

ANALYSIS OF THE OPERATING COSTS OF PASSENGER CARS DECLARED BY VEHICLES' MANUFACTURERS AND OBTAINED BY USERS

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Resume

Every year, there are more and more cars on the roads that cause pollution. To reduce it, conventional vehicles have started to be replaced by electric and hybrid vehicles. Therefore, the average fuel/energy consumption of electric, hybrid, spark ignition and self-ignition vehicles over a test distance of 100 km was investigated. The test results were then compared to the manufacturer's data and the average difference between the manufacturer's data and the test data is shown. The largest average difference in fuel consumption between the manufacturer's data and the test data was observed for hybrid vehicles (over 230 %) and the smallest for electric vehicles (less than 10 %) and spark ignition vehicles (almost 18 %). Considering costs, the largest difference between manufacturer's data and test data is observed, as in the previous case, in electric vehicles (0.25 €) and the largest in hybrid vehicles (almost 6 € per 100 kilometers driven).

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One of the basic elements of human life is the ability to move. The constant development of technology has made it possible to cover short and long distances in a short time. The invention of the diesel engine contributed to the development of many areas of life, from daily commuting to industry and transcontinental transportation. Constant ocean travel, road traffic and road transport have left a carbon footprint for many years, which has exacerbated the problem of global warming. From the moment of the industrial revolution to the end of the 20th century, nobody thought about environmental protection or emission standards. The first passenger cars were not subject to any emissions restrictions. The emission problems were of interest to many researchers, for example [1-9]. For several years, an important element in those works on car concerns has been the project of replacing vehicles with an internal combustion engine with vehicles with an alternative drive. Shrinking oil resources, increasing environmental pollution and increasingly stringent exhaust emission standards gave rise to the idea of an electric and hybrid vehicle. Vehicles with alternative propulsion are to replace the conventional vehicles in order to contribute to the reduction of exhaust emissions. With the beginning of the new millennium, the stage of presenting ideas for modern electric and hybrid vehicles began and the development of electromobility in the world began. For this reason, the benefits for the user have been analyzed.

In order to comprehensively present what a motor vehicle is, one should refer to its history and cite the names that initiated a new stage in transport [10]. A motor vehicle is a complex device made of many interacting elements [11-13] and each of them plays an important role [14-16].

Internal combustion vehicles will be completely removed from the road by alternative propulsion vehicles over time [17]. Work on electric and hybrid vehicles began several dozen years ago [18-19].

One of the important aspects of the transition to alternative fuels is the environmental impact [20-21]. There are still newer limits and emission standards that contribute to the development of electric and hybrid vehicles. More and more such vehicles appear on the Polish and European market [22]. Research and statistical organizations are emerging on development of the electric and hybrid vehicle market [23]. Hybrid and electric vehicles have also been the subject of many research papers, for example [24-26].

Electricity is an indispensable component of hybrid and electric vehicles. For BEVs, it is the only fuel needed to drive a vehicle. Electricity is produced in Poland from fossil fuels and RES (Renewable Energy Sources) [27].

In 2020, the share of renewable energy in Poland was 17 % (Figure 1), the rest being fossil fuels. Poland is at the forefront of statistics in terms of the consumption of fossil fuels for the production of electricity. One of

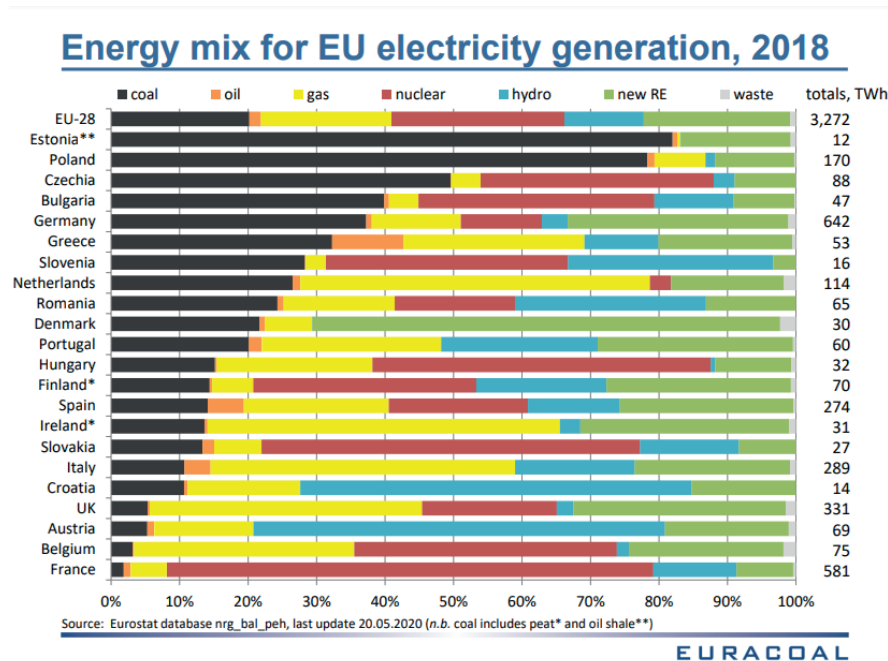


Figure 1 The share of individual sources in electricity production in European countries [28]

Table 1 Comparison of the findings for research measurements to the WLTP procedure recommendations [31]

	WLTP Procedure Values	Values adopted for the test
Distance covered during the test [km]	23.25	100
Average speed [km/h]	4.5	40-50
Maximum speed [km/h]	131	90
Ambient temperature [°C]	23	1-3

the least consuming fossil fuels for energy production countries was Sweden, where the share of fossil fuels in 2020 was only 2 % [27].

A hybrid vehicle is not entirely dependent on electricity, unlike an electric vehicle, as it can only be powered by an internal combustion engine. Charging batteries in electric vehicles can be done at home, thanks to private chargers, or at a charging station. Depending on the current used, two types of chargers can be distinguished. The AC chargers using alternating current with a voltage of 230 – 400 V. Their charging power ranges from 2 to 22 kW. The DC chargers operate on direct current with a voltage of 400-800 V and charge with a power of 50-350 kW [29]. At the end of 2020, there were 1,364 charging stations in Poland. 452 (33 %) are fast charging stations and 912 (67 %) are the AC stations using alternating current [30].

2 Materials and methods

The question of the ecological, economic and utility aspect of a vehicle is the future reference. In each of the above aspects, fuel or energy consumption contributes to improving their efficiency. The selection is made according to the type fuel used to run a vehicle's engine. A study was made of the average fuel/energy

consumption of electric, hybrid and spark and self-ignition vehicles over a test distance of 100 km. The tests were carried out on four labels, i.e. electric, hybrid, spark ignition and self-ignition. Three vehicles were selected for each group and three measurements were made on them to differentiate between the average fuel or energy consumption.

In order to obtain meaningful results, it was determined that the objectives had been previously met for the WLTP procedures. The Worldwide Harmonized Light Vehicle Test Procedure (WLTP) is a test for testing new production vehicles for emissions and fuel consumption. It is important that this procedure is technical, takes into account large speed fluctuations and allows obtaining more accurate data close to the real ones [31]. The test is conducted according to the established principles of methods based on the WLTP procedures to ensure the results of the consumption analysis and their provider of assurance and reliability services.

3 Assumptions for measurements

Table 1 presents selected values of the WLTP procedure and the values adopted for the tests. The selection of values for measurements was made taking

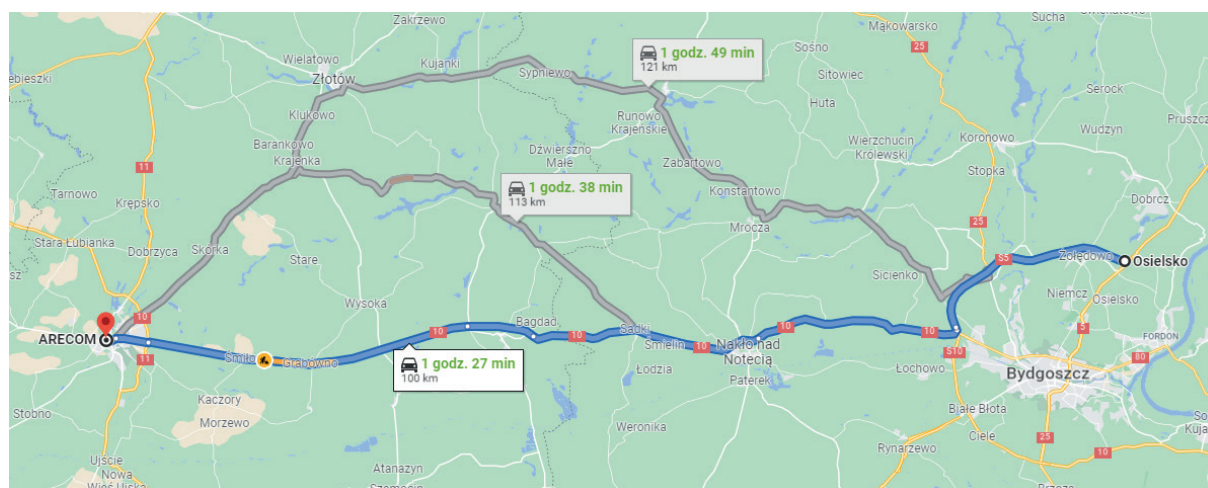


Figure 2 Test section [32]

into account the possibilities and availability of research resources.

The tests were carried out in early winter conditions, which excluded the possibility of setting the temperature higher than 4°C, the speed could not exceed a certain maximum value for legal reasons, because the vehicles travelled in public traffic, where the maximum permissible speed outside the city is 90 km/h.

4 The course of measurements

Before starting the measurements, the vehicle was refuelled (for conventional and hybrid vehicles) or charged (for electric and hybrid vehicles) to full and then waited for about 3 h without starting. The engine was then idled for 2 min before starting. After the designated time, the measurement was started. The car was driven on a flat road along the same 100 km route (from Pila to Osiek, Figure 2) in the city and outside the city by one driver. In order to ensure equal traffic volume conditions between the measurements, the measurements were made on Sunday mornings with low traffic intensity. The interior heating and mandatory lighting were turned on in the vehicle; other additional vehicle equipment was turned off. Fuel consumption was measured using a GPI-EX electronic fuel flow meter and the amount of energy consumed was measured based on the state of charge of the batteries. Weather conditions during the measurements were similar for all the vehicles: no precipitation, no wind, ambient temperature 1-3 °C. There were no traffic disturbances during the measurements and there were no repair or clean-up activities on the road that could affect the speed profile. The same test section was driven 3 times and the arithmetic mean of the fuel/energy consumed was drawn. In the next step the costs for the above difference were determined based on the prevailing fuel prices (PB95 = 1.18 €/l; ON = 1.16 €/l) and energy 0.16 €/kWh).

5 Research object

The choice of a vehicle for technical and operational analysis is a multi-element decision, based on an analysis of the market of vehicles available in Poland and Europe and availability. Taking into account the above factors, certain criteria can be defined in order to perform the correct and reliable tests. The selection of vehicles for technical and operational analysis was made using the following criteria:

- Vehicle manufactured after 2015 - the vehicle selection has been limited to cars from the 2016-2020 period, as it limits the measurement error caused by vehicle wear, which may have hidden defects and unfitness.
- The vehicle is technically fully operational - the vehicle should have up-to-date technical inspections so that during the measurement activities it does not endanger the life and health of the examiner and the test results are not disturbed by unexpected damage to the vehicle.

Tables 2 and 3 show the technical and operational data of the vehicles accepted for testing.

6 Results

6.1 Analysis of the test results of selected electric vehicles

Electric vehicles were analyzed for the first time. As it results from the measurements (Table 4) and the calculation of the average energy consumption based on three measurements, the energy consumption declared by the manufacturer in all the analyzed vehicles differs from the actual state. The data discrepancy in this case could have been influenced by the average vehicle speed. According to the analysis of the results, the average energy consumption is higher than declared by the manufacturer, 6-16 % depending on the vehicle, which

Table 2 Ecological, economic and utility parameters of electric and hybrid vehicles [33]

Vehicle Name	Electric Vehicles			Hybrid Vehicles		
	Nissan Leaf II	Bmw i3	Kia e-Niro	Skoda Superb IV	Bmw X5 45e	Volkswagen Passat GTE
Basic Parameters						
Maximum Power	110 kW	125 kW	100 kW	160 kW	290 kW	160 kW
Range	270 km	297 km	289 km	61.9 km	77 km	60 km
Co2 Emissions	0 g/km	0 g/km	0 g/km	38 g/km	36 g/km	27 g/km
Year of Production	2017	2018	2020	2019	2019	2019
Mileage	39906 km	40134 km	33145 km	53402 km	27025 km	24518 km
Electric Engine						
Engine type	Synchronous	Synchronous	Synchronous	Synchronous	Synchronous	Synchronous
Maximum power	110 kW	125 kW	100 kW	85 kW	83 kW	85 kW
Maximum torque	320 Nm	250 Nm	395 Nm	330 Nm	265 Nm	330 Nm
Charge Time - According to the Manufacturer						
Household socket 2.3 kW	21 h	18 h	18 h	5 h	11:48 h	5 h
11 kW wallbox	7:30. h	4 h	7 h	3:30 h	6:48 h	3:30 h
DC 50 kW charging station	1 h	0:45 h	0:57 h	No DC jack	No DC jack	No DC jack
Battery						
Capacity	40 kWh	42.2 kWh	42 kWh	13 kWh	24 kWh	13 kWh
Engine						
Engine type	not applicable	not applicable	not applicable	Spark ignition	Spark ignition	Spark ignition
Maximum power	not applicable	not applicable	not applicable	110 kW	210 kW	115 kW
Maximum torque	not applicable	not applicable	not applicable	250 Nm	450 Nm	250 Nm
Performance						
Maximum speed	144 km/h	150 km/h	155 km/h	224 km/h	235 km/h	222 km/h
Acceleration 0 - 100 km/h	7.9 s	7.3 s	9.8 s	7.7 s	5.6 s	7.4 s
Mixed cycle energy consumption	16.9 kWh/100 km	15.8 kWh/100 km	15.3 kWh/100 km	17.3 kWh/100 km	25.7 kWh/100 km	15.7 kWh/100 km
Fuel consumption	-	-	-	1.9 l/100 km	1.6 l/100 km	1.2 l/100 km
Range	270 km	297 km	289 km	61.9 km	77 km	60 km
Dimensions						
Length	4490 mm	4011 mm	4375 mm	4869 mm	4922 mm	4775 mm
Width	1788 mm	1775 mm	1805 mm	1864 mm	2004 mm	1832 mm
Height	1530 mm	1577 mm	1560 mm	1468 mm	1745 mm	1483 mm
Wheelbase	2700 mm	2570 mm	2700 mm	2841 mm	2975 mm	2783 mm
Front / rear track	1540/1555 mm	1571/1576 mm	1576/1585 mm	1584/1570 mm	1656/1686 mm	1578/1586 mm
Luggage compartment capacity	385 l	260 l	451 l	485 l	500 l	402 l
Mass						
Minimum empty weight	1545 kg	1345 kg	1592 kg	1730 kg	2510 kg	1729 kg
Maximum total weight	1995 kg	1710 kg	2080 kg	2251 kg	3150 kg	2230kg

Table 3 Ecological, economic and operational parameters of vehicles with spark-ignition and self-ignition engines [34]

Vehicle Name	Vehicles with Spark-Ignition Engines			Compression-Ignition Vehicles		
	BMW X4	Skoda Rapid II	Opel Corsa E	BMW 5 F10	Audi A4 B9	Renault Megane IV GrandTour
Basic Parameters						
Maximum power [kW]	135	80	55	140	110	66
Range	890 km	1196 km	776 km	1400 km	1381 km	1270 km
Co ₂ emissions	168 g/km	106 g/km	132 g/km	132 g/km	111 g/km	195 g/km
Year of production	2019	2018	2017	2016	2017	2016
Mileage	69952 km	65478 km	757875 km	61578 km	72547 km	51265 km
Engine						
Engine type	Spark ignition	Spark ignition	Spark ignition	Self-ignition	Self-ignition	Self-ignition
Maximum power	135 kW	80 kW	55 kW	140 kW	110 kW	66 kW
Maximum torque	290 Nm	200 Nm	130 Nm	400 Nm	340 Nm	220 Nm
Performance						
Maximum speed	215 km/h	200 km/h	167 km/h	229 km/h	221 km/h	174 km/h
Acceleration 0 - 100 km/h	8.3 s	9.8 s	14 s	8.1 s	8.9 s	14.1 s
Fuel consumption	7.3 l/100 km	4.6 l/100 km	5.8 l/100 km	5.0 l/100 km	4.2 l/100 km	3.7 l/100 km
Dimensions						
Length	4752 mm	4483 mm	4021 mm	4907 mm	4726 mm	4626 mm
Width	1918 mm	1706 mm	1746 mm	1860 mm	1842 mm	1814 mm
Height	1621 mm	1461 mm	1481 mm	1462 mm	1427 mm	1457 mm
Wheelbase	2864 mm	2602 mm	2510 mm	2968 mm	2820 mm	2717 mm
Front / rear track	1620/1666 mm	1463/1500 mm	1472/1472 mm	1600/1626 mm	1572/1555 mm	1591/1586 mm
Luggage compartment capacity	525 l	550 l	285 l	560 l	480 l	580 l
Mass						
Minimum empty weight	1795 kg	1170 kg	1081 kg	1800 kg	1505 kg	1312 kg
Maximum total weight	2400 kg	1630 kg	1595	2375 kg	2030 kg	1911

is € 0.20-040 respectively. Carrying out tests in winter, at a temperature of 1-3 °C, affects the battery and its discharge rate.

6.2 Analysis of the test results of selected hybrid vehicles

Hybrid vehicles are another of the analyzed vehicles. Based on the analysis of the test results presented in Table 5, it was found that the change in values of individual results, as in the case of electric vehicles, could have been influenced by the average speed during the measurements. The analysis showed significant differences between the fuel and energy consumption stated by the manufacturer and the test result, exceeding 189 %. This is due to the fact that the tests were carried out in the mixed driving mode, so the tested vehicle was forced to frequent momentary changes in speed, which forced the internal combustion engine to start and thus the use of conventional fuel. As the measurements show, this resulted in an increase in fuel consumption. This result is highly unsatisfactory due to the significant

differences in fuel consumption. Taking into account the costs of electricity consumption, one will cover 100 km with the cheapest Volkswagen Passat GTE and Skoda Superb IV and the most expensive BMW X5 45e. The difference between the energy consumption value declared by the manufacturer and the measured value is small, about 20 %.

6.3 Analysis of the test results of selected vehicles with a spark ignition engine

A spark-ignition car was analyzed successively. After analyzing the data in Table 6, the average fuel consumption may amount to 25-30 % - which corresponds to 1.6-2.1 €, higher than declared by the manufacturer. The exception is the Opel Corsa, where the manufacturer's results are consistent with the data obtained during the measurements. A slight change in the average speed has little effect on the amount of fuel consumed, with the exception of the Skoda Rapid. The reason for the increase in fuel consumption was the low temperature during the tests.

Table 4 Electric vehicle test results [35-37]

Car data / model	Nissan Leaf 2			BMW i3			Kia e-Niro		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Distance [km]	100	100	100	100	100	100	100	100	100
Average speed [km/h]	43	46	44	45	41	43	44	46	43
Temperature [°C]	1	2	1	2	3	2	3	3	3
Energy consumption per 100 km [kWh] / value [€]	17.7/ 2.83	18.7/ 2.99	17.9/ 2.86	17.8/ 2.85	16/ 2.56	16.5/ 2.64	17.6/ 2.82	18.1/ 2.90	17.6/ 2.82
Average energy consumption per 100 km [kWh] / value [€]	18.1/ 2.89			16.8/ 2.68			17.8/2.85		
Manufacturer declared consumption [kWh] / value [€]	16.9/2.70			15.8/2.53			15.3/2.45		
Difference in energy consumption [%] / value [€]	7.1/0.19			6.3/0.15			16.3/0.40		
Average [%] / value [€]				9.9/0.25					

Table 5 Test results for hybrid vehicles [37-39]

Car data / model	BMW X5 45e			Skoda Superb IV			Volkswagen Passat GTE		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Distance [km]	100	100	100	100	100	100	100.1	100	100.1
Average speed [km/h]	47	43	44	45	46	45	49	47	48
Temperature [°C]	3	3	3	2	2	2	2	2	1
Fuel consumption per 100 km [l] / value [€]	7.5/ 8.85	7.2/ 8.50	7.4/ 8.73	5.5/ 6.49	5.6/ 6.61	5.5/ 6.49	6.5/ 7.67	6.5/ 7.67	6.5/ 7.67
Average fuel consumption per 100 km [l] / value [€]	7.4/ 8.69			5.5/ 6.53			6.5/ 7.67		
Fuel consumption declared by the manufacturer [l] / value [€]	2.1/ 2.48			1.9/ 2.24			2.1/ 2.48		
Fuel consumption difference [%] / value [€]	252.4/6.21			189.5/ 4.29			209.5/ 5.19		
Average [%] / value [€]				234.1/ 5.23					
Energy consumption per 100 km [kWh] / value [€]	36.92/ 5.91	35.14/ 5.62	37.14/ 5.94	26.00/ 4.16	25.15/ 4.02	22.81/ 3.65	21.67/ 3.47	22.80/ 3.65	24.07/ 3.85
Average energy consumption per 100 km [kWh] / value [€]	36.40/5.82			24.65/3.94			22.85/3.66		
Manufacturer declared consumption [kWh] / value [€]	29.10/4.66			21.31/3.41			20.31/3.23		
Difference in energy consumption [%] / value [€]	25.1/1.16			20.4/0.53			12.51/0.43		
Average [%] / value [€]				19.34/0.71					

Table 6 Test results for vehicles with a positive-ignition engine [37-38, 40]

Car data / model	BMW X4			Skoda Rapid II			Opel Corsa E		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Distance [km]	100	100	100	100	100	100	100	100	100
Average speed [km/h]	46	48	46	42	45	43	47	47	47
Temperature [°C]	1	1	1	2	2	2	2	3	2
Fuel consumption per 100 km [l] / value [€]	9.1/ 10.74	9.1/ 10.74	10.74/ 12.59	6.96/ 6.4	7.55/ 7.5	6.49/ 6.7	7.35/ 7.8	6.84/ 6.8	5.8/ 6.84
Average fuel consumption per 100 km [l] / value [€]	9.1/ 10.74			5.9/ 7.00			5.8/ 6.84		
Fuel consumption declared by the manufacturer [l] / value [€]	7.3/ 8.61			4.6/ 5.43			5.8/ 6.84		
Fuel consumption difference [%] / value [€]	24.7/ 2.1			28.3/ 1.57			0/ 0		
Average [%] / value [€]				17.7/ 1.22					

Table 7 The results of tests of vehicles with a compression-ignition engine [37, 41-42]

Car data / model	BMW 5 F10			Audi A4 B9			Renault Megane IV GrandTour		
Data	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Distance [km]	100	100	100	100	100	100	100	100	100
Average speed [km/h]	46	45	46	49	47	49	44	44	42
Temperature [°C]	4	4	4	2	2	2	3	3	3
Fuel consumption per 100 km [l] / value [€]	7.3/ 8.47	7.3/ 8.47	7.3/ 8.47	6.3/ 7.31	6.3/ 7.31	6.4/ 7.42	6.2/ 7.19	6.2/ 7.19	6.1/ 7.08
Average fuel consumption per 100 km [l] / value [€]	7.3/ 8.47			6.3/ 7.35			6.2/ 7.14		
Fuel consumption declared by the manufacturer [l] / value [€]	5/ 5.80			4.2/ 4.87			3.7/ 4.29		
Fuel consumption difference [%] / value [€]	46/ 2.67			50/ 2.48			67.6/ 2.85		
Average [%] / value [€]				54.2/ 2.67					

6.4 Analysis of the test results of selected diesel vehicles

Self-ignition cars are the last of the studied groups of vehicles. The data in Table 7 shows that during the measurements the vehicles maintained an average speed of 42-49 km/h and their fuel consumption was higher than the manufacturer's assurances by 46-65 %. This is due to the conditions under which the test was carried out and also due to the temperature, the fuel demand increased, which in turn increased its consumption. These results are below expectations because the Renault Megane IV GrandTour, despite the low engine power, does not differ much from the other tested diesel vehicles.

7 Discussion

In order to accurately illustrate the differences between the actual fuel consumption and declared by the manufacturer, the percentage difference between the obtained results was compared. As shown by the data in the Table 8, the discrepancies are huge and surprising. Despite the opinion that hybrid vehicles, apart from electric vehicles, are economical, the research results showed that the difference in fuel consumption between the measured value and the value declared by the manufacturer is huge and amounts to 234.1 %. The fuel consumption of the diesel vehicles is 54.2 % higher.

Energy consumption in electric vehicles was on average higher by 9.9 %, which in the case of low temperatures is a satisfactory result. Taking into account the costs difference between the declared and measured fuel consumption by the tested vehicles, it follows that the smallest difference occurs in the case of electric vehicles and the largest in the case of hybrid vehicles.

8 Conclusions

Assessing all the obtained results, it can be concluded that the level of fuel/energy consumption remains at an acceptable level. The differences were largely due to independent factors such as the weather conditions. The air temperature adopted by the manufacturer during the test was 23 °C and during the tests it did not exceed 4 °C. The air temperature has a great influence on the combustion of the fuel-air mixture. Based on the research, it can be assumed that the differences of 10-20 % in winter conditions are acceptable and the energy consumption of electric vehicles is also within the limits that allow one to believe that these vehicles are a good replacement for the conventional ones.

One of the important elements that the average car user pays attention to is the fuel consumption of a given vehicle. The conducted research shows that in terms of ecology, hybrid vehicles fulfil their role as a replacement for a combustion vehicle and in terms of fuel consumption and the economic aspect, it can be

Table 8 Average difference in fuel consumption of the tested vehicles

Vehicle type	Average percentage difference	Cost [€]
Electric vehicles	9.9	0.25
Hybrid vehicles - fuel	234.1	5.94
Hybrid vehicles - energy	19.34	
Vehicles with positive-ignition engine	17.7	1.22
Vehicles with a compression-ignition engine	54.2	2.67

concluded that dynamic driving and winter conditions are not favorable for these vehicles. The electric vehicle proves in every way that it is the successor to vehicles with internal combustion engines.

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