Article citation info:
Wawrzyniak M, Merkisz J, Chłopek Z. The results of a hybrid vehicle testing in real-world conditions. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-222662

Mateusz WAWRZYNIAK
Jerzy MERKISZ
Zdzisław CHŁOPEK

Combustion Engines
Polish Scientific Society of Combustion Engines

The results of a hybrid vehicle testing in real-world conditions

ARTICLE INFO

Received: 2 March 2026
Revised: 29 May 2026
Accepted: 29 May 2026
Available online: 8 July 2026

This paper presents the results of tests on a hybrid petrol-electric vehicle with external additional charging of the electric battery (a so-called "PHEV" solution). The tests were primarily intended to measure energy consumption, but vehicle speed was also recorded. The tests were conducted on test routes representing urban and rural driving. The tests were conducted for various vehicle control strategies. The hybrid drive and controlled battery charging strategies were implemented for zero and full initial battery charge. Additional tests were conducted in "sport" mode to achieve the highest power output. The tests were conducted with various measurement systems: based on measurements from the fuel dispenser, the on-board computer, the MyBMW application, and the external EOBD interface. It was found that there were no significant differences in the measurement results between the systems used. The results showed that the sensitivity of average speed measurements to the control strategy for all test route stages was on the order of 6–16%. The sensitivity of average volumetric fuel consumption measurements to the control strategy for all test route stages was on the order of 4–80%. Whereas the sensitivity of the average speed measurement results to test route stages for all control strategies was on the order of (33–53)%. The sensitivity of average volumetric fuel consumption measurements to test route stages across all control strategies was on the order of 19–60%.

Key words: *road vehicles, driving tests, fuel consumption, hybrid drive*

1. Introduction

The study focused on a hybrid vehicle with a combustion engine and an electric motor, with an external battery charging system [5–7, 12, 13, 15–17].

Hybrid combustion-electric drives offer many advantages, combining the characteristics of both combustion engine and electric motor drives [9].

The most important advantages of a hybrid vehicle's electric motor drive are as follows [9–11, 14]:

– Electric motor drive avoids the emission of pollutants contained in the combustion engine exhaust gases. Pollution from electric-vehicle motors is limited to particulate matter from tribological vapors, primarily from the vehicle's braking system and the friction between the tires and the road surface. Reducing exhaust emissions by using electric drives is particularly important for motorization in urban centers.
– Vehicle drives with electric motors also contribute to reducing noise emissions, which is particularly important in urban operation.
– The combined use of a combustion engine and electric motor drive improves the vehicle's dynamic operating characteristics – this is particularly important in urban traffic.

The key advantages of using an internal combustion engine in a hybrid vehicle are as follows [9]:

– The most important advantage of using an internal combustion engine in a hybrid vehicle is the increased vehicle range compared to a vehicle powered solely by an electric motor.
– Another advantage is the combined use of an internal combustion engine in the drive system with an electric motor, which improves the vehicle's dynamic characteristics.

There are various design solutions for hybrid drives – primarily in series, parallel, and mixed systems [13].

Among hybrid drive system solutions, a particularly important one is an intermediate form between a classic hybrid drive and an electric drive – one that includes additional external charging of the electric battery. This solution is called a PHEV [1, 5–7]. This solution has a significant advantage over an electric drive: it mitigates the notable range limitation of an electric vehicle.

A passenger vehicle with a PHEV drive is the subject of research, the results of which are presented in this paper.

2. Research method

The test vehicle was a BMW 5 Series Touring 530e xDrive passenger car (G31 generation). Table 1 presents the characteristics of the car's drive system [3].

Table 1. Drivetrain characteristics of the BMW 5 Series Touring 530e xDrive (G31) [3]

Parameter	Characteristic
Drivetrain type	Full PHEV hybrid system All-wheel drive
Combustion engine	BMW TwinPower Turbo technology R4, V_{ss} = 1998 cm³, N_{eN} = 135 kW/5000–6500 min^{-1}, M_{eM} = 300 N·m/1350–4000 min^{-1}
Electric motor	Synchronous integrated with the 8-speed Steptronic gearbox, N_{max} = 80 kW/3140 min^{-1}, M_{max} = 265 N·m /100–2500 min^{-1}
System power	215 kW
System torque	420 N·m
Transmission	8-speed Steptronic automatic transmission
Accumulator	Lithium-ion, 354 V, 12 kWh (10.4 kWh net)
Fuel consumption, CO_2 emissions	2.4–2.2 dm³/100 km, 54–50 g CO_2/km
Range	48–53 km (EV), ~ 700 km (ICE & EV)
Top speed	225 km/h (limited electronically)

The study focused on fuel and energy consumption. The study was conducted based on:
- vehicle control strategies
- route characteristics
- fuel consumption measurement system.

The following vehicle control strategies were considered [3]:
- Strategy 1: start SOC = 100% – „hybrid” mode
- Strategy 2: start SOC = 0% – „hybrid” mode
- Strategy 3: start SOC = 100% – „battery control” mode
- Strategy 4: start SOC = 0% – „battery control” mode
- Strategy 5: start SOC = 0% – „sport” mode.

The following hybrid vehicle operating modes were considered [3]:
- „Hybrid” – the default operating mode, in which the system optimizes the interaction of both power sources: the combustion engine and the electric motor. At low speeds, electric drive is preferred, while at high speeds, the combustion engine is used.
- „Battery control” – the driver sets the battery charge level to be maintained or reached. Electric energy can be saved for urban driving after an extra-urban section of the route.
- „Sport” – both engines operate simultaneously to achieve maximum power.
- Vehicle control strategies vary significantly. There is a particularly significant difference in the degree of initial battery charging, especially in "battery control" mode.

The tests were conducted on the following routes:
- Stage 0 – technical section (Fig. 1)
- Stage I – extra-urban section (Fig. 2)
- Stage II – city loop (Fig. 3)
- Stage III – extra-urban return section (Fig. 4).

Vehicle movement characteristics during selected sections vary significantly, particularly on extra-urban sections, on city loops and technical sections. Vehicle movement conditions typical of driving in urban centers, especially in traffic congestion, are characterized by low average speed, high acceleration, and a significant proportion of idle time. Driving in moderate traffic congestion at medium speeds is characterized by low to medium load on the drive system. The average vehicle speed and low acceleration are also moderate. Driving at high speeds places a high load on the drive system, but at the same time provides high operating stability [8].

The above tests are similar to the RDE (Real Driving Emissions) test and, further, to the WLTC (Worldwide harmonized Light duty Test Cycle) test [2, 15].

The following speed and fuel consumption measurement systems are tested [3]:
- based on measurements from the fuel dispenser
- from the on-board computer
- from the MyBMW application
- from the external EOBD interface.

Detailed analyses were performed for individual vehicle control strategies and routes, which determine the nature of the traffic:
- average vehicle speed – v_{AV}
- average volumetric fuel consumption – q_{AV}.

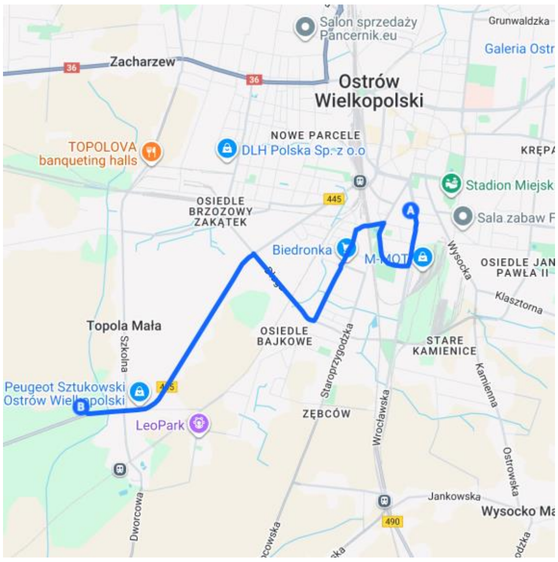

Fig. 1. Stage 0 – technical section [Google Maps]

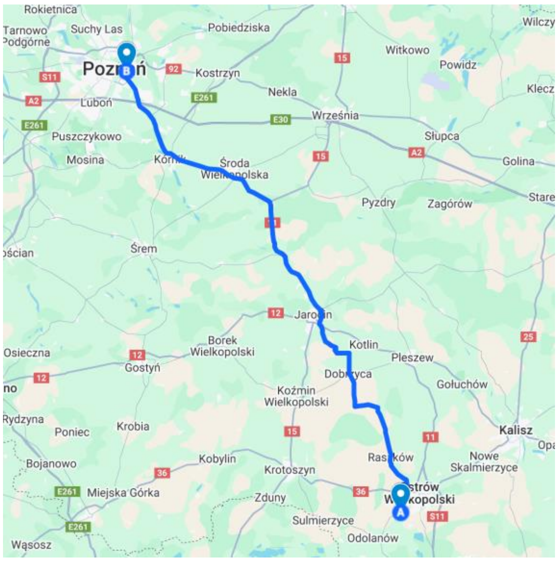

Fig. 2. Stage I – extra-urban section [Google Maps]

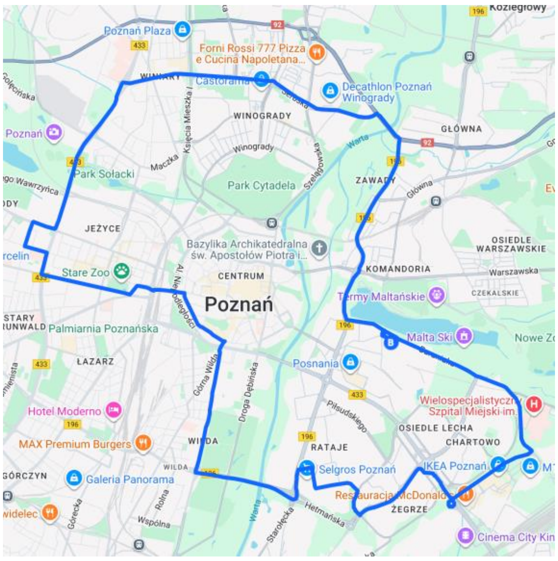

Fig. 3. Stage II – city loop [Google Maps]

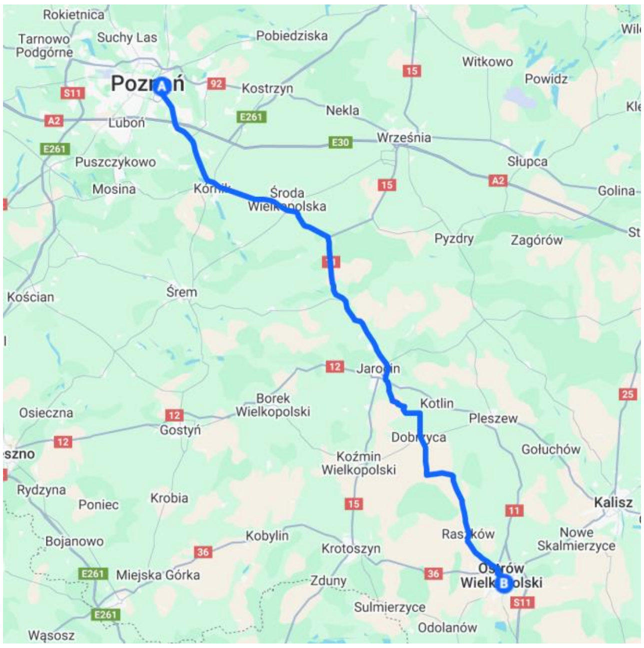

Fig. 4. Stage III – extra-urban return section [Google Maps]

3. Research results

Table 2 presents the test results for hybrid vehicle control strategy 1.

Table 2. Research results for the hybrid vehicle control strategy 1: S – distance, v_{AV} – average velocity, average distance volumetric fuel consumption – q_{AV}, volumetric fuel consumption – Q

Stage	S [km]			
	On-board computer	App MyBMW	EOBD	
Stage 0	7.5	7.7	7.7	
Stage I	120.7	121.0	115.7	
Stage II	29.1	29.0	29.2	
Stage III	121.8	121.0	115.7	
Together	279.1	278.7	260.6	
Stage	v_{AV} [km/h]			
	On-board computer	App MyBMW	EOBD	
Stage 0	41.2	39.9	39.9	
Stage I	67.5	67.6	61.7	
Stage II	20.5	19.8	20.4	
Stage III	65.3	66.0	61.4	
Together	60.9	61.2	58.1	
Stage	q_{AV} [dm^3/100 km]			
	On-board computer	App MyBMW	EOBD	
Stage 0	13.6	13.6	13.6	
Stage I	4.0	3.9	4.3	
Stage II	10.3	10.3	10.6	
Stage III	6.7	6.6	7.2	
Together	6.1	6.0	6.7	
Stage	Q [dm^3]			
	On-board computer	App MyBMW	EOBD	Refueling
Stage 0	1.0	1.0	1.0	
Stage I	4.8	4.7	5.0	
Stage II	3.0	3.0	3.1	
Stage III	8.2	8.0	8.3	
Together	17.0	16.7	17.5	17.3

Table 3 presents the test results for hybrid vehicle control strategy 2. Table 4 presents the test results for the hybrid vehicle control strategy 3. Table 5 presents the test results for the hybrid vehicle control strategy 4.

Table 3. Research results for the hybrid vehicle control strategy 2: S – distance, v_{AV} – average velocity, average distance volumetric fuel consumption – q_{AV}, volumetric fuel consumption – Q

Stage	S [km]			
	On-board computer	App MyBMW	EOBD	
Stage 0	7.5	7.5	7.2	
Stage I	121.9	122.0	123.5	
Stage II	28.2	28.0	28.4	
Stage III	121.0	121.0	122.6	
Together	278.6	278.5	274.5	
Stage	v_{AV} [km/h]			
	On-board computer	App MyBMW	EOBD	
Stage 0	42.5	42.6	38.4	
Stage I	58.3	58.3	55.9	
Stage II	23.8	23.8	22.9	
Stage III	61.7	62.0	60.2	
Together	55.9	56.0	55.4	
Stage	q_{AV} [dm^3/100 km]			
	On-board computer	App MyBMW	EOBD	
Stage 0	8.3	8.3	9.1	
Stage I	6.8	6.6	7.1	
Stage II	9.5	9.4	9.7	
Stage III	6.7	6.6	6.8	
Together	7.1	6.9	7.5	
Stage	Q [dm^3]			
	On-board computer	App MyBMW	EOBD	Refueling
Stage 0	0.6	0.6	0.6	
Stage I	8.3	8.1	8.7	
Stage II	2.7	2.6	2.8	
Stage III	8.1	8.0	8.4	
Together	19.7	19.3	20.5	20.7

Table 4. Research results for the hybrid vehicle control strategy 3: S – distance, v_{AV} – average velocity, average distance volumetric fuel consumption – q_{AV}, volumetric fuel consumption – Q.

Stage	S [km]			
	On-board computer	App MyBMW	EOBD	
Stage 0	7.5	7.5	7.2	
Stage I	122.0	122.0	122.6	
Stage II	29.0	29.0	27.7	
Stage III	118.7	119.0	113.7	
Together	277.2	277.5	264.1	
Stage	v_{AV} [km/h]			
	On-board computer	App MyBMW	EOBD	
Stage 0	36.5	36.6	26.5	
Stage I	68.4	68.2	60.2	
Stage II	32.0	32.0	28.9	
Stage III	69.4	69.4	62.3	
Together	64.2	64.1	58.5	
Stage	q_{AV} [dm^3/100 km]			
	On-board computer	App MyBMW	EOBD	
Stage 0	5.6	5.5	6.0	
Stage I	6.5	6.4	6.8	
Stage II	0.0	0.0	0.0	
Stage III	6.6	6.4	7.1	
Together	5.8	5.7	6.4	
Stage	Q [dm^3]			
	On-board computer	App MyBMW	EOBD	Refueling
Stage 0	0.4	0.4	0.4	
Stage I	7.9	7.8	8.4	
Stage II	0.0	0.0	0.0	
Stage III	7.8	7.6	8.1	
Together	16.2	15.8	16.9	17.2

Table 5. Research results for the hybrid vehicle control strategy 4: S – distance, v_{AV} – average velocity, average distance volumetric fuel consumption – q_{AV}, volumetric fuel consumption – Q

Stage	S [km]		
	On-board computer	App MyBMW	EOBD
Stage 0	7.5	7.6	7.6
Stage I	120.7	121.0	122.3
Stage II	28.2	28.0	26.8
Stage III	118.7	119.0	113.8
Together	275.1	275.6	262.8
Stage	v_{AV} [km/h]		
	On-board computer	App MyBMW	EOBD
Stage 0	36.3	36.3	31.6
Stage I	61.0	61.0	59.0
Stage II	24.8	24.8	22.3
Stage III	56.6	56.4	51.8
Together	54.7	54.7	53.0
Stage	q_{AV} [dm^3/100 km]		
	On-board computer	App MyBMW	EOBD
Stage 0	6.6	6.5	6.7
Stage I	8.9	8.6	9.1
Stage II	0.0	0.0	0.0
Stage III	6.2	6.0	6.8
Together	6.8	6.5	7.3

Stage	Q [dm^3]			
	On-board computer	App MyBMW	EOBD	Refueling
Stage 0	0.5	0.5	0.5	
Stage I	10.7	10.4	11.1	
Stage II	0.0	0.0	0.0	
Stage III	7.4	7.1	7.7	
Together	18.6	18.0	19.3	18.8

Table 6 presents the test results for the hybrid vehicle control strategy 5.

Table 6. Research results for the hybrid vehicle control strategy 5: S – distance, v_{AV} – average velocity, average distance volumetric fuel consumption – q_{AV}, volumetric fuel consumption – Q

Stage	S [km]		
	On-board computer	App MyBMW	EOBD
Stage 0	7.5	7.5	7.1
Stage I	120.7	121.0	122.3
Stage II	28.1	28.0	26.8
Stage III	118.6	119.0	113.7
Together	274.9	275.5	262.8
Stage	v_{AV} [km/h]		
	On-board computer	App MyBMW	EOBD
Stage 0	25.7	25.6	23.3
Stage I	68.0	68.1	65.8
Stage II	22.2	22.4	20.1
Stage III	61.9	62.5	56.4
Together	59.5	59.9	57.7
Stage	q_{AV} [dm^3/100 km]		
	On-board computer	App MyBMW	EOBD
Stage 0	10.1	10.1	11.0
Stage I	6.8	6.4	6.8
Stage II	10.1	10.0	11.4
Stage III	7.0	6.8	7.5
Together	7.3	7.0	7.9

Stage	Q [dm^3]			
	On-board computer	App MyBMW	EOBD	Refueling
Stage 0	0.8	0.8	0.8	
Stage I	8.2	7.7	8.3	
Stage II	2.8	2.8	3.0	
Stage III	8.3	8.1	8.6	
Together	20.1	19.4	20.7	21.0

As the first step in analyzing the test results, it was decided to check the sensitivity of the test results to the measurement methods used. The coefficient of variation of the test results was used as a measure of sensitivity.

Table 7 presents the coefficient of variation of the average vehicle speed for all route stages and all vehicle control strategies. The test results were also presented in Fig. 5.

Table 7. Coefficient of variation – W of average velocity – v_{AV} for all stages and all strategies of vehicle control

	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Stage	W [v_{AV}]				
Stage 0	0.015	0.047	0.143	0.064	0.045
Stage I	0.042	0.020	0.058	0.016	0.016
Stage II	0.015	0.019	0.047	0.049	0.049
Stage III	0.031	0.013	0.050	0.040	0.045
Together	0.023	0.005	0.042	0.014	0.016

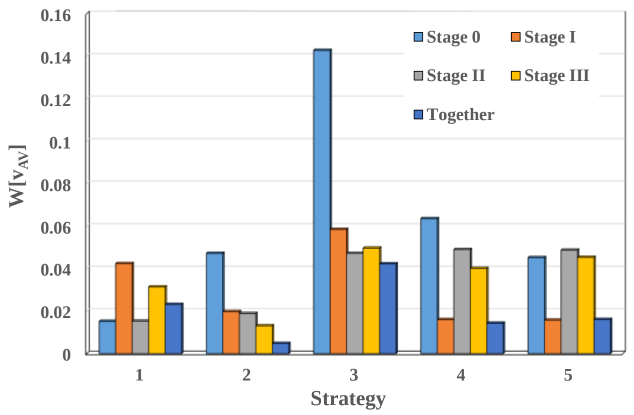

Fig. 5. Coefficient of variation – W of average velocity – v_{AV} for all stages and all strategies of vehicle control

Table 8 presents the coefficient of variation of the average volumetric fuel consumption for all route stages and all vehicle control strategies. The test results were also presented in Fig. 6.

Table 8. Coefficient of variation – W of average distance volumetric fuel consumption – q_{AV} for all stages and all strategies of vehicle control

	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Stage	W [q_{AV}]				
Stage 0	0.000	0.042	0.041	0.015	0.045
Stage I	0.046	0.028	0.027	0.022	0.016
Stage II	0.015	0.013	0.000	0.000	0.049
Stage III	0.038	0.013	0.045	0.051	0.045
Together	0.051	0.031	0.050	0.049	0.016

The highest coefficient of variation for average vehicle speed was 0.037, while the average value for volumetric fuel consumption on the road was 0.030. Therefore, the sensitivity of the test results to the measurement methods used was low, so it was decided to use the test results from the on-board computer for further consideration.

Figure 7 presents the average vehicle speed, and Fig. 8 the average volumetric fuel consumption on the road for all route stages and all vehicle control strategies.

To scale fuel consumption measurement methods, we compared measurements from the on-board computer with those obtained during refueling. Figure 9 presents the results of a comparison of fuel consumption between the on-board computer and refueling.

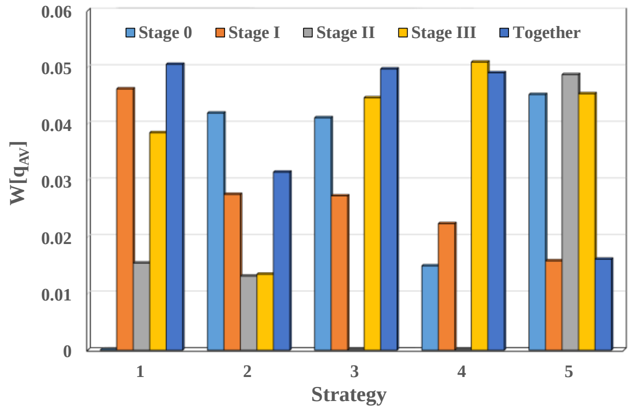

Fig. 6. Coefficient of variation – W of average distance volumetric fuel consumption – q_{AV} for all stages and all strategies of vehicle control

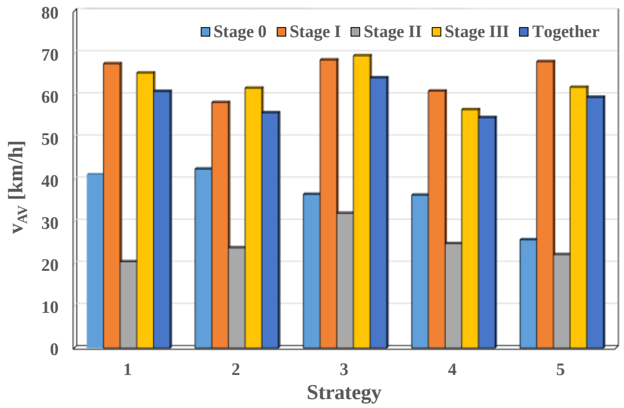

Fig. 7. Average vehicle velocity – v_{AV} for all stages and all strategies of vehicle control

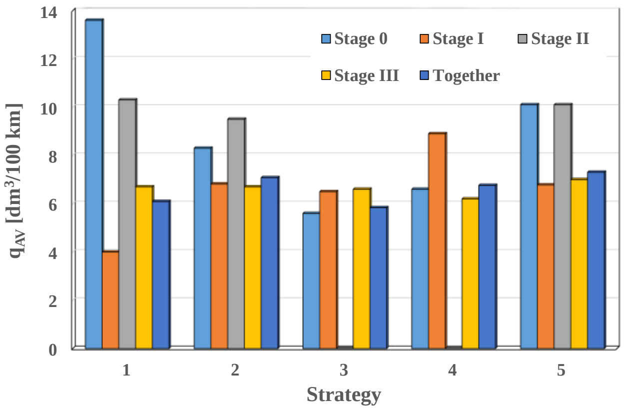

Fig. 8. Average distance volumetric fuel consumption – q_{AV} for all stages and all strategies of vehicle control

The consistency between fuel consumption measurements based on the on-board computer and those based on vehicle refueling was found to be good. The relative difference between fuel consumption measurements based on the on-board computer and those based on vehicle refueling was within the range of 0.009 to 0.053, with an average value of 0.033.

Next, the sensitivity of the average vehicle speed and average volumetric fuel consumption measurements to the control strategy was tested for all route stages. The results for the coefficient of variation of average vehicle speed and average volumetric fuel consumption were presented in Table 9.

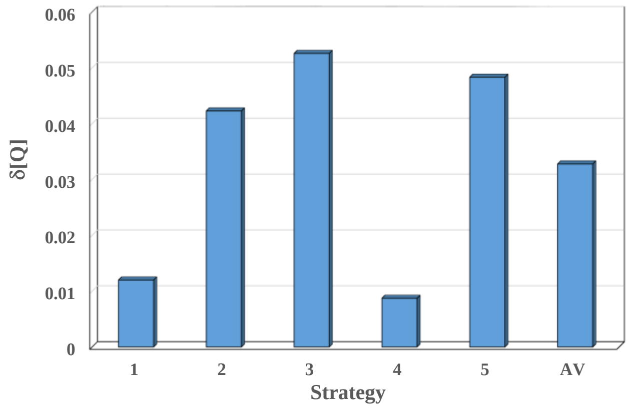

Fig. 9. Relative difference in fuel consumption based on the on-board computer readings and based on refueling the vehicle – δ

Table 9. Coefficient of variation – W of average vehicle velocity – v_{AV} and average distance volumetric fuel consumption – q_{AV} for all stages

Stage	W[v_{AV}]	W[q_{AV}]
0	0.162	0.320
1	0.065	0.236
2	0.160	0.818
3	0.067	0.039
Together	0.058	0.085

The results of the coefficient of variation of the average vehicle speed were shown in Fig. 10 and the average volumetric fuel consumption in Fig. 11.

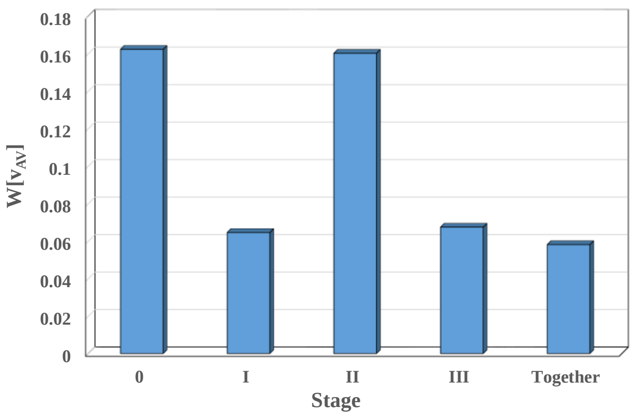

Fig. 10. Coefficient of variation – W of average vehicle velocity – v_{AV} for all strategies of vehicle control

The sensitivity of average vehicle speed measurement results to the control strategy for all route stages was on the order of 6–16%.

The sensitivity of average volumetric fuel consumption measurements to the control strategy across all route stages was on the order of 4–80%.

The sensitivity of average vehicle speed and average volumetric fuel consumption measurement results to the route stages for all control strategies is presented in Table 10.

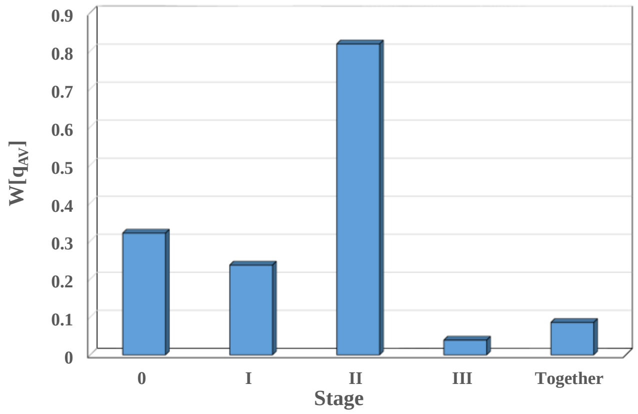

Fig. 11. Coefficient of variation – W of average distance volumetric fuel consumption – q_{AV} for all stages

Table 10. Coefficient of variation – W of average vehicle velocity – v_{AV} and average distance volumetric fuel consumption – q_{AV} for all strategies of vehicle control

Strategy	W[v_{AV}]	W[q_{AV}]
1	0.396	0.419
2	0.526	0.446
3	0.337	0.583
4	0.331	0.608
5	0.465	0.189

The results of the coefficient of variation of the average speed were shown in Fig. 12 and the average volumetric fuel consumption in Fig. 13.

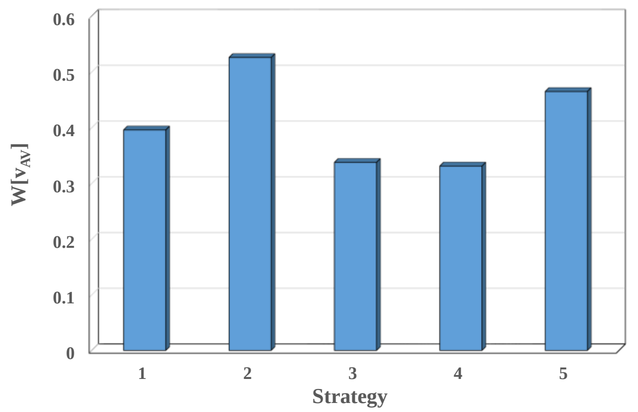

Fig. 12. Coefficient of variation – W of average vehicle velocity – v_{AV} all strategies of vehicle control

The sensitivity of average vehicle speed measurements to route stages across all control strategies was on the order of 33–53%. The sensitivity of the average volumetric fuel consumption measurement results at the route stages across all control strategies was on the order of 19–60%.

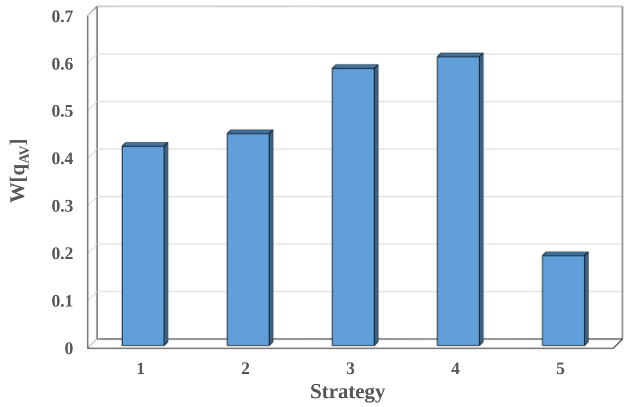

Fig. 13. Coefficient of variation – W of average distance volumetric fuel consumption – q_{AV} all strategies of vehicle control

4. Summary

Based on the research conducted, the following conclusions can be drawn regarding the use of PHEV:

1. Vehicle traffic conditions typical of driving in city centers, especially in traffic jams, are characterized by low average speeds, high accelerations, and a high proportion of idle time.

   Driving in moderate traffic conditions at medium speeds is characterized by low to medium load on the drive system. The average vehicle speed is moderate and accelerations are low.

   Driving at high speeds places high loads on the drive system, yet it maintains high operating stability.

   The control of a PHEV significantly impacts the drive system's operation. The initial state of charge of the electric battery is a key factor. The initial state of charge of the electric battery determines the vehicle's electric range, with significant consequences for fuel consumption and exhaust emissions. Exhaust emissions from electric drive are limited to particulate matter from tribological vapors, primarily from the braking system and tire-road surface interaction.
2. The impact of the PHEV's drive system operating conditions is assessed by its impact on driving speed and fuel consumption for various route characteristics and control strategies.

   The highest average speed is for extra-urban sections, the lowest for the city loop.

   The highest volumetric fuel consumption was observed in the technical section, followed by the city loop, and the lowest in the extra-urban section.

   There was no significant effect of the control strategy on the average vehicle speed and volumetric fuel consumption. Of course, in strategy 3, with the battery fully charged and the electric motor operating, fuel consumption was lowest.
3. The sensitivity of the measurement results to the use of the vehicle speed and fuel consumption measurement system was found to be low.
4. The consistency between the fuel consumption measurements based on the on-board computer and those based on refueling was found to be good. The relative difference between fuel consumption measurements

from the on-board computer and those from refueling was 0.009-0.053, with an average of 0.033.
5. The sensitivity of average vehicle speed measurement results to the control strategy for all route stages was on the order of 6–16%. The sensitivity of average volumetric fuel consumption measurements to the control strategy across all route stages was on the order of 4–80%.
6. The sensitivity of average vehicle speed measurement results to the route stages for all control strategies was on the order of 33–53%. The sensitivity of average volumetric fuel consumption measurements to route stages across all control strategies is on the order of 19–60%.

It is advisable to continue this work at a significantly expanded scope:
1. Continuous recording of vehicle speed and fuel consumption. This would enable the design of driving tests corresponding to vehicle motion under empirical test conditions, the synthetic results of which are presented in this paper, as well as the analysis of measurement results in the following domains:
   - time (including statistical analysis and analysis of dynamic properties using the average speed product of speed and acceleration modulus as a measure of the dynamic properties of the velocity process [4])
   - frequency
   - process values.
2. Conducting exhaust emission tests under the following conditions:
   - actual conditions on the test routes selected, consistent with those selected in this work
   - on a chassis dynamometer in tests corresponding to actual driving conditions in the empirical tests.

Nomenclature

AV	average value
CO_2	carbon dioxide
EOBD	European On Board Diagnostic
EV	electric drive
ICE	combustion engine
M_{eM}	maximum torque of the combustion engine
M_{max}	maximum torque of the electric motor
N_{eN}	rated power of the combustion engine
N_{max}	maximum power of the electric motor
Q	volumetric fuel consumption
R	in-line arrangement of cylinders
S	distance
SOC	state of charge
v	velocity
V_{ss}	displacement of the combustion engine
W	coefficient of variation
δ	relative difference
q	distance volumetric fuel consumption

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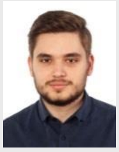
Mateusz Wawrzyniak, Eng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.

e-mail: *mateusz.wawrzyniak.1@student.put.poznan.pl*



Prof. Jerzy Merkisz, DSc., DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.

e-mail: *jerzy.merkisz@put.poznan.pl*

Prof. Zdzisław Chłopek, DSc., DEng. – Institute of Environmental Protection – National Research Institute, Poland.

e-mail: *zdzislaw.chlopek@kobize.pl*