Comparison of fuel consumption between a vehicle with standard and hybrid drive system

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Abstract. The article presents systems of alternative vehicle drive. Fuel consumption tests were performed between a car with a traditional drive, and hybrid in city traffic conditions. The research was carried out on a selected route, located within the agglomeration of the city of Krakow. The aim of the research was to determine the difference in fuel consumption of compared cars in real urban traffic conditions. The tests were carried out at different times of the day, which resulted in different traffic volumes.

1. Introduction
Restrictions on the emission of toxic exhaust components force the designers of drive systems to apply innovative often complicated solutions. Vehicles with hybrid, electric and also electric vehicles with fuel cells are becoming more and more popular.

Hybrid cars are becoming more and more popular in European countries. According to Toyota Motor Poland data, the sale of hybrid models from this manufacturer increased by 44% in 2017 as compared to the previous year. Hybrid cars currently account for 40% of the total sales of Toyota Motor Europe, while in Western Europe up to 50%.

Electric vehicles are currently not very often found on European roads. The reason is the lack of sufficient infrastructure for fast charging of the battery. In addition, charging the electric car battery with current obtained from coal-fired or brown coal-fired power plants is the transfer of the emission of toxic exhaust components from a car traveling on the road to the power plant.

Currently the only serially produced model of electric-driven car powered by electricity from fuel cells is Toyota Mirai. The model is available in a few European countries. Due to modern and innovative technical solutions, Mirai is treated as a car of the future.

2. Characteristics of the hybrid drive system
The hybrid drive used in motor vehicles is a combination of an internal combustion engine with a motor-generator or two motor-generators. This solution has been used in the automotive industry since the late 90s of the twentieth century.

Hybrid drives due to the way in which the combustion engine is connected to an electric machine can be divided into three groups. Here, serial, parallel and serial-parallel hybrid drive systems are distinguished.

The serial hybrid system consists of an internal combustion engine and two electric machines. In serial hybrid systems, the combustion engine is not mechanically connected to the wheels. It is used to drive an electric generator. The electric motor is responsible for driving the car, using the electric
current obtained during operation of the internal combustion engine or electric energy batteries. If the batteries that are used to power the electric motor are charged, the engine does not run. The combustion engine is started only when the electric charge accumulated in the accumulator runs out, then it drives the electric generator that charges the batteries.

Undoubtedly, the biggest advantage of serial hybrid system is the ability to run the internal combustion engine in the field of largest efficiency allowing reduction of the emission of toxic exhaust components and increase the efficiency of the propulsion system.

An important disadvantage of such a system is its high mass and high production costs. The serial hybrid system is also characterized by the lowest efficiency among all solutions. The serial hybrid system is shown in Fig.1.

In a parallel hybrid drive, the combustion engine is primarily responsible for the vehicle drive while the electric motor has only an auxiliary function. Parallel hybrid system can exist in three configurations: drive with one clutch, drive with two clutches and drive with separated axes.

In the configuration of a hybrid parallel drive with one clutch the combustion engine is permanently connected to an electric motor - it is not possible to separate the operation of these two drive units, so the car cannot move only in purely electric mode. Such a solution also negatively affects the recovery of braking energy, because the internal combustion engine puts additional resistance during deceleration. In this solution, the electric unit is most often used as a starter and an alternator [1].

The disadvantage of the hybrid parallel drive is the lack of driving in pure electric mode and lack of the recovery of all energy during braking.

A different situation occurs in a hybrid drive with two clutches, where the combustion engine is connected to the electric unit by means of a separable clutch, which enables their independent operation. This solution allows driving only in electric mode. During braking, the motors are also disconnected, which allows you to use all the generated energy to charge the batteries.

The disadvantages of a hybrid system with two clutches include the difficulty in choosing the size of the clutch between the internal combustion engine and the electric engine to ensure a smooth start of the combustion engine while driving in pure electric mode, which has a direct impact on the comfort of traveling.

In the case of a hybrid parallel drive with separated axes, the combustion engine and the electric unit are not mechanically connected to each other. The combustion engine is responsible for the drive of the front wheels and the electric engine for the drive of the rear axle wheels. In this solution, the electric motor can also recover energy during braking. It is not possible to create an electric current during a stop of car. It is therefore necessary to use a classic starter which is responsible for starting the combustion engine and an alternator which at the standstill will be responsible for maintaining the operation of electricity and electronics.

The above solutions are burdened with many disadvantages. Such systems require the use of an additional starter and an alternator which increases the mass and cost of the entire system. Another disadvantage is the traction properties of the vehicle which during the switching and disconnecting of the electric drive will exhibit understeer. The parallel hybrid system is shown in Fig.2.

A hybrid serial-parallel system was created from the combination of the two systems described above. It is built from a conventional internal combustion engine and two electrical units – moto-generators, which can act as an electric motor or an electric generator. A very important element of the whole system is the planetary gearbox, which replaces the gearbox. The first moto-generator can serve as an independent drive for the vehicle, auxiliary drive for the internal combustion engine or the generator of electricity recovered during braking. The second moto-generator can act as an electric generator and charge the battery or directly drive the first moto-generator. It is also used to start the combustion engine when driving in electric mode[1].

The advantage of the serial-parallel system due to the use of a planetary gearbox, called the E-CVT, is a continuously variable transmission. The disadvantage of this solution is a specific sound,
especially during urban or motorway driving that results from the high speed of electric machines. The diagram of the serial-parallel circuit is shown in Fig.3.

The serial-parallel system is used primarily in vehicles manufactured by the TOYOTA concern, which is considered one of the most reliable propulsion systems[1].

![Figure 1. Scheme of a serial hybrid system][2]

![Figure 2. Scheme of a parallel hybrid system][2]

![Figure 3. Scheme of a serial-parallel hybrid system][2]
3. Characteristics of the electric drive system
The history of the development of electric vehicles with electric drive is much longer than that of motor vehicles with an internal combustion engine. The first electric-powered carriages were constructed in the 30s of 19th century. Carriages of this type were developed until the beginning of the 20th century, when in the automotive industry combustion engines started to be used to drive vehicles. The use of internal combustion engines allowed increase of the range of vehicles and reduce the cost of production, thanks to which vehicles with internal combustion engines were available to a larger group of recipients. Due to the significant technological progress, performance and lack of pollutant emissions the vehicles with an electric drive system are now developing.

The electric vehicle drive system is composed of an electrical machine, which is responsible for the drive of the vehicle, a battery that stores electrical energy, and the driver, who is responsible for the conditions of the optimal operation of the whole system. Many vehicles with an electric drive system are also equipped with a system that allows energy to be recovered during braking by the same electric machine.

In the modern world, the advantage of an electric vehicle is the cost of its operation. Due to the economic aspects and energy policy, the cost of electricity used to drive vehicles is nearly 10 times lower.

Despite the great advantages, electric vehicles with electric drive are burdened with many disadvantages. The biggest disadvantage of an electric vehicle is its range and the way of storing energy. In many cases, a dedicated station is necessary to charge an electric vehicle, which additionally increases the cost of vehicle operating. An important problem is the method of obtaining electricity, which will be used to charge the batteries. If electricity is obtained from coal or brown coal combustion, then the electric vehicle is not ecologically clean because the emission of toxic exhaust components is transferred from the car to the power plant. The lack of a properly adapted electricity network is a major development barrier for electric vehicles. Too high network load from being charged vehicles can lead to damage of transmission lines and long-term interruptions in the supply of electricity. The electric vehicle drive system is shown in Fig.4.

4. Characteristics of the propulsion system with fuel cells
Technical development of the car with an electric drive system is a vehicle in which the batteries are charged with electric energy obtained from the fuel cell located in the vehicle. The first mass-produced vehicle with fuel cells is the Toyota Mirai.

The main element of this type of vehicle propulsion system is an electric motor with a power of 113 [kW] and a maximum torque of 335 [Nm]. The most important element of the propulsion system
is fuel cell where hydrogen is produced during the hydrogen oxidation reaction and steam is the product of oxidation process. Hydrogen is stored on board the vehicle in special tanks where 5 kg of this fuel enables to cover about 550 km. Electricity obtained from fuel cells and recovered during braking is stored in a nickel-metal-hydride NiMH battery. The accumulated electricity goes to the converter, where the voltage is increased to 650 [V]. The correctness of the operation of the entire drive unit is controlled by the power controller that manages the energy flow process.

Vehicles equipped with this type of propulsion systems are now considered to be vehicles of the future. An important advantage of this type of vehicle in comparison to vehicle charged from electrical network is a total lack of toxic exhaust emission and greater range without need for long charging. Filling hydrogen tanks in the Toyota Mirai requires a similar time as refuelling a standard fuel tank and takes about 4 minutes. Currently a large limitation of the development of vehicles powered by fuel cells is the lack of adequate hydrogen refuelling infrastructure, as well as the lack of a cheap and environmentally friendly method of producing this fuel. The scheme of a vehicle powered by fuel cells from hydrogen tanks is shown in Fig.5.

![Figure 5. Scheme of a vehicle powered by fuel cells from hydrogen tanks][4]

5. Experimental tests of fuel consumption.

5.1. Introduction - the subject of research
The aim of the research was to determine the difference in fuel consumption between a car with a spark-ignition engine constituting a reference vehicle and a car equipped with a hybrid drive. The tests consisted of simultaneous measurement in real traffic conditions the average value of fuel consumption by the test vehicle and the reference vehicle. The research concerned a Toyota Yaris third-generation car from the same production period (2017). Both vehicles had standard equipment - differences in equipment did not affect the test result. The initial course of vehicles was similar.

5.2. Characteristics of drive systems of tested vehicles
The applied systems in Toyota Yaris car with standard drivetrain allow achieving better engine performance, lower fuel consumption and lower emission of harmful exhaust components.

Applied engine management systems in Toyota Yaris car with hybrid drive system allow for the implementation of the Atkinson cycle characterized by a prolonged expansion stroke. In addition, the use of an electric engine coolant pump eliminated the V-belt.

The engine equipped in this way is characterized by better overall efficiency and lower emission of harmful exhaust components. Maximum effective power is 55 [kW] at 4800 min⁻¹, maximum torque 111 [N·m] at 3600 - 4400 min⁻¹. In this vehicle the engine cooperates with the gearbox of the hybrid power unit containing the engine-generator No. 1 (MG1) and the engine-generator No. 2 (MG2) being an integral part of the planetary gear. These are permanent magnet motors, air-cooled, where MG1 acts as a generator and starter, while MG2 acts as a generator and drives the wheels. The maximum
engine power of MG2 is 45 [kW], the maximum torque 169 [N·m]. The Toyota drive system is equipped with the TOYOTA Hybrid System-II (THS-II). This system optimally controls the 1NZ-FXE engine and the No. 1 and No. 2 (MG1 and MG2) generators and motors. The driving force is transmitted through the hybrid drive system's gearbox. In addition a voltage-changing system is used including a HV battery with a rated voltage of 144 [V] and a booster converter increasing the operating voltage to 520 [V] DC. The maximum power of the hybrid system of the tested vehicle is: 73.6 [kW]. The maximum output power is the total power output of the engine and MG2 engine-generator controlled by the THS-II system. The output power of the MG2 engine-generator depends on the voltage from the HV battery.

Table 1. Data of Toyota Yaris car

|                               | Toyota Yaris with standard drivetrain (vehicle A): | Toyota Yaris with hybrid drive system (vehicle B): |
|-------------------------------|---------------------------------------------------|---------------------------------------------------|
| The number and arrangement of cylinders: | 4-cylinder in line engine (2NR-FKE) | 4-cylinder in line engine (1NZ-FXE) |
| Timing mechanism:             | 16-valve, DOHC, chain drive (with VVT-iE and VVT-i) | 16-valve, DOHC with VVT-i |
| Fuel system:                  | multi-point indirect injection                    | multi-point indirect injection                    |
| Displacement:                 | 1496 cm³                                          | 1497 cm³                                          |
| Maximum power:                | 82 [kW] at 6000 min⁻¹                              | 55 [kW] at 4800 min⁻¹                             |
| Maximum torque:               | 136 [N·m] at 4400 min⁻¹                            | 111 [N·m] at 3600 - 4400 min⁻¹                     |

6. Research methodology
The urban tests of fuel consumption for the vehicles described above were made on the basis of the average fuel consumption reading in l / 100km from the vehicle's on-board computer. To compare the result, each vehicle was equipped with a fuel flowmeter Aquametro type VZO 4 OEM and its installation in the vehicle is shown in Fig. 6. The 8-bit AVR ATmega 328/P microcontroller was used to process the signal from the flowmeter. The indication from the on-board computer of the vehicle and the GPS receiver were used to verify the distance travelled. Measurement error of the devices was negligibly small and was not significant from the point of view of research methodology. The signal was processed and counted in a program specially prepared for the conducted research, based on the LabVIEW programming environment. The block diagram of the measurement system is presented in Fig. 7. The above solution allowed for precise recording to the elaborated matrix temporary and total fuel consumption during the conducted tests.

Figure 6. Fuel flowmeter Aquametro type VZO 4 OEM
Research on comparative fuel consumption in real urban traffic conditions was carried out on roads in the Kraków agglomeration. The vehicles were moved along a previously determined route, the length of which was 23.8 km. The route has been chosen so that the volume of traffic on them was large or very large, which allowed for testing the vehicles in real traffic conditions of the urban agglomeration. The route included urban roads with a permissible speed of 50 km/h in built-up areas and two-lane city roads with a permissible speed of 70 km/h. There were a large number of crossings with traffic lights on the roads on which the tested vehicles were moving. During the measurements, the drivers of leading vehicles were changing to eliminate the way of driving. The time of rides and the speed of movement of vehicles on the designated route were dependent on the conditions and intensity of road traffic. In total, each of the tested vehicles travelled a designated route 6 times during 3 trips by each driver. During the tests, the total mileage of each vehicle was 153 km in total and the drivers were in constant contact with each other over the phone. The vehicles were loaded only with the weight of the driver, the air conditioning system was constantly switched on with the temperature set to 21ºC and daytime running lights were also switched on. No other electrical appliances were switched on during the tests. Before the measurements, the pressure in the tires was checked and the value of which corresponded to the factory requirements.

7. Results of tests
The first round consisting of three rides took place from 12: 22 to 14:24. During the first ride, the traffic was low and smooth. The average fuel consumption read from the on-board computer of the Toyota Yaris 1.5 was by 2,6 l/100 km lower than for the Toyota Yaris 1.5 HSD. In the case of second and third ride the difference was successively 2,1 l/100 km and 2,2 l/100 km in favour of the Toyota Yaris 1.5 HSD.

During the second round which took place on 21/03/2018 from 15: 18 to 19: 26, with the same number of rides as the first, the traffic intensity significantly increased and the vehicle movement took place with a large share of idling speed. The road conditions significantly affected the fuel consumption of both vehicles. For the first run of the second round, the difference in average fuel consumption was 3,2 l/100 km in favour of a hybrid vehicle. For subsequent journeys, the difference was 3,1 l/100 km and 1,70 l/100 km also for a hybrid vehicle. The individual values of average fuel consumption are shown in Fig.8. and in Fig.9. The total fuel consumption during individual trips is presented in Fig.10.
**Figure 8.** Average fuel consumption read from the vehicle's on-board computer

**Figure 9.** Average fuel consumption read from the laboratory flow meter
8. Summary and conclusions

Based on the conducted tests, it was found that the average fuel consumption during the entire test cycle for the Toyota Yaris 1.5 car, read from the on-board computer was 6.69 l/100 km. For the measurement performed with laboratory flow-meter placed in the vehicle the average fuel consumption was also 6.69 l/100km. For the Toyota Yaris 1.5 HSD, the average fuel consumption during the entire test cycle read from the on-board computer was 4.90 l/100km, and for the case of measurement performed by a laboratory flow-meter placed in the vehicle 4.84 l/100km. The difference in average fuel consumption during tests was 1.85 l/100km (27.68%) in favour of the Toyota Yaris 1.5 HSD.

The conducted tests confirm greater economy of a hybrid vehicle than a vehicle powered by a spark-ignition engine in urban traffic. When driving in high traffic conditions and high share of engine idling speed, the average fuel consumption was up to 41.33% lower for a hybrid vehicle.

For research purposes it is necessary to conduct further tests in off-highway, motorway and mixed-cycle traffic.

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