted with hybrid, conventional and electric (range extender) powertrains. Three vehicles were used in the research project. The first one was a passenger car with a full hybrid powertrain. The vehicle was fitted with a 1.6 dm^3 spark ignition engine. The second one was fitted with a 2.2 dm^3 diesel engine. The third one was fitted with a 125 kW electric motor and a 28 kW combustion engine used as a range extender. The investigations were carried out according to the RDE (Real Driving Emission) methodology on a test route composed of urban, rural and highway portions. The test route was set in the Poznan agglomeration, and its distance was approx. 80 km. For the measurements, the authors used SEMTECH-DS from the PEMS (Portable Emissions Measurement System) equipment group. Based on the obtained results, the authors validated the test route in terms of the RDE compliance and determined the exhaust emissions and fuel mileages. The authors also analyzed the influence of the conditions of the measurements on the powertrain characteristics of each of the tested vehicles.

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

Citation: Ziółkowski, A.; Fuć, P.; Jagielski, A.; Bednarek, M.; Konieczka, S. Comparison of the Energy Consumption and Exhaust Emissions between Hybrid and Conventional Vehicles, as Well as Electric Vehicles Fitted with a Range Extender. *Energies* **2023**, *16*, 4669. https://doi.org/10.3390/en16124669

Academic Editors: K. T. Chau and Francisco P. Brito

Received: 6 April 2023
Revised: 23 May 2023
Accepted: 6 June 2023
Published: 12 June 2023

1. Introduction

One of the main attributes of advancing globalization is mobility, understood as, inter alia, the ability to quickly move from point A to point B. It is largely made possible by private road transport, which, aside from its positive aspects, also has some negative consequences, such as road accidents, traffic congestion, noise and exhaust emissions [1]. According to recent data, in Europe alone, one may observe an increase in the number of vehicles in use [2]. Due to the fact that transport is heavily dependent on fossil fuels, this sector is also responsible for a significant part of the emissions of greenhouse gases. A standard motor vehicle generates approx. 4.6 tons of carbon dioxide [3]. Exclusively in the European Union in 2017, road transport was responsible for the emissions of over 20% of CO_2 [4]. The above facts have prompted legislators to make vehicles independent from liquid and gaseous fuels, such as gasoline, diesel fuel or LNG/LPG. Therefore, recent years have seen a dynamic advancement of the hybridization and electrification technologies of vehicle powertrains. This has resulted in such solutions as BEVs (Battery Electric Vehicles), FCEVs (Fuel Cell Electric Vehicles) and HEVs (Hybrid Electric Vehicles) [5]. Even though their market share is small (in 2022, in the European Union, the share of BEV vehicles was 0.5%, and that of HEV vehicles was 1.2% [6]), the advancement of alternative powertrains and the replacement of conventional powertrains with the hybrid and electric ones are the main method of transport defossilization. According to the data of the International Energy

Agency, the sales of electric vehicles are growing. The agency also forecasts that this trend will continue, and that the number of electric vehicles sold will reach 300 million, thus setting the new vehicle market share on the level of 60% [7]. When in use, BEVs and FCEVs are zero-emission vehicles, while HEVs generate significantly lower emissions of exhaust gas compounds compared to conventional vehicles [5]. In the case of electric vehicles, the problem is far more complex because they require electric energy, which, in many countries, is still made from fossil fuels. The production of electric energy generates pollution. An opportunity to improve the pollution balance is the use of electric energy from alternative sources, such as windfarms or photovoltaics. The technological advancement thereof and the market share should gradually increase as the electric vehicle market grows.

The technological advancement of vehicle powertrains is also a consequence of the changes in the emission-wise homologation legislation. Recent years have brought about fundamental changes in the vehicle testing procedures. Measurements under real-world conditions (RDE) have been introduced. As has been proven in a variety of studies [8,9], no other methodology allows for such a comprehensive empirical determination of the relations among the exhaust emissions, engine usable parameters and road conditions. Prior to the introduction of RDE testing, frequently performed laboratory tests did not fully reproduce the vehicles' actual exhaust emissions or the actual road conditions [10–12]. RDE tests are carried out using PEMS (Portable Emission Measurement Systems) equipment, enabling a detailed analysis of the exhaust emissions and engine operating parameters. Such equipment allows for testing vehicles as well as other non-road machinery [13,14].

Hybrid and electric vehicles are today primarily dedicated for use in urban and rural traffic conditions. This is related to the recovery of large amounts of kinetic energy and its subsequent conversion to electric energy. The latter is stored in batteries, providing a source of energy needed for the electric motors. In the case of hybrid powertrains also fitted with combustion engines, the use of electric energy significantly improves the fuel consumption and exhaust emissions. In the discussed group of vehicles, the electric energy is used primarily during drive-off, requiring a greater amount of torque. In urban driving, the variability in acceleration is most intense, which allows the process of energy recovery [5].

Many researchers have analyzed the influence of the operating conditions of hybrid powertrains on fuel consumption and exhaust emissions [15–19]. Similar to conventional vehicles, it is vital to determine the exhaust emissions or energy consumption of alternative powertrains under real-world conditions. Liu, Ivanco and Filipi attempted to determine the impact of the driving style (aggressive driving) on the fuel consumption of a hybrid vehicle [20]. The fuel consumption of a PHEV under urban driving conditions was also a subject of research in [21]. In hybrid vehicles, exhaust emissions are also a significant problem. The authors of [22] tested a plug-in hybrid in the laboratory and under real-world conditions. The analysis of the results showed that in PHEV vehicles, the emissions of carbon dioxide were significantly varied depending on the powertrain operating mode. The presented results show that the emissions of CO_2 were much lower during the battery discharge mode. Yet, as the authors indicate, some of the operating modes selected by drivers significantly increase the emissions of CO_2, which then levels off the balance of the emissions of this exhaust component. The same authors of [23] expanded their investigations through the analysis of the emissions of particulate matter from the same research objects, revealing much greater emissions of PN during cold start. This problem pertains to both hybrid and conventional powertrains, which is confirmed by the results presented in [24]. The influence of low temperatures on the exhaust emissions was also the subject of research by Suarez-Berota, Palovic et al. [25], as well as by Alvarez and Weilenmann [26]. The authors of the said publications investigated the influence of low temperatures on the emissions from a hybrid vehicle. When studying the relevant literature, one may infer that world-class scientists comprehensively research hybrid vehicles. The authors of [27] analyzed the emissions of nitrogen oxides, particle number (PN) and fuel consumption from a PHEV vehicle under real-world conditions. Moreover, in [28], the authors investigated the exhaust emissions and fuel consumption of a plug-in hybrid vehicle according to the RDE procedure. The authors also focused on the factors influencing the exhaust emissions, drawing attention to the facts of increased fuel consumption with active climate control and increased carbon dioxide when driving uphill. Wag et al. used the PEMS equipment to determine the exhaust emissions and energy demand of a PHEV vehicle depending on the driving mode [29]. The authors of [30] focused on the determination and analysis of the total specific energy consumption of a PHEV vehicle.

A study of the relevant literature has led to the conclusion that there are a multitude of publications, yet they mainly focus on vehicles with a single type of alternative powertrain. In order to accurately and critically assess the environmental benefits from the substitution of conventional vehicles with, inter alia, hybrid ones, it is fundamental to perform a comparative analysis of the exhaust emissions and energy consumption thereof. A comparison of the exhaust emissions and energy consumption of conventional, electric and hybrid vehicles is presented in [31]. Such a comparison of conventional and hybrid vehicles is also presented in [32]. In this case, the authors performed their investigations in both laboratory and real-world conditions. It is noteworthy that both hybrid and conventional vehicles had higher fuel consumption during RDE testing compared to that performed under laboratory conditions. Alternative powertrains, however, had an approx. 23–49% lower fuel demand in the test carried out according to the RDE guidelines. He, Ty et al. performed a comprehensive assessment of the influence of a cold start and road gradient on the fuel consumption in hybrid, electric and conventional vehicles (fitted with spark ignition and diesel engines). These investigations also confirmed the fact that, under warm-engine conditions, HEV vehicles generate approx. 30% less carbon dioxide [33]. In order to supplement the existing publications regarding exhaust emissions from vehicles fitted with different powertrains, the authors of this paper decided to perform RDE testing on a conventional vehicle, PHEV and electric vehicle (the latter fitted with a range extender).

2. Materials and Methods

2.1. The Test Route

In September 2017, the EURO 6C standard was introduced for vehicles of the PC and LDV categories. Upon implementation of the regulations, the method of the performance of the exhaust emission measurements was modified. The values of the admissible limits of individual exhaust components were also changed. The NEDC test was replaced with the WLTC procedures, and the measurement of the exhaust emissions under the RDE conditions became mandatory. In the said measurements, assumptions related to the test route were laid out so as to ensure the reproducibility of the performed tests. The most important of these assumptions are as follows:

(a) The test route should be composed of three portions:
- The urban portion: distance min. 16 km, maximum vehicle speed 60 km/h, duration 29–44% of the entire test time with a tolerance of 10%;
- The rural portion: maximum vehicle speed 60–90 km/h, distance min. 16 km, duration 23–43% of the entire test time with a tolerance of 10%;
- The highway portion: vehicle speed in excess of 90 km/h, distance min. 16 km, duration 23–43% of the entire test time with a tolerance of 10%;

(b) The share of the stationary vehicles on the urban portion should fall in the range of 6–30%;

(c) On the highway portion, it is expected that the vehicle will drive with a speed of at least 100 km/h for a minimum of 5 min;

(d) The maximum speed of the vehicle should not exceed 145 km/h (higher speeds are admitted but their shares cannot exceed 3% of the test);

(e) The entire test should last from 90 to 120 min;

(f) The test should start with the urban portion, and then the rural and highway portions should follow (small deviations from this order are allowed);

(g) The relative road gradient between the start and end points should not exceed 100 m;

(h) The vehicle should be driven by a single driver on all test route portions;
(i) Pauses and unnecessary stops are not allowed during the tests.

The exhaust emission measurements were carried out on the Poznań_RDE route designed by the authors. It starts at the location of Poznan University of Technology and runs through the nearby city districts (southeastern parts) and downtown Poznan (urban portion). Upon covering the urban part, the route leads to the eastern parts of the city and then through the main thoroughfares towards national road no. 92 (Figure 1). During the investigations on the said route, a smooth passage from the urban to the rural portion took place that ended on the S11 highway (the western part of the city beltway), where the last part of the test began (highway portion). The test route was performed mainly on the eastern part of the beltway (A2 motorway). The described portion ended at the Poznan Krzesiny motorway exit. Upon completion, the driver returned to the start point of the test procedure. The total distance of the test route was approx. 75–80 km. The divergence related to the covered distance results from the fact that it is fundamental to abide by the driving time rule, which is a minimum of 90 and a maximum of 120 min. Depending on the road congestion, it is possible to finish the measurement early prior to returning to the start point so as not to exceed the maximum RDE test time.

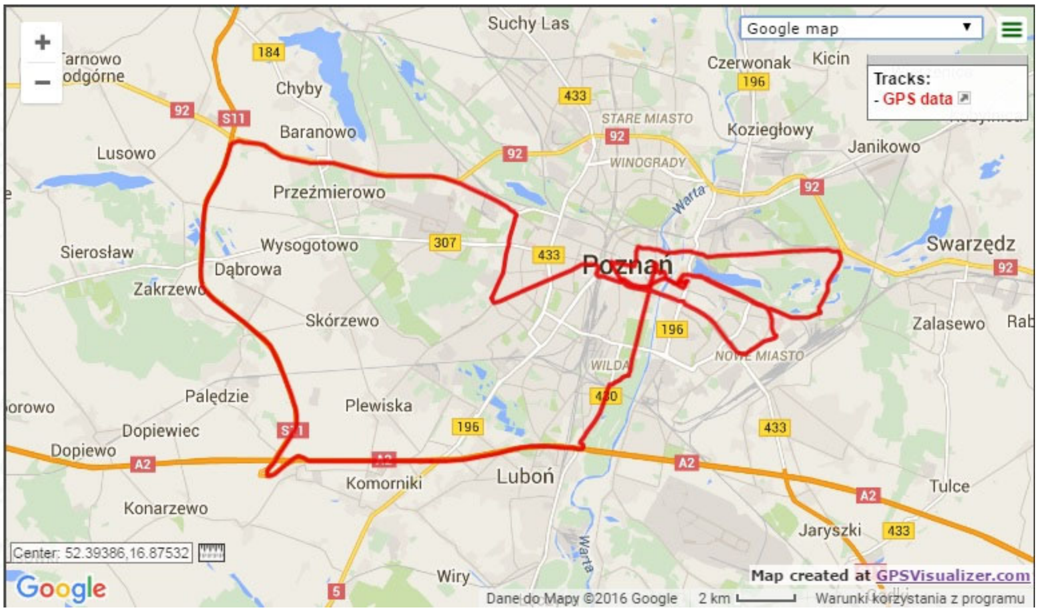


Figure 1. Poznan agglomeration with the course of the RDE test route marked.

2.2. Measurement Equipment

For the measurement of the exhaust emissions and fuel consumption, the authors used SEMTECH-DS, a portable analyzer (Figure 2). This equipment belongs to the PEMS group and allows for measuring the following:

(a) Concentrations of CO_2, CO, NO_x, THC and O_2;
(b) Mass exhaust gas flow, its temperature and pressure;
(c) Temperature, pressure and humidity of the ambient air;
(d) Vehicle GPS speed and position;
(e) Basic engine operating parameters pulled from the vehicle OBD system.

SEMTECH-DS is one of the first compact real-world exhaust emission measurement systems. It is composed of a central control unit and an exhaust mass flow meter. The exhaust sample from the exhaust system is fed to the system through a heated line maintaining a temperature of 191 °C. The temperature in the heated line is maintained to prevent the condensation of the hydrocarbon fractions on the tube walls. The exhaust sample first goes through a PM filter. Then, it is transferred to the flame ionization detector (FID), where the concentration of THC is measured. Next, the sample is chilled to 4 °C, and the measurements of NO_x = (NO + NO_2) in the non-dispersive ultraviolet (NDUV) analyzer, as well as of CO, CO_2 and HC in the non-dispersive infrared (NDIR) analyzer, are performed. At the final stage, an electrochemical detector measures the concentration of O_2 (Table 1). SEMTECH-DS is equipped with an independent weather station providing the readings of the temperature, pressure and humidity of the ambient air. These quantities are measured through a sensor fitted outside of the vehicle. The GPS position and vehicle speed are also measured during the tests. SEMTECH-DS allows for connecting (through adapters) to the vehicle on-board diagnostic system and the recording of the basic engine operating parameters (Figure 3). The system supports the majority of the data transmission protocols. The authors' approach to testing based on the application of the PEMS equipment is fully justified in light of the measurement technology development trends. The confirmation of the above is the introduction of the RDE homologation procedures. It is noteworthy that, in recent years, RDE tests have become the main source of knowledge on exhaust emissions from the PC, LDV (Light-Duty Vehicle) and HDV (Heavy-Duty Vehicle) vehicle categories. Tests performed under real-world conditions are increasingly often used for non-road vehicles. Increasing use has also been observed for other vehicle and engine categories, including two-wheelers.

Figure 2. SEMTECH-DS equipment used during the investigations.

Table 1. SEMTECH-DS technical specifications.

Parameter	Measurement Method	Measurement Range	Measurement Accuracy
THC	Flame ionization	0–10,000 ppm	±2.5%
NO_x	Non-dispersive ultraviolet	0–3000 ppm	±3%
CO	Non-dispersive infrared	0–10%	±3%
CO_2	Non-dispersive infrared	0–20%	±3%
O_2	Electrochemical	0–20%	±1%
Exhaust gas flow	Mass flow T_{max} up to 700 °C		±2.5% ±1%

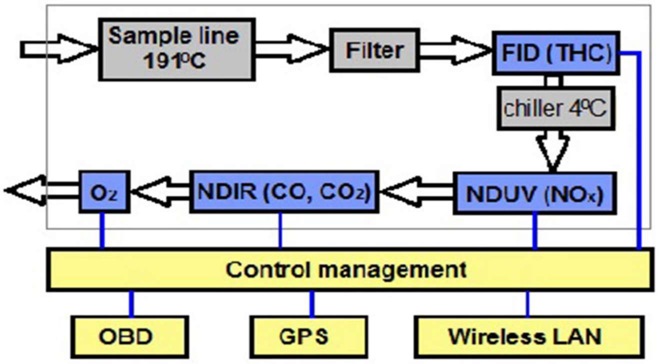


Figure 3. Diagram of the SEMTECH-DS equipment used in the investigations.

2.3. Research Objects

In the RDE investigations, the authors used a mixed-configuration hybrid vehicle, a conventional vehicle and an electric vehicle fitted with a range extender. The powertrain of the HEV-category vehicle was fitted with a piston spark ignition engine as the primary source of power and an electric motor with a NiMH battery as the secondary source of power. The combustion engine had four cylinders of a total displacement of 1.6 dm^3. Its maximum power was 80 kW.

The second research object was a vehicle fitted with a 2.2 dm^3 diesel engine. Its maximum power was 150 kW, and it was additionally fitted with aftertreatment systems, such as EGR (Exhaust Gas Recirculation), a DPF (Diesel Particulate System), a DOC (Diesel Oxidation Catalyst) and SCR (Selective Catalytic Reduction) (Figure 4).

Figure 4. Vehicle B.

The third of the research objects was an electric vehicle fitted with a range extender (combustion engine). In this case, the combustion engine served the purpose of an emergency power generator. Its power output was merely 28 kW (Figure 5). Selected data related to the research object are presented in Table 2. The fundamental indicator describing the dynamics of vehicles is their unit power. It is the quotient of the maximum usable power of the engine and its gross vehicle weight. Calculating the indicator for vehicle A gave a value of 0.55 kW/kg, and for vehicle B, a value of 0.53 kW/kg was obtained (Table 2). Therefore, the difference in these ratios is only 3.5%. It is therefore acceptable to compare the two vehicles on the basis of the unit power factor.

Figure 5. Vehicle C.

Table 2. Characteristics of the research objects.

	Vehicle A	Vehicle B	Vehicle C
Ignition	Spark ignition	Compression ignition	Spark ignition
Displacement	1.6 dm^3	2.2 dm^3	0.7 dm^3
Number and arrangement of cylinders	4 in-line	4 in-line	2 in-line
Maximum power output of combustion engine	80 kW	150 kW	28 kW
Maximum power output of electric engine	32 kW	------	125 kW
Unit power output index	0.55 kW/kg	0.53 kW/kg	0.08 kW/kg
Injection system	GDI	Common Rail	MPI
Aftertreatment	TWC	EGR, DPF, DOC, SCR	TWC
Transmission	Automatic	Automatic	Automatic
External dimensions length/width/height	4.47/1.82/1.45 m	4.82/1.94/1.80 m	4.00/1.78/1.58 m
Total weight	1870 kg	2950 kg	1620 kg

3. Results

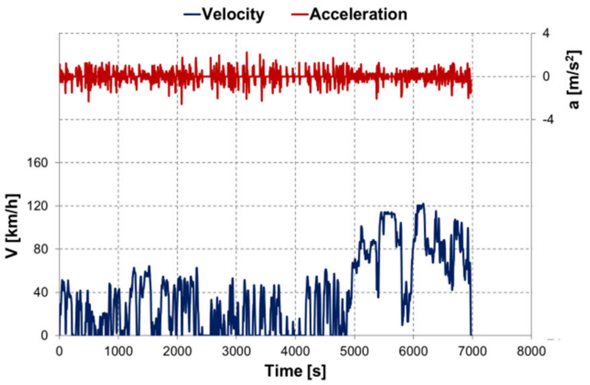
Prior to the analysis of the exhaust emissions, it was necessary to confirm the fulfilment of the test drive requirements set out in the standard procedure. As mentioned earlier, the measurements for all the vehicles were performed on a workday before noon. The duration of each of the test drives was in the 90–120 min range, and their distance was approx. 80 km (Table 3). The requirement of the minimum distance of 16 km for each test portion (urban, rural, highway) was also fulfilled (accumulated positive elevation increment included).

According to the RDE requirements, the first stage was the urban drive. The distance that vehicle A covered at this stage was 32.4 km, which was 39.2% of the total time. Vehicle B covered a distance of 29.4 km, and vehicle C covered 35.1 km. The vehicles also fulfilled the time-share requirement. For the rural drive, the greatest distance (25 km) was covered by vehicle A. A similar situation occurred in the highway portion of the test, where vehicle A covered a distance greater by 3.5 km compared to vehicle B. All vehicles fulfilled the requirement of the time share of the individual drive stages and the maximum stationary time in the urban cycle. During the highway cycle, the vehicles did not exceed the speed of 145 km/h; hence, the requirement of not exceeding a speed of 145 km/h for more than 3% of the cycle time and a minimum of 5 min of driving in excess of 100 km/h was fulfilled. The smallest change in the accelerations of the research objects was recorded for the highway cycle (Figure 6).

Table 3. Parameters required during RDE test drives.

No.	Parameters	Units	Value Vehicle A	Value Vehicle B	Value Vehicle C
1.	Total distance	km (-)	82.6	70.41	80.56
2.	Total time	min. (90–120)	117	113	106
3.	Cold-start duration	min. (5)	5	5	5
4.	Urban distance	km (>16)	32.4	29.41	35.31
5.	Rural distance	km (>16)	24.49	18.71	22.32
6.	Highway distance	km (>16)	25.71	22.28	22.93
7.	Share of urban distance	% (29–44)	39.23	41.77	43.83
8.	Share of rural distance	% (23–43)	29.64	26.58	27.71
9.	Share of highway distance	% (23–43)	31.13	31.65	28.47
10.	Average speed in the urban cycle	km/h (15–40)	23.40	20.65	27.61
11.	Speed in the highway cycle exceeding 145 km/h	km/h (<3%)	0	0	0
12.	Speed in the highway cycle exceeding 100 km/h	Min. (>5)	9.70	8.88	10.88
13.	Stationary time in the urban cycle	5% (6–30)	28.57	29.67	25.65
14.	Start and end points, absolute elevation difference	M (<100 m)	3.4	19	7.6
15.	Accumulated positive elevation increment	m/100 km (<1200 m/100 km)	454.36	581.12	623.90

When investigating vehicles utilizing hybrid powertrains or range extenders, it is justified to determine the extent of use of the electric equipment during the drive. In order to determine this, it is necessary to perform an analysis of the engine usable parameters. The engine speed is fundamental in this case. For the analysis, the authors adopted a 0–1 system, where 1 denoted the use of the combustion engine only, and 0 the electric motor only. The analyses did not include the mode of the parallel operation of the engine and electric motor. In the entire RDE test, the level of hybridization for vehicle A was 54%, and for vehicle C, it was 29%. Therefore, the first of the analyzed vehicles used the electric motor to a greater extent. It is noteworthy that vehicle C is classified as electric, and the combustion engine exclusively serves the purpose of an auxiliary power source (battery charging). During the test drive in the highway cycle, vehicle A operated several times using the electric motor exclusively (Figures 7 and 8). This phenomenon is characteristic of hybrid vehicles, as the highway cycle is characterized by an increased energy demand that must be supplied mainly by the combustion engine. The phenomenon of braking energy recuperation does not occur often either, which is tantamount to the fact that, during highway driving, the batteries are hardly ever charged. In the case of vehicle C, the use of the electric motor was not recorded. The vehicle fitted with the conventional powertrain was not taken into account, as it was not fitted with an alternative powertrain.



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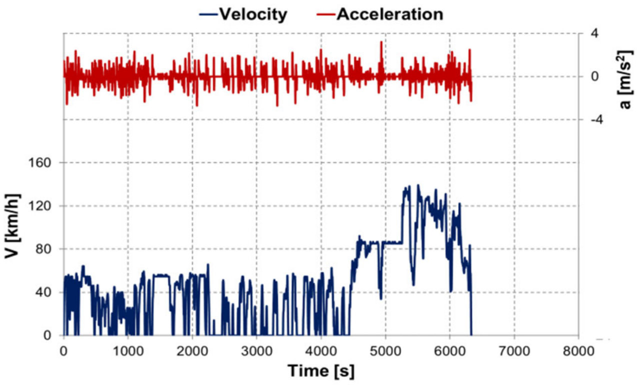

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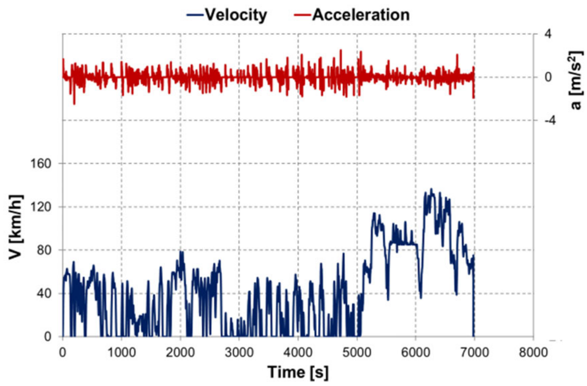

(**c**)

Figure 6. Tracings of speeds and accelerations recorded during the test drives: (**a**) vehicle A; (**b**) vehicle B; (**c**) vehicle C.

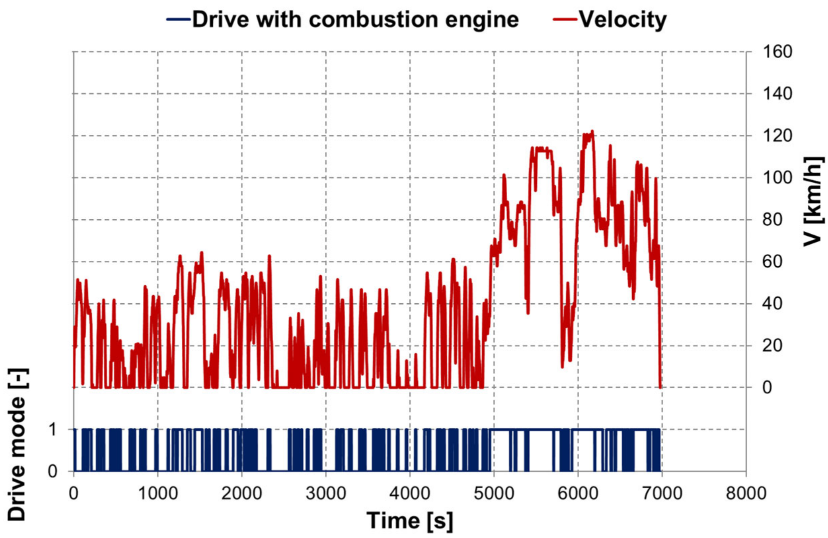

Figure 7. Operating time share of the combustion engine and electric motor during the test drive (vehicle A).

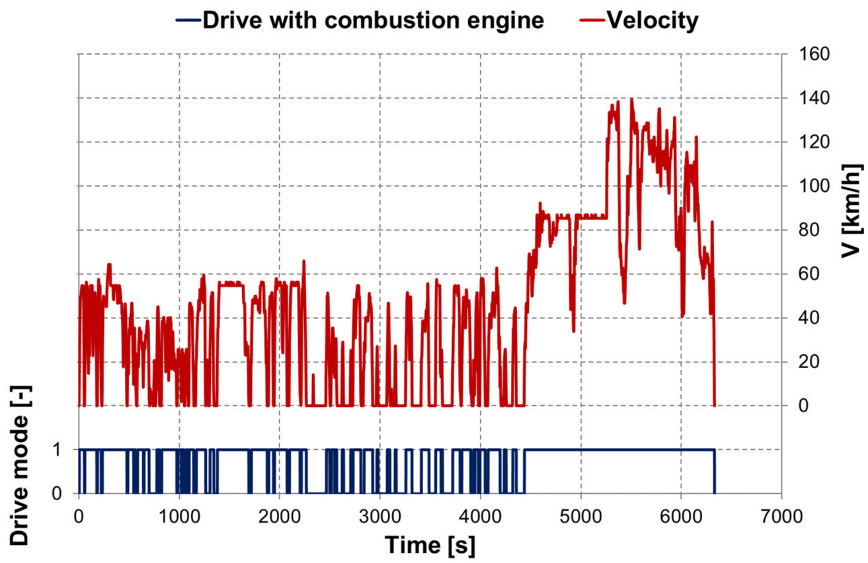

Figure 8. Operating time share of the combustion engine and electric motor during the test drive (vehicle C).

In order to determine the operating conditions of the combustion engines, the authors used the characteristics of the operating time share in the engine speed and load intervals. When analyzing the obtained data, the authors observed that, approx. 50% of the time, vehicle A used the electric motor. The combustion engine operated in the engine speed range S (1600; 2800>, at the load E (40; 60%>. Given the fact that its main source of power was the combustion engine, the characteristics of vehicle B were more elaborate compared to vehicle A. Approx. 20% of the time, the engine operated in the speed range (400; 800>, at the load (0; 20%>. The values of (1200; 1600> can be assumed as the main engine speed intervals, which directly result from the characteristics of diesel combustion engines (a lower speed range compared to the spark ignition engine). In the case of the last vehicle, where the combustion engine served the purpose of a range extender, two main ranges of loads needed to be distinguished. The first one, relating to the operation in the electric mode (approx. 20%), indicated that the vehicle had surplus energy and did not require the combustion engine to activate in order to extend the vehicle range. The second range was the exclusive operation of the electric motor, 30% of which was the operation at the load of (80; 100%>. For electric vehicles fitted with range extenders, this situation should not occur, as the energy surplus in the batteries should be sufficient to meet the demand of the powertrain (Figure 9).

Aside from the conditions of the operation of the powertrains during the RDE tests, the authors also performed an analysis of the exhaust emission intensity and determined the road emissions and fuel mileages of the vehicles. The highest value of the emissions of CO was recorded for vehicle C (Figure 10), occurring for the maximum engine speed (3600; 4800> at the load (40; 100%>. This was mainly attributed to the operation of the engine at its maximum load in the rural and highway cycles. The lowest emission intensity was recorded for vehicle B. This was attributed to the type of engine (diesel) and the operation of the oxidation catalyst (DOC). A different situation was observed for the emission intensity of NO_X (Figure 11). Its highest values occurred for vehicle B throughout the entire test. A trend was observed that, as the engine speed and load grew, the values of this emission followed suit. Vehicles A and C were equipped with spark ignition combustion engines fitted with three-way catalysts (TWCs) with a rate of NO_x conversion of 95%, which is clearly higher compared to the SCR systems used in diesel engines (vehicle B was equipped with this system). The EGR system applied here, the primary task of which is to feed the exhaust gas to the combustion chamber in order to reduce the global combustion temperature responsible for the NO_x formation, did not help either [33]. Vehicles A and B were characterized by a similar intensity of the said exhaust component. This was particularly attributed to the exhaust gas aftertreatment in both cases. The emission intensity of CO_2 was similar—its highest values were recorded for vehicle B throughout the entire test (Figure 12). Two parameters influenced this situation. The first was the engine displacement, which was greater compared to vehicles A and C. Another key parameter was the fact that vehicles A and C could recuperate the vehicle's braking energy, thereby assisting the electric part of the powertrain and reducing the energy consumption, which naturally thwarts the CO_2 emission intensity (directly proportional to the fuel consumption).

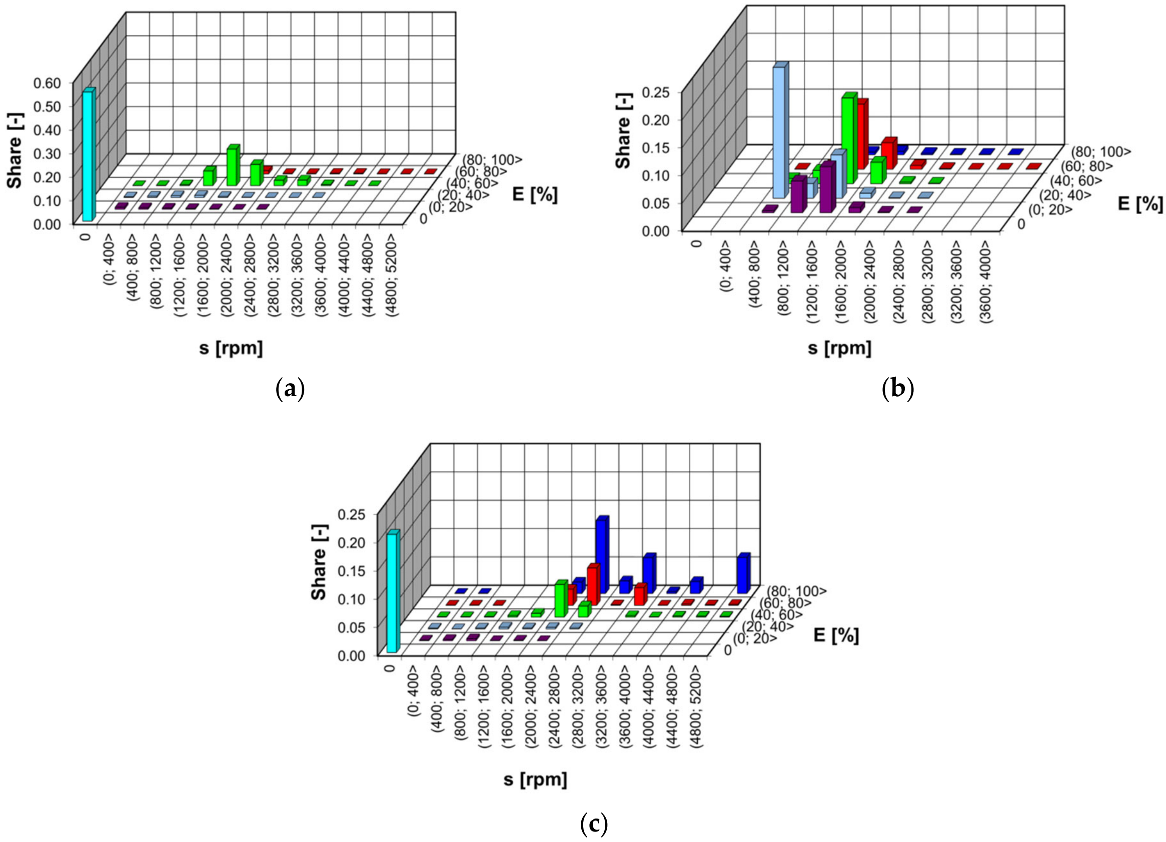

Figure 9. Operating time-share characteristics depending on the combustion engine speed and load: (**a**) vehicle A; (**b**) vehicle B; (**c**) vehicle C.

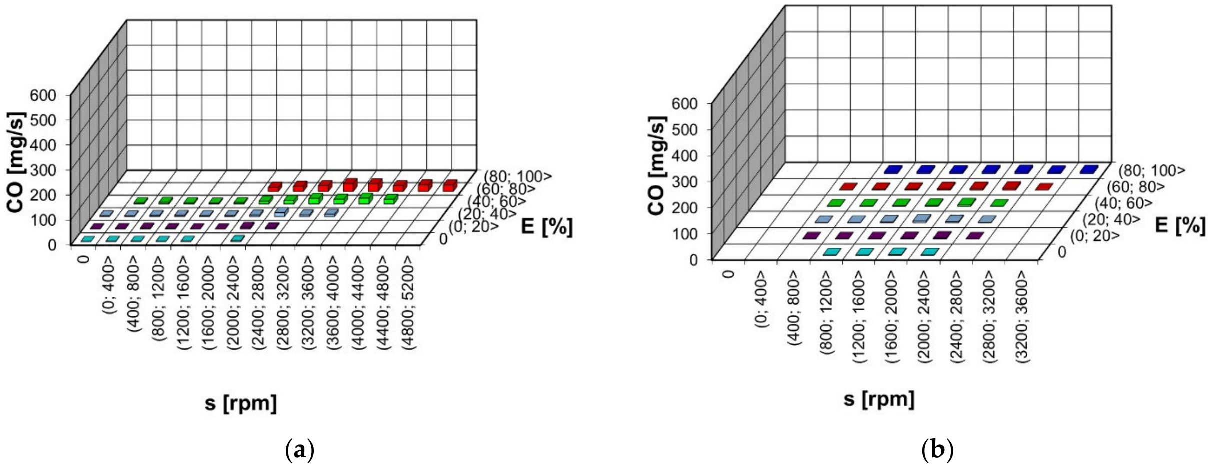

Figure 10. *Cont.*

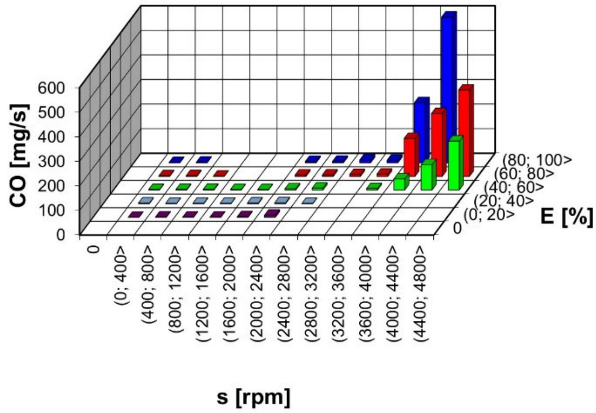

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Figure 10. Emission of CO generated in the RDE cycle: (**a**) vehicle A; (**b**) vehicle B; (**c**) vehicle C.

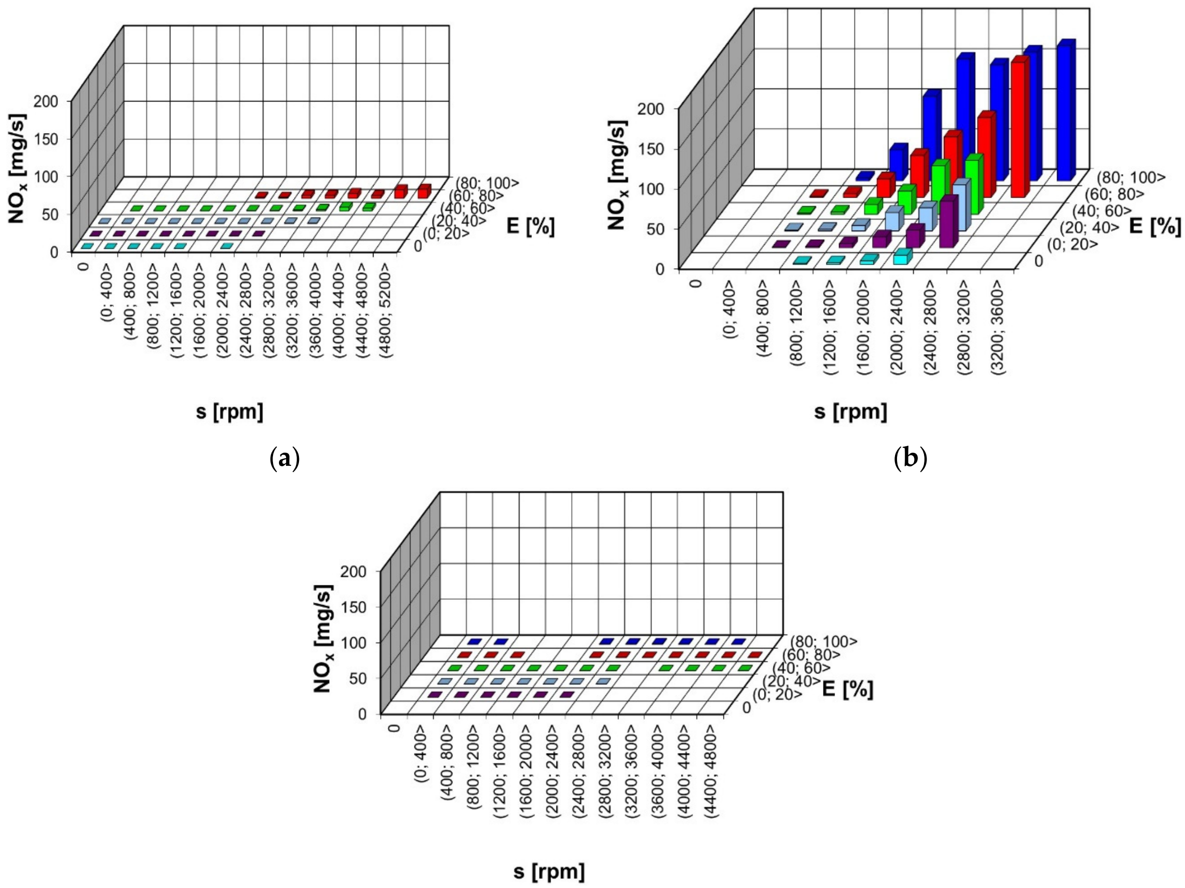
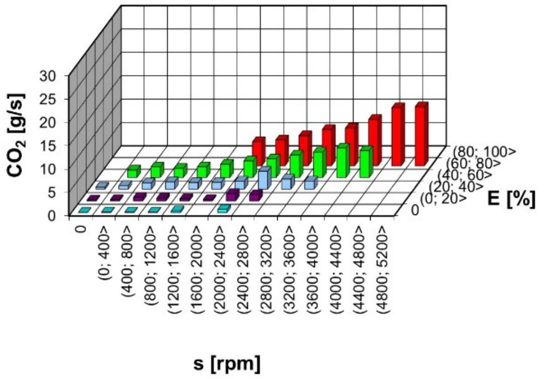


Figure 11. Emissions of NO_x recorded in the RDE cycle: (**a**) vehicle A; (**b**) vehicle B; (**c**) vehicle C.

In order to better depict the influence of the type of powertrain on the emissions of CO_2 (fuel consumption), the authors determined the road emissions thereof (Table 4). It was observed that, from all the tested vehicles, vehicle A generated the lowest values of this component in all parts of the RDE test. The accumulated results from the entire test were as follows: a total of 57% less compared to vehicle B, and 41.5% less compared to vehicle C.



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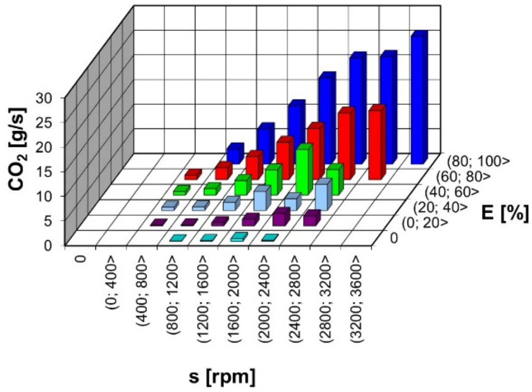

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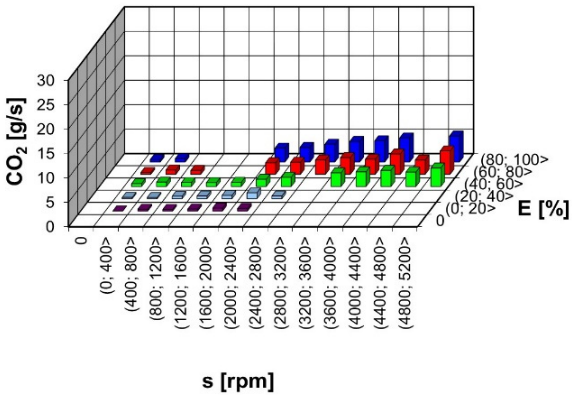


(**c**)

Figure 12. Emissions of CO_2 recorded in the RDE cycle: (**a**) vehicle A; (**b**) vehicle B; (**c**) vehicle C.

Table 4. Parameters obtained during RDE test drives.

	Vehicle A	Vehicle B	Vehicle C
Total	123.01 g/km	194.72 g/km	174.09 g/km
Urban portion	118.17 g/km	254.77 g/km	187.37 g/km
Rural portion	116.52 g/km	134.63 g/km	174.95 g/km
Highway portion	134.86 g/km	176.27 g/km	152.81 g/km

The final stage of the analysis of the results obtained in the RDE test was the assessment of the fuel consumption by individual vehicles. The authors applied the carbon balance method, in which the road emissions of CO, THC and CO_2 of a vehicle and fuel density (ρ) are used to determine the fuel consumption. The carbon balance method is considered to be one of the most accurate ways of determining mileage fuel consumption. The method is defined by the following formula [5]:

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

The average values of the fuel consumption are shown in Figure 13, along with the average consumption on the individual road portions. Based on the obtained results, one can observe that all three research objects had the lowest average fuel consumption in the rural portion. In each part of the test, vehicle A (HEV) had the lowest fuel consumption. Similar conclusions were drawn by the authors of [32], who compared an HEV vehicle and a conventional gasoline vehicle. A comparison of the fuel consumption of conventional and hybrid vehicles was also performed by the authors of [34]. Their analysis showed a significant fuel economy of the vehicle fitted with the alternative powertrain. The investigations described in [35,36] showed that HEV vehicles were characterized by a 23–49% lower fuel consumption compared to the combustion engine vehicles. It is noteworthy that, in the discussed investigations, the lowest fuel consumption of the HEV vehicles occurred in the urban cycle of the performed test.

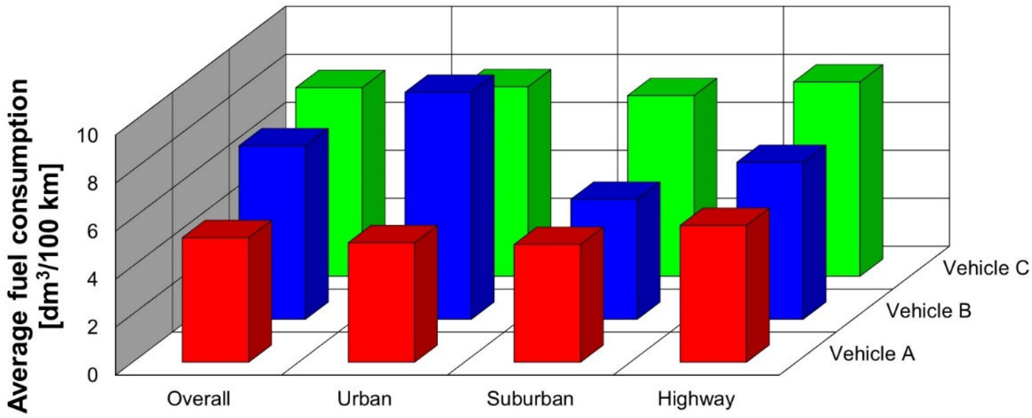
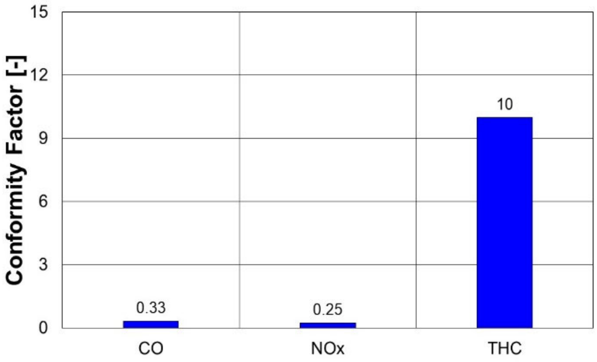
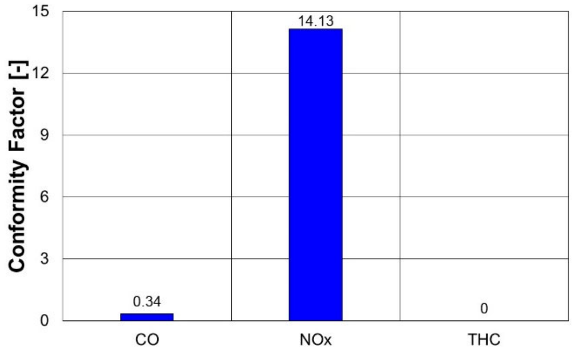


Figure 13. Average fuel mileage from the RDE test route.

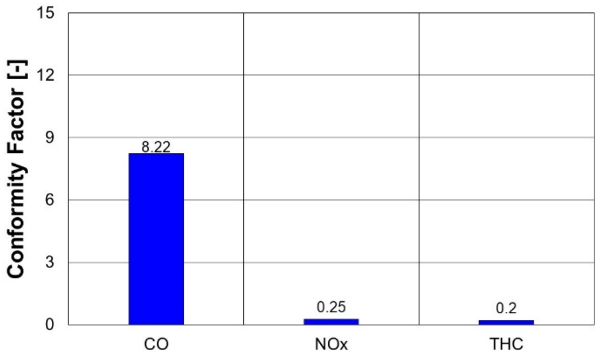
The end stage of the analysis of the results was the comparison of the RDE road emission with the values set forth in the Euro 6c standard. The authors decided to determine the conformity factor (CF), being the ratio of the total emissions from the RDE test and the admissible values specified in the standard. The CF factor for CO was 0.33 for vehicle A, 0.34 for vehicle B and 8.22 for vehicle C. When analyzing the obtained conformity factor for NO_x, we obtained the following results: vehicle A: 0.25; vehicle B: 14.13; vehicle C: 0.25. The final pollutant taken into account was THC. Vehicle A reached a value of 10, and vehicle C a value of 0.2. Vehicle B was not analyzed given its overall low THC emissions, which are characteristic of vehicles fitted with diesel engines. Given that, according to the standard, the CF for CO and NO_x should not exceed 2.1, this condition was not fulfilled for vehicle C in terms of CO, nor for vehicle B in terms of NO_x (Figure 14). The CF factor was also calculated by the authors of [37], where RDE tests of a hybrid vehicle were described. In this case, the CF condition (also for the Euro 6c standard) remained unfulfilled for CO and NO_x (the values were 2.9 and 2.5, respectively). The above-described conformity factors were also calculated for the RDE tests of a conventional vehicle and a hybrid vehicle, as described in [38]. The vehicles described in the paper were Euro 5-compliant. The alternative powertrain vehicle was characterized by lower CF values. Yet, as the authors proved, the emissions of all the investigated exhaust components were low. The emission limit condition was not fulfilled by the vehicle fitted with the combustion engine only in terms of carbon monoxide. Its CF was in excess of 2.



(**a**)



(**b**)



(**c**)

Figure 14. Conformity factors of the objects under investigation: (**a**) vehicle A; (**b**) vehicle B; (**c**) vehicle C.

4. Conclusions

Based on the investigations discussed in the paper, the authors confirmed the correct selection of the test route in the Poznan agglomeration. The route was selected according to the RDE guidelines. The realization of the test route compliant with the requirements of the latest emission standards is currently the most troublesome aspect in this type of research. The investigated research objects were hybridized at the level of 54% for vehicle A and 29% for vehicle C. As has been mentioned, one should note that vehicle C was equipped with a combustion engine serving the purpose of a range extender; hence, its operating range was significantly different compared to vehicle A, whose combustion engine, aside from its battery-charging purpose, can also serve as a direct source of torque. Vehicle A, a full hybrid, was characterized by the highest average fuel mileage on the individual RDE test portions. Vehicle C (combustion engine serves as a range extender in this case) had the best results in the rural and highway cycles. Vehicle B (fitted with a conventional powertrain), in the rural and highway cycles, had similar results to vehicle A. Out of all three research objects, the best results, in terms of the exhaust emissions, were obtained by vehicle A. Vehicle A was an HEV. Vehicle B was characterized by the highest emissions of CO_2 and NOx. The obtained results for vehicle B were influenced by the fact that it was equipped with a conventional powertrain fitted with a diesel engine. The absence of the three-way catalyst had an adverse effect on the vehicle exhaust emissions.

Author Contributions: Conceptualization, A.Z., P.F., A.J. and M.B.; methodology, A.Z., P.F., A.J., M.B. and S.K.; software, A.Z., P.F. and S.K.; formal analysis, A.Z., P.F. and A.J.; writing, M.B., A.J. and A.Z., writing—review and editing, A.Z. and A.J.; visualization, M.B. and S.K.; supervision, A.Z. and P.F.; project administration, A.Z.; funding acquisition, P.F. All authors have read and agreed to the published version of the manuscript.

Funding: The study presented in this article was performed within the statutory research (Contract No. 0415/SBAD/0326).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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