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Mateusz SZRAMOWIAT
Andrzej SZAŁEK

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Analysis of the operation of the hybrid drive system in the light of the proposed Euro 7 standard

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The article presents the issues of energy recovery in the hybrid drive system of a vehicle. Road tests of a vehicle equipped with a hybrid powertrain were carried out in accordance with the recommendations of the RDE test. In these studies, measurements of braking energy recovery were carried out in urban, rural and motorway traffic conditions. The analysis of the obtained test results may constitute a premise for the creation of an appropriate strategy for the operation of the hybrid drive system in terms of meeting the requirements of the currently prepared Euro 7 standard.

Key words: *hybrid drive system, real driving emissions, Euro 7 standard, vehicle road tests*

1. Introduction

The activities of the European Commission in the field of new test procedures used to measure emissions of toxic exhaust gas components, in practice, may result in a complete suspension of the production of internal combustion engines intended for passenger cars. This applies especially to the preliminary assumptions for the Euro 7 standard, which is to apply from 2025. According to the new assumptions, the changes would concern both a drastic reduction of the permissible emission limits, but also the method of conducting measurements. For example, the proposal provided for the reduction of the CO_2 emission limit for combustion engines from the current value of 95 g/km to 30 g/km and the NO_x emission limit for nitrogen oxides from 60 mg/km to 30 mg/km. Moreover, it was planned to introduce changes to the RDE (Real Driving Emissions) test procedure, the test sections of which cover various traffic conditions in which the instantaneous emission value is subject to changes. For this reason, the so-called divergence factor, which determined the acceptable differences. According to the proposal, in the Euro 7 standard, the emission value of individual exhaust components could not exceed the established limits, regardless of the traffic conditions in the test, as well as regardless of the version of the vehicle's additional equipment, including e.g. when the vehicle is moving with a roof rack or a trailer. In addition, it was proposed to equip the vehicle with an emission monitoring system, and the time to meet these requirements was set at 15 years or 240 thousand kilometers.

As the automotive industry would not be able to meet these conditions, and would not be able to ensure an adequate supply of zero-emission vehicles, even by carrying out a deep modernization of the currently produced engines, the AGVES (Advisory Group on Vehicle Emission Standards) advisory group operating at the European Commission strongly recommended a relieved version of the initial bill of law. The legal regulations proposed in this recommendation, although they will constitute a further evolution of the currently applicable Euro 6d standard, are assessed as technically very demanding. One of the most important changes is leaving the so-called difference factor used to calculate the emissions from a real road test. Thanks to this, the increased emission in a given section of the route will be able to be compensated by a reduced emission in another section of the test. This will allow not only to meet the requirements of the new Euro 7 standard, but also to further development of internal combustion piston engines, especially in hybrid drive systems with zero emissions when driving in electric mode or during energy recovery [1].

2. Characteristics of an internal combustion engine operation in a hybrid drive system

In a hybrid system, the internal combustion engine works with one or two electric machines. In addition to operating the vehicle with an internal combustion engine and supporting it with an electric motor, this system allows operation with an electric drive only [6].

The most important advantage of this system is the possibility of recovering some energy through an electric current generator, which is activated during braking and when the vehicle is moving by inertia. The recovered energy is stored in an energy accumulator which powers the propulsion electric motor. As a rule, these are electric accumulator batteries with a sufficiently high voltage level (usually nickel-metal-hydride NiMH or lithium-ion Li-Ion) [7–9].

In all types of standard vehicles, braking energy is usually irretrievably lost and converted into heat in the braking systems [11].

Internal combustion engines with spark ignition systems presently used in the hybrid drive, usually work in a cycle similar to the Atkinson cycle in which one can use a larger value of compression ratio than standard engines, which contributes to increased overall efficiency. In addition, the control system forces the engine to work in this area characteristics, which achieves the highest energy conversion efficiency and minimum emission of toxic fumes. Including avoiding engine operation with a high load, where nitrogen oxide emission is the highest [2, 3].

All the above-mentioned features of the hybrid powertrain, compared to standard systems, give a measurable effects in the form of reduced fuel consumption and resulting lower carbon dioxide emissions, as well as reduced emission of toxic exhaust components.

Possible operating states of the hybrid drive system:
- hybrid drive (diesel-electric),
- combustion engine,
- electric drive,
- supporting the internal combustion engine with an electric motor,
- generator operation of the electric machine,
- braking with energy recovery,
- disengaging the drive system (start/stop system).

3. The effects of using a hybrid drive system

The effects of the hybrid drive system are already visible during the initial analysis carried out on the basis of a comparison of selected factory parameters of a vehicle equipped with this system with a vehicle equipped with a standard drive system. For this purpose, two Toyota Yaris models were compared, the first of which: the Yaris 1.5 Dynamic Force Multidrive S with a standard driveline and automatic transmission, and the second: the Yaris 1.5 Hybrid Dynamic Force e-CVT with a hybrid driveline and series stepless transmission.

According to the factory data, the performance of both vehicles is similar.

Table 1. Specifications of Yaris 1.5 Vehicle Dynamic Force Multidrive S and Yaris 1.5 Hybrid Dynamic Force E-CVT

	Yaris 1.5 Dynamic Force Multidrive S	Yaris 1.5 Hybrid Dynamic Force e-CVT
Acceleration time 0-100 km/h [s]	10.2	9.7
Top speed [km/h]	180	175
Fuel consumption according to the WLTP procedure [dm^3/100 km]	5.3–5.7	3.8–4.3
Carbon dioxide CO_2 emissions according to the WLTP procedure [g/km]	125–133	87–98
Curb weight [kg] min/max	1065/1145	1080/1190

The significantly more favourable parameters of the hybrid drive system result mainly from the possibility of recovering the braking energy and the vehicle moving without the combustion engine switched on in certain traffic conditions. Therefore, from the point of view of the proposed requirements of the new Euro 7 standard, the hybrid drive system, compared to other solutions, has the greatest development potential due to the significant share of emission-free operation [5].

4. Analysis of the operation of the hybrid drive system during road tests

In order to verify the factory data, road tests of the Toyota Yaris 1.5 Hybrid Dynamic Force e-CVT car in real road traffic conditions were carried out at the Department of Motor Vehicles at the Cracow University of Technology, according to the RDE test recommendations. The tests were carried out on 28-29 January 2021 in real road traffic conditions in the area of the Krakow agglomeration during a road test consisting of the participation of the vehicle in urban traffic, in suburban traffic and on the motorway. Their main goal was to conduct an in-depth analysis of the operation of the hybrid drive system during various phases of the test. Besides, additional tests were performed consisting in the assessment of energy recovery during braking in various speed ranges of the vehicle.

Test parameters:
- Total test distance: S = 73.04 km, total test time: t = 96 min.
- City route: S = 17.27 km, t = 40 min.
- Suburban route (Rural): S = 35.6 km, t = 33 min.
- Motorway route: S = 35.6 km, t = 23 min.

Energy distribution in a hybrid drive system should be analysed in various components responsible for vehicle propulsion and energy recovery. The propulsion system of the Toyota Yaris 1.5 Hybrid Dynamic Force e-CVT can be assigned to the group of hybrid series-parallel systems. It is equipped with two electric machines marked with the symbols MG1 and MG2, a 3-cylinder spark ignition engine working according to the Atkinson cycle and a planetary continuously variable transmission [10]. The analysis of energy flow in the hybrid drive system of this vehicle was carried out on the basis of measurements of electric energy received and transmitted by the traction battery and both MG1 and MG2 electric machines. For the measurement of electrical energy and other parameters used in the existing sensors mounted in the vehicle and a dedicated diagnostic software allowing the registration of the selected parameters in real time with a frequency of 10 Hz. Moreover, on the basis of fuel consumption and its calorific value, calculations of the thermal energy processed in the internal combustion engine were performed. During carrying out this analysis, the individual energy streams in the collective diagrams are marked with rectangles of different colours. They mean in turn:
- red rectangle: electricity absorbed by the traction battery of the vehicle, which comes from both energy recovery and the operation of the internal combustion engine,
- red dashed rectangle: electric energy given by the traction battery to the vehicle drive and power supply to the internal installation of the vehicle,
- yellow rectangle: electricity generated by the MG1 electric machine,
- yellow dashed rectangle: electricity supplying the MG1 machine to start the internal combustion engine,
- green rectangle: energy recovered by the MG2 generator in the process of braking or moving the vehicle by inertia,
- green dashed rectangle: electricity supplying the MG2 machine while the vehicle is electrically powered (the energy comes from the MG1 machine and the traction battery),
- blue rectangle: thermal energy released in the combustion engine (due to its high value – it is given on the chart on a scale 10 times smaller than the other components).

Figures 1, 2 and 3 show the energy distribution in the hybrid drive system during the driving test in real road traffic conditions.

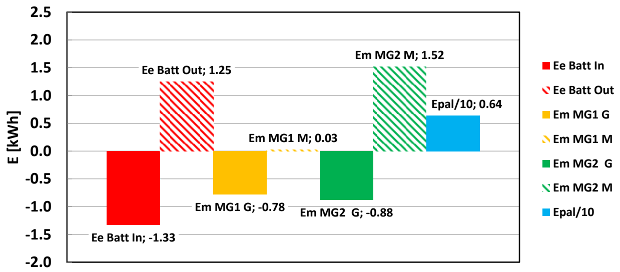

Fig. 1. Energy distribution in the hybrid drive system in the city part (City) of the RDE test (Toyota Yaris 1.5 Hybrid Dynamic Force e-CVT)

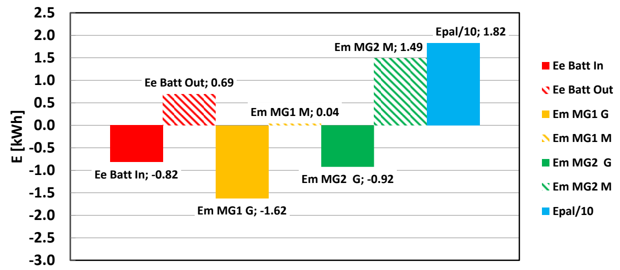

Fig. 2. Energy distribution in the hybrid drive system in the motorway part of the RDE test (Toyota Yaris 1.5 Hybrid Dynamic Force e-CVT)

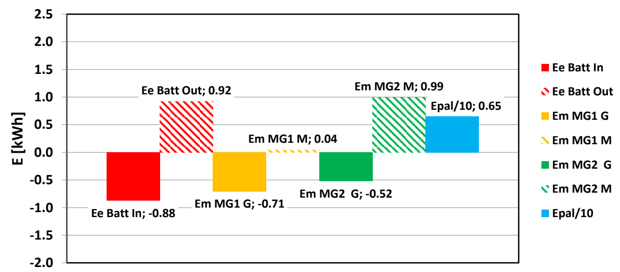

Fig. 3. Energy distribution in the hybrid drive system in the rural part of the RDE test (Toyota Yaris 1.5 Hybrid Dynamic Force e-CVT)

From the point of view of the analysis of the energy balance in the hybrid drive system, the green rectangle deserves attention, which indicates that 0.88 kWh of energy was recovered in the city cycle (City), 0.92 kWh in the motorway cycle, and 0.52 kWh in the extra-urban cycle. In total, in the entire RDE test on the 73.04 km route, 2.32 kWh of energy was recovered.

5. Analysis of the operation of the hybrid drive system during the braking test

During the tests, a brake test was also carried out from the initial speed of 53 km/h until the vehicle stopped (Fig. 4). This test was performed during the urban part of the test and had the characteristics of a typical stop for a vehicle in city traffic before the crossing of the streets with traffic lights. The distance from the beginning of the test, when the driver, seeing the red signal of the signaling device, took his foot off the accelerator pedal until the vehicle stopped, was approx. the 200 m braking process (Fig. 4). In the initial phase of the process, the reduction of the vehicle speed was mainly caused by the load on the MG2 electric machine, which recovers braking energy. Only in the final phase of the vehicle stopping process, the main reason for the reduction in speed was the operation of the friction linings of the braking system. The energy recovered by the MG2 electric machine at each point of the braking process was also measured (Fig. 5). The reduction of energy recovery in the final phase of the braking process resulted from the lower possibility of generating electricity due to the low rotational speed and due to the operation of the friction brake.

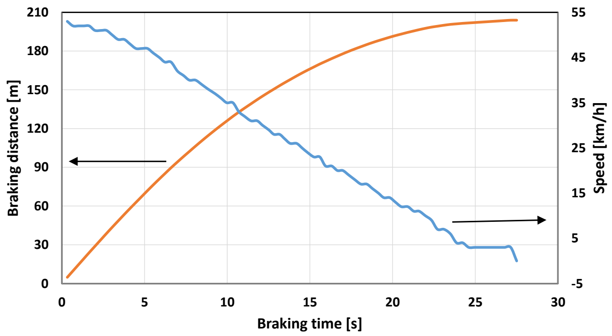

Fig. 4. The course of the braking process in the hybrid drive system

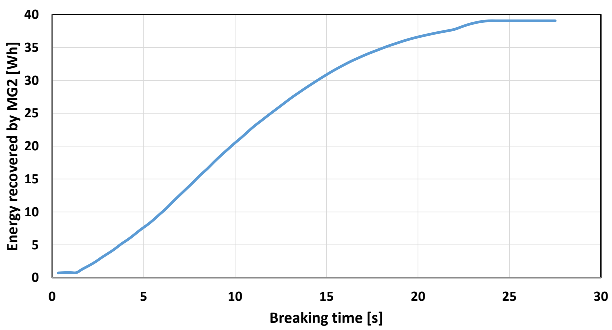

Fig. 5. The course of energy recovery in the braking process in a hybrid drive system

The total value of energy recovered in the test was approx. 39 Wh, while the energy supplied to the traction battery was approx. 37 Wh (Fig. 6). The difference, amounting to about 2 Wh, resulted from the losses related to energy transmission and the necessity to use it to power the vehicle accessories.

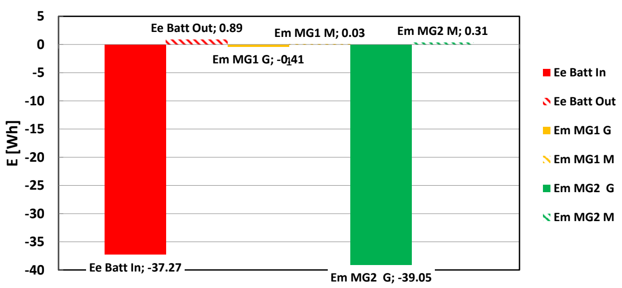

Fig. 6. Energy distribution in the hybrid drive system during braking

6. Conclusions

A characteristic feature of reciprocating heat engines is the high variability of the achieved efficiency of the engine in its field of operation. The hybrid drive system allows the optimal use of the engine's operating area, where it achieves the greatest efficiency, while the shortage or excess of developed torque is compensated by the electric machine. Thanks to such a system, it is possible to significantly reduce fuel consumption by motor vehicles and reduce heat emission and the emission of toxic components to the environment.

The most important advantage of hybrid drive systems in motor vehicles is the recovery of braking energy, which is irretrievably lost in standard vehicles, causing the environment to be loaded with heat. An important feature of the cooperation of a heat engine with an electric machine is the possibility of mutual supplementation of energy demand in the vehicle drive system, implemented according to the adopted criteria of energy consumption optimization.

Contemporary compact cars powered only by electricity usually have a battery with an electric capacity of 40–60 kWh, which allows for a range of 400–500 km. BEVs that are powered solely by electricity are currently subject to a number of limitations in terms of range, refill time and the amount of energy that can be stored. Therefore, during the transition period, a lot of attention should be paid to the development and optimization of hybrid drive systems.

In the context of the research, the energy recovery of approx. 2.3 kWh on a route with a length of approx. 70 km and variable road conditions in the hybrid drive system of the Toyota Yaris 1.5 Hybrid Dynamic Force e-CVT is significant and has a significant importance from the point of view of the rational use of energy in transport. This results in a significant reduction in fuel consumption in relation to a similar class of vehicles equipped with a conventional drive system. Preliminary studies of braking energy recovery, carried out in urban traffic, show a great potential for the development of a special control algorithm, allowing for the optimal selection of the strategy of cooperation between a piston heat engine and an electric machine, based on the criterion of energy savings in transport.

Such actions meet the legislative activity of the European Commission in the field of new emission limits and measurement procedures, especially with regard to the initial assumptions provided for the Euro 7 standard. In practice, it is currently the only possibility of further use of internal combustion engines to power passenger cars.

Nomenclature

RDE	Real Driving Emissions	Li-Ion	lithium-ion cell
AGVES	Advisory Group on Vehicle Emission Standards	e-CVT	Electronic Continuously Variable Transmission
NiMH	nickel metal hydride	BEV	Battery Electric Vehicle

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Mateusz Szramowiat, MEng. – Faculty of Mechanical Engineering, Cracow University of Technology.
e-mail: *mateusz.szramowiat@pk.edu.pl*

Andrzej Szałek, DEng. – Advisor of the Board, Toyota Motor Poland Company Limited, Warsaw.
e-mail: *andrzej.szalek@toyota.pl*