Comparison of CO2 emissions and fuel consumption of a hybrid vehicle and a vehicle with a direct gasoline injection engine

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Abstract. The article presents the results of CO2 emission and mileage tests performed in real operating conditions using mobile measuring devices from the PEMS (Portable Emission Measurement System) group. The tests were performed on two different routes, which represented the conditions of urban, extra-urban and motorway driving. The measurements were performed on a working day of the week at similar times, so as to ensure high repeatability of traffic conditions. Two research objects were used in the research. The first was a vehicle with a hybrid drive system, and the other was equipped with a spark-ignition engine with direct petrol injection. Both vehicles adhered to the Euro 5 emissions standard. Based on the obtained results, the operating time share characteristics were determined, both for the ambient conditions and for the drive systems operation. As a result, it was possible to determine the operating time in electric mode of a hybrid drive system and to determine the impact of measurement conditions on obtained CO2 emission and fuel consumption values for both tested vehicles.

1. Introduction

Increasing the efficiency and reducing the fuel consumption of vehicle drive systems is a complex multi-aspect process that every car vehicle manufacturer carries out according to an independently developed and implemented strategy [10, 12, 13, 14]. This often requires major structural changes both to the engine itself as well as its accessories. Due to cyclical changes in the regulations regarding exhaust emissions, manufacturers are obliged to adapt their products to the set legal limits. These regulations are the main factor determining the development of drive units. In terms of efficiency, the average individual CO2 road emission limits are of key importance. It is the reduction in the consumption of conventional energy sources (primarily gasoline and diesel) in the road transport sector that is currently one of the main challenges awaiting manufacturers of motor vehicles. The implementation of the Euro 6 emissions standard for PC and LDV category vehicles and the introduction of the Euro VI standard for HDVs (Heavy Duty Vehicle) necessitated the use of an extensive exhaust gas aftertreatment system consisting of a series of catalytic converters and a diesel particulate filter [2, 3, 7, 8]. Each of these elements generates power losses resulting from the internal resistance of the exhaust gas flow, thereby increasing the proportion of the exhaust system losses, which also increases the fuel consumption of the vehicle. In addition to adapting the drive systems to these standards, constructors must meet the expectations of customers who, above all, make their vehicle purchase choice based mainly on its operation and reliability. In the case of costs, mainly fuel consumption and the lifespan of materials and operating
fluids are taken into account. This is particularly important for the commercial vehicles group, ones that often travel a distance of more than 100,000 km in any given year [16]. The term reliability in the case of internal combustion engines is understood as their durability (engine, accessories, exhaust gas aftertreatment system) and the probability of a malfunction or a serious failure.

In addition to the structural changes presented above, hybrid and fully electric systems are introduced in conventional drive systems. In the case of vehicles with hybrid drives, mild hybrid and full hybrid solutions are offered. In the case of full hybrid passenger cars, spark-ignition engines of the Atkinson-Miller cycle with the MPI (Multi Point Injection) injection system are the most commonly used in the drive system. The article presents a comparison between the fuel consumption and CO$_2$ emission of a vehicle equipped with such a drive system and a vehicle having a conventional drive system with a direct gasoline injection engine GDI (Gasoline Direct Injection).

2. Construction solutions

All automotive manufacturers have a propulsion systems development roadmap, but many technologies are widely used by a large group of vehicle manufacturers. As an example, downsizing and downspeeding can be mentioned, as ideas that are used in the design of new combustion engines. At present, development trends are moving away from downsizing and going towards rightsizing instead, which, according to the constructors, aims to strike a balance between the fulfillment of legislative requirements and the expectations of the vehicle users. As an example of the application of downsizing and rightsizing in SI and CI engines, the solutions applied by BMW and GM (General Motors) companies were analysed. The BMW group has implemented the TwinPower Turbo Gasoline Engine Technology for their SI engines, which uses turbocharging, timing systems with VALVETRONIC and Bi-VANOS variable valve lifts along with a high-pressure direct gasoline injection. Klauer et al. [5] predicted that this technology would be sufficient to meet the Euro 6 and the European CO$_2$ emissions limits as well as SULEV in the United States. The 4- and 6-cylinder inline engines (figure 1) use one turbocharger. In the case of V-type engines, two turbochargers were used [5]. There is a catalytic system a short distance from the turbocharger exhaust gas outlet, which results in the aftertreatment system reaching its light-off temperature much faster. This is the temperature at which the catalytic reactor reaches a 50% conversion rate.

Mattes et al. [6] presented a 3-cylinder TwinPower Turbo Gasoline Engine, which was used in BMW i8 hybrid vehicles. It is a unit with a displacement volume of V$_{CE}$ = 1.5 dm$^3$ with a rated power of P = 170 kW (231 hp) and generating a torque of T = 320 N·m. It is an engine made in accordance with the tenants of the downsizing method and its volume to power indicator is N$_v$ = 113.3 kW/dm$^3$, and the compression ratio is $\varepsilon$ = 9.5. In order to achieve such a high compression ratio, the constructors have developed a high-pressure gasoline direct injection system, with a maximum injection pressure of 20 MPa. In addition to the downsizing technology for SI engines, the BMW group also adopted it for their CI engines, as the TwinPower Turbo Diesel Engine Technology. Such a manufacturer's policy led to the implementation of a modular construction of both types of the internal combustion engines. This
concept assumes the adoption of a standard volume of a single cylinder (for SI and CI engines), which equals ~ 0.5 dm$^3$. Then, on this basis, the engine is built – for example, three cylinders form a motor with a displacement volume of $V_{CE} = 1.5$ dm$^3$, and four with $V_{CE} = 2.0$ dm$^3$ (figure 2). This allows the use of a large number of common parts for each of the engine types. According to Nefischer et al. [11] the number of modular components and parts for a given engine type must be greater than 60% of the total number. The assumption was to make common parts for SI and CI engines in the range of 30–40%. The modularity of engine construction will contribute to the reduction of the individual level of CO$_2$ road emissions, which will make it easier to meet the legislative requirements in this area.

Rightsizing, according to GM and Opel designers, aims to strike a balance between meeting the legislative requirements on emissions and the vehicle users expectations. Therefore, the new engine will generate a greater maximum torque than its predecessor, which will be $T = 235$ N·m. The rated power will also increase, to $P = 155$ kW. Designers paid a lot of attention to reducing the noise from the engine unit and its accessories by [1]:

a) isolation of high pressure injectors from the engine head, which limits the transmission of energy pulsation and the generated acoustic wave from the injector to the head and the engine block (the pump and the fuel container were also acoustically isolated),

b) change of the chain structure and other elements of the valve timing system,

c) changing the intake manifold structure,

d) using a forged crankshaft,

e) more effective soundproofing of the engine and the engine compartment.

In addition to the introduction of a new SI engine group, GM and Opel engineers have also developed a new CI engine – the MDE (Midsize Diesel Engine). An example of such a unit is a 4-cylinder engine with a displacement of $V_{ss} = 1.6$ dm$^3$ meeting the Euro 6 emissions standard (table 1) [1]. In order to determine the operational parameters of the developed group of MDE engines, tests were carried out on the Opel Zafira Tourer Ecoflex equipped with a 1.6 CDTI engine meeting the Euro 6 standard. The NEDC test yielded a CO$_2$ road emission value of 109 g/km and a fuel consumption of 4.1 dm$^3$/100 km [13]. In comparison to the previous CI engines of this manufacturer with the displacement $V_{CE} = 2.0$ dm$^3$, a reduction in CO$_2$ road emissions by 10 g/km was achieved. This confirms the advantage of new construction solutions used in MDE engines over the previous ones.

![Figure 2. BMW’s strategy for the construction of SI and CI engines [11].](image)

| Parameter          | Unit   | Value       |
|--------------------|--------|-------------|
| Displacement       | cm$^3$ | 1.6         |
| Number of cylinders/setup | in-line/4 |             |
| Cylinder diameter  | mm     | 79.7        |
| Piston stroke      | mm     | 80.1        |
| Compression ratio  | –      | 16          |
| Max. power         | kW     | 100 @ 3500–4000 rpm |
| Torque             | N·m    | 320 @ 2000 rpm   |
| Emission standard  | –      | Euro 6      |

Table 1. The 1.6 dm$^3$ Midsize Diesel Engine parameters [1].
3. Research methodology

3.1 Characteristic of the route
In order to mimic the real operating conditions of motor vehicles, a test route was chosen for the measurement which represented urban, rural and motorway driving (figure 3). Its total length was 28.5 km and was carried out within the Poznań agglomeration. Its first section (A–B) took place in typically urban conditions, then the next section was in rural conditions (B–C). Both of these sections provide access to the Krzesiny junction (C) where the motorway section began. It ended at the Komorniki junction (D). This communication route is the southern bypass of Poznań. Then, the drive was completed in urban conditions again (D–A). Such a course of the research route made it possible to assess the fuel consumption and CO₂ emissions in the whole operating range of the drive systems of the tested vehicles.

![Figure 3. Test route visualization.](image)

3.2 The test vehicles
The measurements were made using two motor vehicles marked as vehicle A and vehicle B. The first vehicle was equipped with a hybrid drive system, which included a spark-ignition engine (Atkinson-Miller cycle) with a $P = 73$ kW multi-point petrol injection and an electric engine with $P_E = 60$ kW power. The second vehicle was equipped with a drive unit made using the downsizing approach, which uses direct gasoline injection and a turbocharger with a release, with a displacement volume of 1.2 dm³ and a maximum rated power of $P = 77$ kW. Both combustion engines met the Euro 5 emission standard and were equipped with a three-way TWC catalytic converter along with a lambda probe.

![Figure 4. Vehicles used for measurements: a) vehicle A, b) vehicle B.](image)
Table 2. Characteristics of the test objects.

| Parameter                                | Vehicle A                              | Vehicle B                              |
|------------------------------------------|----------------------------------------|----------------------------------------|
| Type of propulsion                       | Hybrid                                 | Conventional                           |
| Type of combustion engines               | Spark ignition (Atkinson-Miller) with MPI | Spark ignition with GDI                |
| Number of cylinders / configuration      | 6 / straight                           | 6 / straight                           |
| Displacement                             | 1.8 dm$^3$                             | 1.2 dm$^3$                             |
| Maximum power of combustion engines      | 73 kW @ 5200 rpm                       | 77 kW @ 5000 rpm                       |
| Maximum torque of combustion engines     | 142 N·m @ 4000 rpm                     | 175 N·m @ 1550–4100 rpm               |
| Emission standard                        | Euro 5                                 | Euro 5                                 |
| Exhaust gas afttreatment                 | TWC with lambda control                | TWC with lambda control                |
| Maximum power of electric engine         | 60 kW                                  | –                                      |
| Maximum torque of electric engine        | 153 N·m                                | –                                      |
| Type of battery / capacity               | Ni-MH / 6.5 A·h                        | –                                      |

3.3 Research equipment
The Semtech-DS mobile measuring device from the PEMS group was used to measure exhaust emission and fuel consumption and measured the following parameters:

a) concentrations of CO$_2$, HC, THC and O$_2$,
b) flue gas mass flow rate, temperature and pressure of exhaust gases,
c) temperature, pressure and humidity of the ambient air,
d) the speed and location of the vehicle,
e) basic parameters of the combustion engine operation recorded from the vehicle's on-board diagnostic system.

Semtech-DS is one of the first compact systems for the measurement of exhaust emissions in real operating conditions of vehicles. It consists of a central analyser unit, a flow meter for measuring the exhaust mass flow rate, as well as temperature and pressure of exhaust gases. A sample of exhaust gases from the exhaust system is supplied to the central analyser unit through a heated elastic pipe, which maintains the temperature of 191°C (figure 5). This is to prevent the condensation of hydrocarbon fractions on the walls of the pipe.

![Figure 5. The Semtech DS work schematic.](image-url)
The obtained exhaust gas sample first passes through a PM filter. Then the sample goes to the Flame Ionization Detector (FID), where the THC concentration measurement is performed. Subsequently, the sample of exhaust gases is cooled down to 4°C and the \( \text{NO}_x = (\text{NO} + \text{NO}_2) \) measurement is performed in the NDUV (Non-Dispersive Ultraviolet) analyser and \( \text{CO}, \text{CO}_2 \) and \( \text{HC} \) in the NDIR (Non-Dispersive Infrared) analyser. The final stage is the measurement of the \( \text{O}_2 \) concentration, which is carried out with the use of an electrochemical sensor. The Semtech DS instrument is equipped with its own meteorological station enabling the measurement of the temperature, pressure and humidity of the ambient air. The measurement of these quantities is done with a sensor that is mounted outside the vehicle. It is also possible to measure the position and speed of the vehicle using a GPS (Global Positioning System) device, also mounted outside the vehicle. The device enables connection (using adapters) to the diagnostic network (OBD or CAN) of the vehicle engine and registration of the basic drive unit operation parameters. Most data transmission protocols are supported. The data read from the OBD systems of the tested vehicles was necessary to determine the operating time share of the electric part of the hybrid drive system. Fuel consumption was calculated using the carbon balance method, which is described in detail in [4, 8, 11].

4. Results – analysis and discussion

The analysis of the test results began with a comparison of the measurement conditions. According to the selected test route, the drive began with an urban section where the vehicle speed did not exceed 60 km/h. For both vehicles the total time of this section was about 120s (figure 6). Then, rural and motorway conditions were tested. From 1000 s after the test start, the last urban section began for both tests. However, some data points were registered in this section, where the vehicles exceeded 60 km/h. For vehicle A on the whole test route, the average speed was 57.9 km/h, and for vehicle B it was 56.2 km/h. This indicates that the journeys were similar, meaning that they can be compared. It should be noted that the test drives were performed during a weekday in the morning by the same driver.

Vehicle A obtained a higher average speed of 1.5 km/h during the first stage of the test route (city driving) than vehicle B (figure 7). In the next section of the test route, the difference was significantly higher and amounted to 6.2 km/h – also in favour of the first test vehicle. During the motorway drive section, the smallest differences in the average speed were obtained, the average speed for these sections was respectively: for vehicle A 101.3 km/h, and for vehicle B 102.2 km/h. In the final section, the second of the tested vehicles also obtained a higher speed by 3 km/h. In the middle of the route, the speed differences of both vehicles did not exceed 5%. Only in the rural and last urban sections, these values amounted to 8% and 10% respectively. However, it did not affect the total values comparison obtained in both test drives.

In order to determine the vehicles drive systems operating conditions, the operating time density characteristics in terms of the crankshaft speed intervals and engine load were determined. It should be

![Figure 6. Speed and acceleration characteristics of the test vehicles: a) vehicle A, b) vehicle B.](image-url)
noted that the engine load value was recorded from the EOBD diagnostic system and is expressed by the ratio of the current torque to the maximum occurring at a given engine operating point. When determining the operating time density characteristics, the assumptions described in [9, 15] were used. Their author states that in the preparation of such characteristics, left or right-closed sets should be used. In previous works, however, this was not clearly defined. Thanks to this method, greater accuracy is achieved in the performed analyses. The operating time density characteristics also include the internal combustion engine stop (crankshaft speed and engine load equal to 0), which allowed to determine the use of the electric part of the hybrid drive system.

![Figure 7](image)

**Figure 7.** Average speed comparison of both vehicles in individual stages of the test route.

Regarding the analysis of the operating conditions of the tested vehicles drive systems in the first urban section, it was found that the electric part use share for the hybrid drive vehicle A was 17% (figure 8). In contrast, in the remaining route sections the combustion engine operated mainly in the maximum load range – 61% of the operating time spent in the range (80; 100%). In the case of vehicle B the internal combustion engine operated in low and medium load ranges in the vast majority of the test drive. Very similar results were observed for the rural and motorway sections – vehicle A’s engine operated in the maximum load range, and vehicle B at a relatively low torque values (figures 9–10). This was directly related to the need to recharge the hybrid system batteries when driving in urban and motorway conditions. The braking energy recovery is limited in this case due to the vehicle travelling with constant speed or acceleration values. The largest use of electricity for the tests occurred in the last urban part and amounted to 57% of the analyzed section fragment duration (figure 11).

![Figure 8](image)

**Figure 8.** Operating time density characteristics in the crankshaft rotational speed and engine load ranges for urban driving conditions (A–B): a) vehicle A, b) vehicle B.
In order to clearly present the drive systems performance along with the CO\textsubscript{2} emission value, a simplified designation of the combustion engine operation for both types of drives was chosen – if the internal combustion engine is active, the value is 1, and in case of electric powered drive (with the internal combustion engine inactive), the value is 0.
combustion engine turned off) this value is 0 (figure 12). For vehicle A, the use of the electric hybrid system drive mode occurred only in urban driving conditions. Only the internal combustion engine was used in rural and motorway driving. A large share of electricity consumption was observed (31% of the total test duration) in urban drive sections, which influenced the CO₂ emission characteristic. For vehicle A, this value varied between 0–12.7 g/s, and the average was 2.4 g/s. For vehicle B, an average CO₂ emission of 8 g/s was calculated. A higher emission value variability of CO₂ was also observed, which resulted from using exclusively the internal combustion engine during the journey.

The noted significant share of electric energy used by vehicle A in both urban driving sections was reflected in the fuel consumption being lower by 1.1 dm³/100 km and 3.1 dm³/100 km for the two parts of the urban section respectively compared to vehicle B (figure 13). Such a big difference in the last test drive section was the result of this increased use of the electric drive. Driving in urban conditions is characterized by high variability of vehicle accelerations, which increases the opportunities of using braking energy recovery. In rural and motorway driving, the share of the energy recuperation process is limited, which means that vehicles with hybrid drives can consume more fuel than conventional internal combustion engines on such routes. This relationship was confirmed by the obtained measurement results, where in the considered conditions vehicle B achieved a fuel consumption lower by 8 and 11% than vehicle A. In the case of the whole drive, the vehicle was characterized by lower overall energy consumption as well. The average fuel consumption was 6.7 dm³/100 km, where vehicle B obtained a value higher by 1 dm³/100 km.

![Figure 12. Driving mode changes in the test vehicles used: a) vehicle A, b) vehicle B.](image-url)
Figure 13. Average fuel consumption values obtained in individual sections of the test route.

5. Conclusion
The measurements carried out in real operating conditions allowed to determine not only the CO$_2$ emissions and fuel consumption, but also to analyze the operating conditions of both types of drive systems. In the case of the vehicle equipped with a hybrid drive system, the internal combustion engine used in the drive system operated mainly in the maximum load range (80, 100%). This relationship occurred in all conditions in which the tests were performed. Another notable aspect of the hybrid drive system was driving using the energy stored in the battery. This electric drive mode was present only in the urban part of the test route and its share was 30–57%. This leads to a tangible benefit in reducing CO$_2$ emissions and thus fuel consumption. The direct petrol injection engine has a 20–40% higher fuel consumption, which was mainly the result of the highly variable acceleration, for which the internal combustion engines show an increased energy demand. In the case of the hybrid drive, when accelerating the vehicle from zero, mostly the electric drive mode is used, and a large part of the energy used comes from the braking energy recuperation process. On the other hand, in the rural and motorway driving conditions, the hybrid system also uses the energy supplied by the internal combustion engine - cases of driving only in electric mode was not observed. It is thus confirmed that the use of hybrid vehicles is most favorable mainly in urban conditions.

6. References
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