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Analysis of energy consumption and recovery by the electric motor and generator of a HEV hybrid vehicle

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This article presents an analysis of the operation of the electric motor, generator, and internal combustion engine within the hybrid powertrain system of a Toyota Corolla. To compare energy utilization data from these sources, a specially designed diagnostic scanner was used in our laboratory to capture data from the vehicle's Controller Area Network (CAN).
The tests were conducted on a laboratory chassis dynamometer, taking into account the NEDC (New European Driving Cycle) and WLTP (Worldwide Harmonised Light Duty Vehicle Test Procedure) protocols. Additionally, experiments were performed under real urban traffic conditions. The analysis of the collected data provided detailed insights into the operation of the aforementioned components, which are integral to the powertrain during characteristic driving scenarios. For selected test fragments, an analysis of energy consumption and recovery by the electric motor and generator is presented.

Key words: *hybrid powertrain system, CAN diagnostic scanner, NEDC and WLTP tests, NEDC test, recovery and energy consumption by HEV*

1. Introduction

Modern hybrid powertrains are complex; optimal energy-flow management is therefore essential for high overall efficiency [1, 4, 6, 13, 14, 21]. There are wide varieties of drive systems, differing in design, operating strategy and the method of power distribution between combustion engines and electric motors [2, 8, 10, 16]. Car manufacturers use their own energy management strategies tailored to their needs, which makes it difficult to assess the efficiency of individual solutions [3, 5, 9, 11, 12, 15, 19]. In the Toyota Corolla 1.8 Hybrid equipped with a 5th generation hybrid system, a drive system consisting of an internal combustion engine and two electric motor-generators was used [24]. The single planetary gear set sums the torques of the individual sources.

The drive system provides stepless gear change (E-CVT), enabling the vehicle to reach a maximum speed of 180 km/h [20, 24].

This article attempts to present the performance of individual drive sources, including a comparison of the behaviours of MG1/MG2 electric machines and the ICE engine under various operating conditions: during standardized tests and in real-world traffic conditions. The analysis was based on selected test fragments: at start, during acceleration, at constant speed, and during deceleration, i.e., under variable load conditions and for different battery charge states.

In order to analyse data on the use of energy from the above-mentioned sources, a specially designed diagnostic scanner was used to capture data from the vehicle's CAN network [17, 18, 23]. The tests of the vehicle's drive system operation were performed on a chassis dynamometer during WLTP and NEDC tests and in real city traffic. The operation of individual electric motors and engines in different phases of vehicle movement is presented in the following section.

2. Tested vehicle drive system

The object of the research and analysis was a Toyota Corolla 1.8 Hybrid equipped with a 5th generation hybrid drive system. The drive system uses Hybrid Synergy Drive® technology. This is a system that connects two three-phase synchronous AC electric machines (MG – motor generator) with an internal combustion engine (ICE). The drive system parameters of the tested vehicle are presented in Table 1.

The summation of the energy of individual drive sources is carried out by the E-CVT gearbox, using a single planetary gear for this purpose [24].

The combustion engine operating according to the Atkinson cycle is connected to the planetary gear satellite carrier. The MG1 electric motor (reversible machine - motor or generator), working mainly as a generator and acting as a starter for the combustion engine, is connected to the sun gear of the planetary gear. The MG2 electric motor (reversible machine - motor or generator) is connected via a cylindrical gear to the ring wheel of the planetary gear, from which the torque is directed to the final drive of the vehicle's drive system. The E-CVT system works by selecting the appropriate operating conditions of individual drive system components to meet the current energy demand.

Differentiation of the speed at the input of the vehicle's final drive is achieved by comparing the speeds of the MG2 and MG1 electric motors when the combustion engine is not operating, or of the MG2 and the combustion engine when the latter is used to drive the vehicle. At this time, the MG1 engine works as a generator, supplying the MG2 electric motor with electricity and charging the traction battery. At the same time, by loading the combustion engine, it increases its efficiency. This allows for approaching the optimal operating range of the combustion engine. Figure 1 shows the kinematic diagram of the drive system of the tested Toyota Corolla 5th generation vehicle.

Table 1. Drive system parameters

Internal combustion engine	
Number and arrangement of cylinders	4, in-line, Atkinson cycle
Timing system	4 valves per cylinder, DOHC with VVT-i
Fuel supply system	Direct fuel injection
Displacement	1798 cm^3
Piston diameter x stroke	80.5 × 88.3 mm
Compression ratio	13
Maximum power	72 kW at 5200 rpm
Maximum torque	142 Nm at 3600 rpm
Electric motor MG2	
Maximum voltage	600 V
Maximum power	70 kW at 13500 rpm
Maximum torque	185 Nm
Electric motor MG1	
Maximum voltage	600 V
Maximum power	23 kW
Maximum torque	40 Nm
Battery	
Type	Lithium-ion
Nominal voltage	207.2 V
Capacity (3HR)	0.85 kWh

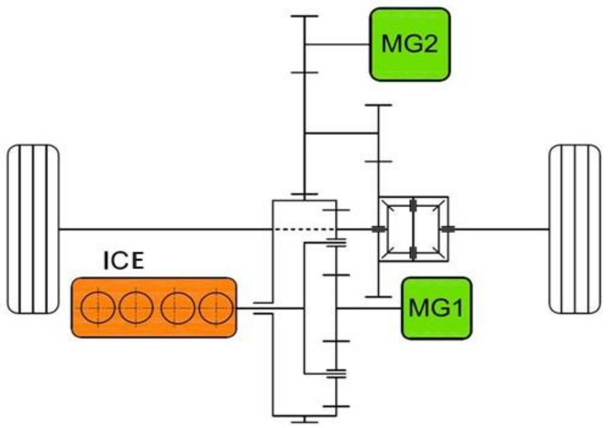

Fig. 1. Kinematic diagram of the HEV Toyota Corolla 5th generation drive system

This system can operate in various modes that automatically adjust based on load and driving dynamics. The hybrid drive system of the Toyota Corolla Hybrid can operate in series and parallel configurations. It can also operate solely in electric mode or use the internal combustion engine and electric motors simultaneously. The vehicle's drive system is a self-charging system. The battery is charged both during regenerative braking and during internal combustion engine operation.

3. Different operating modes of the hybrid drive system

When stationary, both the combustion engine and the electric motor are automatically switched off to reduce fuel consumption and exhaust emissions. In this phase, the system operates in standby mode, monitoring the battery charge level and readiness to restart the drive. This is possible thanks to the Start-Stop system, which minimizes energy losses by switching off the combustion engine when it is not needed.

When starting from a standstill, the hybrid drive system operates in electric mode (EV), which uses only the energy stored in the traction battery for propulsion. The electric motor, due to its ability to generate maximum torque from the moment of start-up, is suitable for initiating movement and driving at low speeds. At this point, the combustion engine is not running, and the vehicle is not emitting exhaust fumes. When accelerating or reaching higher speeds, the system automatically starts the combustion engine and uses the MG1 electric motor to provide additional power, ensuring greater driving dynamics. The combustion engine also starts up when the battery charge level drops below a certain level, and then charges the battery. During low-speed manoeuvres, such as parking, the drive system uses only the electric motor. Such operations require little power and are short-lived, so an electric drive is sufficient. On the other hand, when driving at a constant speed with moderate loads, the hybrid system works in the most energy-efficient way. At low speeds, the main source of power is the electric motor, while the combustion engine operates in support mode, switching on periodically to maintain optimal battery energy levels. At higher speeds, the combustion engine takes over the dominant role, but is still supported by the electric unit, which allows for optimisation of fuel consumption. During full acceleration, for example, when overtaking, the hybrid drive system engages both power sources to provide the maximum available energy. The combustion engine operates in its optimal speed range, while the electric motor provides additional torque, enabling the desired speed to be reached quickly. This is the operating phase in which fuel consumption and exhaust emissions are at their highest. During long-term high-speed driving, the main source of power is the combustion engine, which provides adequate power to maintain high speeds on expressways. The electric motor, in such conditions, plays a supporting role but does not directly drive the vehicle – it supports energy recuperation and provides assistance when a momentary increase in power is needed.

When decelerating, the hybrid drive system recovers energy. The MG2 motor, operating in generator mode, converts the vehicle's kinetic energy into electrical energy, which is stored in the traction battery. During this process, the combustion engine is switched off, and the drive system switches to charging mode. Anticipating driving situations, such as gradual deceleration, maximizes the efficiency of the recuperation process.

During braking, when deceleration is more intense, the system actively recovers energy, converting part of the vehicle's kinetic energy into electrical energy stored in the traction battery.

In situations where braking is long (downhill), it is possible to use mode B, which increases braking force by using the combustion engine's resistance. In this case, the vehicle's drive wheels drive the MG2 motor, operating in generator mode, to charge the traction battery and supply electrical power to the MG1 motor, which, while maintaining the combustion engine's rotational speed, uses its braking torque. It allows for speed control and reduced brake wear.

The smoother and more gradual the braking, the more effective the recuperation process is [24].

4. Vehicle tests during WLTP, NEDC and city traffic tests

4.1. Measuring equipment

The energy flows were determined from data recorded during chassis dynamometer tests and read from the vehicle's CAN network. The diagnostic connector used in OBD (On-Board Diagnostics) systems was used to read data from the CAN (Controller Area Network). For this purpose, a scanner developed at the Department of Combustion Engines and Vehicles at the University of Bielsko-Biala was used, allowing for the reading of 36 selected vehicle operating parameters from the CAN network. The scanner consists of a motherboard with a microcontroller, a network module, a colour touchscreen panel, and DC/DC converters assembled in a single housing. During chassis dynamometer and road-vehicle tests, data from the scanner were recorded at 5 Hz. In both cases, the operating parameters of the drive system components were saved to a memory card. [17, 22]. Figure 2 shows a diagram of the measurement system used in chassis dynamometer tests.

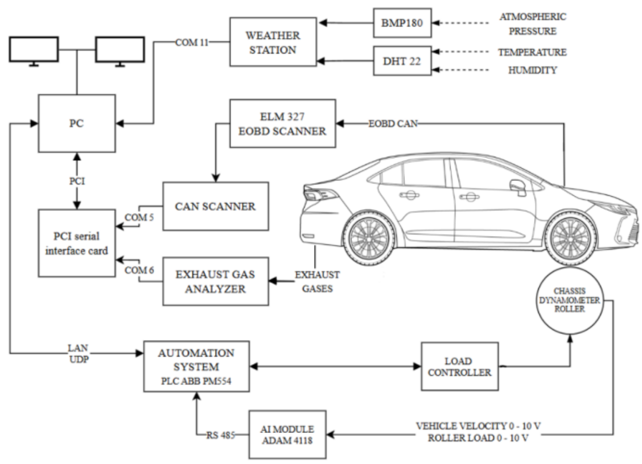

Fig. 2. Diagram of the measurement system used in the energy consumption tests of the Toyota Corolla Hybrid

Due to the significant amount of data to record, only those data ranges were selected that allowed for the assessment of the energy flow in the vehicle during its collection from various sources, i.e., the combustion engine, the traction battery or energy generated during vehicle movement. Additionally, a number of data points were collected to support diagnostics of the drive system of the tested vehicle. This CAN scanner is shown in Fig. 3.

The device allows you to observe the values of 36 selected parameters in real time on the scanner screen. Selected data read from the CAN network were used for the analyses included in the article:

- vehicle speed
- accelerator pedal position
- throttle opening angle
- brake pedal position
- wheel speeds
- engine speed
- electric motors MG1 and MG2 speeds
- engine torque
- electric motors MG1 and MG2 torques
- coolant temperature
- battery charge level (SOC)
- battery voltage
- current intensity of MG1 and MG2 motors
- voltage of MG1 and MG2 motors
- hybrid battery current intensity
- instantaneous fuel consumption.

Fig. 3. ADEL CAN BUS diagnostic scanner

4.2. Vehicle tests

The tests of energy consumption and generation for the Toyota Corolla Hybrid 5th generation were conducted during WLTP and NEDC tests and in real-world city traffic conditions. The tests were performed on a chassis dynamometer at the Department of Combustion Engines and Vehicles at the University of Bielsko-Biala. For technical reasons, the maximum speed during the dynamometer tests was limited to 100 km/h. The real-world drive took place during rush hour in Bielsko-Biała and on a section of the S1 national road. The selected route included driving through streets with numerous intersections controlled by traffic lights, and the final part allowed higher speeds. The selected route traverses mountainous terrain, requiring the need to overcome larger hills and descents.

The tests on the chassis dynamometer and during city driving allowed for the assessment of various driving conditions and thus various operating modes of the hybrid drive system. Figure 4 shows the total energy consumption in the NEDC, WLTP and city traffic tests, with a breakdown of energy drawn from the traction battery, generated by the combustion engine and supplied by the MG1 and MG2 electric motors.

The use of the vehicle's traction battery energy was also analysed. Assessment of the hybrid drive system required selecting fragments from the test results that illustrated the individual operating modes. In the tests carried out, the combustion engine showed the highest energy consumption, respectively: ~5100 kJ in the NEDC test, ~1800 kJ in the WLTP test, and ~5000 kJ in city driving. The MG1 electric motor, which primarily served as a starter for the combustion engine, consumed only a small amount of electricity. The MG2 electric motor used more electricity at start-up, with lower motion resistance and lower driving speeds, whereas the combustion engine required more energy at higher motion resistance and higher driving speeds.

In the individual tests, this consumption was: NEDC ~1800 kJ, WLTP ~3100 and ~2900 kJ in the city driving test.

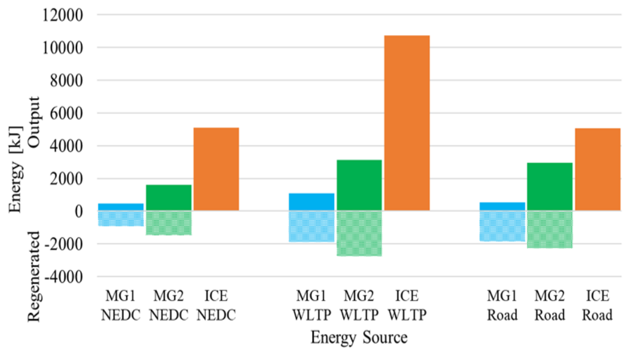

Fig. 4. Total energy consumption during NEDC, WLTP and city driving tests

During vehicle deceleration and braking, the MG2 electric motor, operating in generator mode, recovered part of the vehicle's kinetic energy by converting it to electrical energy. The energy recovered by the MG2 motor in individual tests is similar to the energy required to drive the vehicle. It should be noted that a relatively large amount of electrical energy was generated by the MG1 motor, driven by excess combustion engine power in generator mode.

5. Analysis of energy consumption and recovery during various aspects of vehicle movement

5.1. Starting from a standstill

From the obtained waveforms, fragments were selected to illustrate the hybrid drive system's individual operating modes. The first one concerns starting from a standstill at low speed.

Figure 5 shows the vehicle starting from a standstill with different battery charge levels.

In the case shown in Fig. 5a, the battery of the tested vehicle was charged to 68%. In this case, the vehicle starts moving solely with the MG2 electric traction motor, drawing energy from the battery. At higher speeds (about 35 km/h), the combustion engine powers the vehicle. The MG2 electric motor, to a lesser extent, periodically supports the internal combustion engine.

In turn, the MG1 generator uses the surplus energy of the combustion engine and works in generator mode, charging the battery. Figure 5b shows a case in which the battery was partially discharged (charge level ~30%), leading the combustion engine to serve as the main source of vehicle drive even at low speeds (10 km/h). In this case, the MG1 electric motor, driven by the combustion engine, also generates electricity. The share of the MG2 electric motor in the vehicle drive is insignificant.

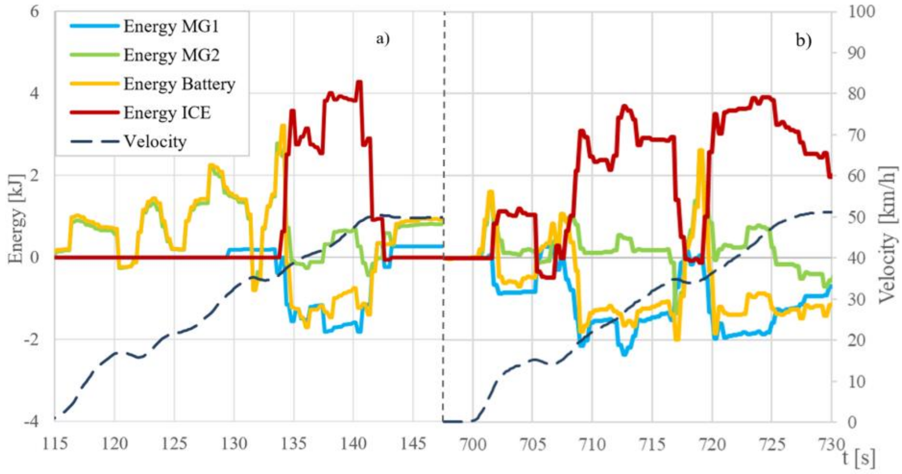

Fig. 5. Accelerating the vehicle at low driving speeds in the NEDC test: a) with a charged battery, b) with a discharged battery

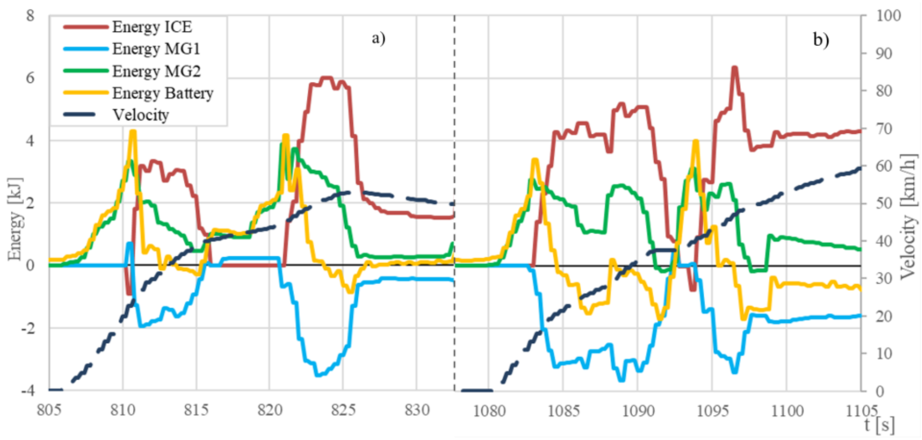

Fig. 6. Vehicle acceleration in a road test: a) with low intensity, b) with high intensity

5.2. Acceleration

Figure 6 shows the vehicle's acceleration at different intensities. In the case shown in Fig. 6a, the vehicle begins to accelerate, initially using only the MG2 electric motor powered by the energy drawn from the traction battery. After the vehicle reaches a driving speed of ~25 km/h, the MG1 electric motor starts the combustion engine. From that moment on, the combustion engine is the main source of drive, which generates more than twice as much energy as the MG2 electric motor. Additionally, the combustion engine is "loaded" by the MG1 motor, which generates electricity used to power the MG2 electric motor. A temporary reduction in the acceleration intensity causes the combustion engine to turn off, and the MG2 motor is responsible for the vehicle drive using the energy drawn from the battery. Figure 6b shows a case in which the vehicle accelerates with high intensity. Initially, the vehicle also moves using the MG2 electric motor at the expense of the battery's energy, but in this case, the combustion engine starts operating sooner, at approximately 15 km/h. Due to the high resistance to motion caused by the vehicle's intensive acceleration, the MG2 electric motor further supports the combustion engine by using energy generated by the MG1 motor, which is powered by the combustion engine.

5.3. Driving at a constant speed

Figure 7 shows the energy flow at fixed speeds of 70 km/h and 100 km/h. In the case shown in Fig. 7a, the vehicle moves at a lower speed, at which the resistance to motion is lower. In this case, only the combustion engine drives the vehicle, generating energy at a level of ~2.8–~3.2 kJ. The MG2 machine operates in generator mode at this stage, recuperating small amounts of electrical energy.

The MG2 machine operates in generator mode at this stage, recuperating small amounts of electrical energy, on average at a level of ~0.3 kJ. Figure 7b shows a fragment of the test in which the vehicle moves at ~100 km/h. In this case, the combustion engine also serves as the main drive source, generating 4 kJ of energy. The MG1 generator uses power from the combustion engine to generate electricity. A small portion is used by the MG2 motor, and the remainder is directed to the traction battery. In the first period of this part of the test, the MG2 motor consumes little electricity and contributes little to supporting the combustion engine. In the final part of the test, the combustion engine reduces the power required to drive the vehicle; this reduction is supplemented by the MG2 electric motor using energy generated by the MG1 electric machine.

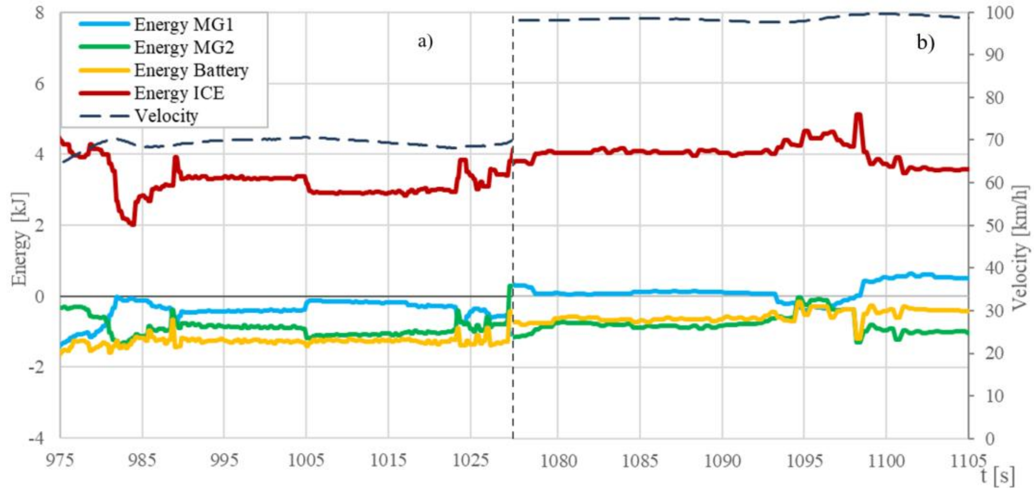

Fig. 7. Driving at a constant speed in the NEDC test: a) driving speed ~70 km/h, b) driving speed ~100 km/h

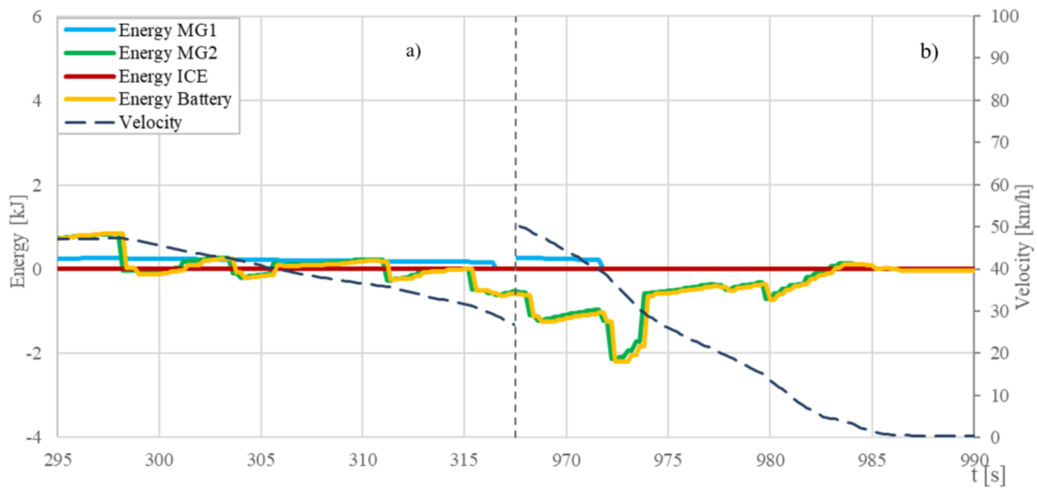

Fig. 8. Deceleration of the vehicle in the WLTP test: a) low intensity, b) high intensity

5.4 Deceleration

Figure 8 shows the energy flow during deceleration. In this phase of the test, shown in Fig. 8a, the vehicle decelerates relatively slowly. In this case, the combustion engine is switched off, and the MG2 motor periodically operates in the drive engine mode, drawing small amounts of energy from the traction battery, then switching to the generator mode to brake the vehicle and recover some of the vehicle's kinetic energy. The MG1 draws negligible electrical power throughout deceleration. Figure 8b shows a phase of the test in which the vehicle decelerates more intensely. In this case, the MG2 motor operates in the generator mode until the vehicle stops. Depending on the braking intensity, it generates varying amounts of electrical energy, which is stored in the traction battery.

6. Summary and conclusions

The study supports the following conclusions:

1. The NEDC and WLTP tests, as well as city driving, were selected for the analyses. The NEDC test includes many ranges with fixed conditions for acceleration, constant speed and vehicle deceleration. The WLTP test is much more dynamic, allowing analysis under rapidly changing vehicle traffic conditions. City driving allows for verification of the obtained results in real conditions.

2. A hybrid drive system based on two electric machines and a combustion engine with a planetary gear designed to sum up the power generated by the system and transfer it to the main gear and wheels, allows for such a selection of the drive source to optimise fuel consumption and, at the same time, recover the greatest amount of energy during deceleration and braking. This has been presented in graphs in individual phases of vehicle movement.

3. During driving, the MG2 motor-generator draws and returns similar amounts of energy to the batteries, regardless of the conditions in which the vehicle is moving, regardless of whether it is a NEDC or WLTP test, or city driving. Driving at high speeds increases the combustion engine's contribution; at higher vehicle speeds, it supplies a correspondingly larger share of the total energy.

4. During driving, the MG1 motor-generator is used to obtain the required driving speed and during the combustion engine operation to generate energy to power the MG2 engine and batteries. During the tests, the amount of generated energy is significantly greater than the energy drawn.

5. During the tests, the battery charge level was monitored by the controller and after the charge level dropped below 30%, the combustion engine was used to recharge them.

6. For high-dynamic acceleration, the combustion engine was mainly used, supported by the MG2 engine in the initial acceleration phase.

7. During intensive braking, the MG2 engine was used to recover energy stored in the battery.

Nomenclature

CAN	controller area network
e-CVT	electronically-controlled continuously variable transmission
EV	electric vehicle
ICE	internal combustion engine
MG1	motor-generator 1
MG2	motor-generator 2
NEDC	New European Driving Cycle
OBD	on-board diagnostics
SOC	state of charge
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

Bibliography

[1] Abdelsattar M, Aly M, Abu-Elwfa S. A review on hybrid electrical vehicles: architectures, classification and energy management. SVU-Int J Eng Sci Appl. 2024;5:93-99. https://doi.org/10.21608/svusrc.2024.263668.1177

[2] Berjoza D, Pirs V, Jurgena I. Research into the regenerative braking of an electric car in urban driving. World Electr Veh J. 2022;13;202. https://doi.org/10.3390/wevj13110202

[3] Braun A, Rid W. Energy consumption of an electric and an internal combustion passenger car. A comparative case study from real world data on the Erfurt circuit in Germany. 20th Euro Working Group on Transportation Meeting, EWGT 2017, 4-6 September 2017, Budapest. Transp Res Procedia. 2017;27:468-475. https://doi.org/10.1016/j.trpro.2017.12.044

[4] Byung Hoon Y, Kyoung Joo K, Hyung Soo M. Fast and robust hybrid starter and generator speed control for improving drivability of parallel hybrid electric vehicles. Energies. 2020;13;5055. https://doi.org/10.3390/en13195055

[5] Chen Y, Wu G, Sun R, Dubey A, Laszka A, Pugliese P. A review and outlook of energy consumption estimation models for electric vehicles. SAE J. STEEP. 2021;2(1):79-96. https://doi.org/10.4271/13-02-01-0005

[6] Ehsani M, Gao Y, Longo S, Ebrahimii K. Modern electric, hybrid electric, and fuel cell vehicles. 3rd Edition. Taylor & Francis Group. 2018.

[7] Emadi A. Advanced electric drive vehicles. CRC Press. Taylor & Francis Group. 2015.

[8] Enang W, Bannister C. Modelling and control of hybrid electric vehicles (a comprehensive review). Renew Sustain Energy Rev. 2017;74:1210-1239. https://doi.org/10.1016/j.rser.2017.01.075

[9] Evtimov I, Ivanov R, Sapundjiev M. Energy consumption of auxiliary systems of electric cars. BulTrans 2017. MATEC Web of Conferences. 2017;133:06002. https://doi.org/10.1051/matecconf/201713306002

[10] Ilyas U, Khan M, Ashfaq U. Energy optimization of hybrid energy storage system (HESS) for hybrid electric vehicle (HEV). Eng Proc. 2021;12:75. https://doi.org/10.3390/engproc2021012075

[11] Lisowski M, Gołębiewski W, Prajwowski K, Danilecki K, Radwan M. Modelling the fuel consumption by a HEV vehicle – a case study. Combustion Engines. 2023;193(2):71-83. https://doi.org/10.19206/CE-157112

[12] Mamala J, Śmieja M, Prażnowski K. Analysis of the total unit energy consumption of a car with a hybrid drive system in real operating conditions. Energies. 2021;14:3966. https://doi.org/10.3390/ en14133966
[13] Pielecha I, Cieślik W, Szałek A. Operation of electric hybrid drive systems in varied driving conditions. Eksploat Niezawodn. 2018;20(1):16-23. https://doi.org/10.17531/ein.2018.1.3
[14] Merkisz J, Pielecha I. Układy elektryczne pojazdów hybrydowych. Wydawnictwo Politechniki Poznańskiej. Poznań 2015.
[15] Miri I, Fotouhi A, Ewin N. Electric vehicle energy consumption modelling and estimation – a case study. Int J Energy Res. 2021;45:501-520. https://doi.org/10.1002/er.5700
[16] Opila D, Wang X, McGee J, McGee R, Cook JA, Grizzle JW. Performance comparison of hybrid vehicle energy management controllers on real-world drive cycle data. Proc Am Control Conf. 2009;4618-4625. https://doi.org/10.1109/ACC.2009.5160503
[17] Parczewski K, Wnęk H. Analysis of energy flow in hybrid and electric-drive vehicles. Energies. 2024;17:1915. https://doi.org/10.3390/en17081915
[18] Merkisz J.; Rychter M.; OBD II System as a future diagnostic methods of vehicles; Eksploat Niezawodn. 2002;1. https://doi.org/10.17531/ein 2002.1.5
[19] Szumska EM, Jurecki R. Parameters influencing on electric vehicle range. Energies. 2021;14:4821. https://doi.org/10.3390/en14164821
[20] Mamala J, Graba M, Mitrovic J, Prażnowski K, Stasiak P. Analysis of speed limit and energy consumption in electric vehicles. Combustion Engines. 2023;195(4):83-89. https://doi.org/10.19206/CE-169370
[21] Fluder K, Pielecha I, Cieślik W. The impact of drive mode of a hybrid drive system on the energy flow indicators in the RDE test. Combustion Engines. 2018;175(4):18-25. https://doi.org/10.19206/CE-2018-403
[22] Żylewski B. Badania i analiza parametrów eksploatacyjnych w pojeździe z napędem hybrydowym (in Polish). Engineering Diploma Thesis. University of Bielsko-Biala 2024.
[23] Controller Area Network (CAN) Overview. NI Engineer Ambiously. 2020;9.
[24] Toyota Motor Corporation; Corolla Hybrid Gasoline-Electric Hybrid Synergy, Drive Hybrid Vehicle Dismantling Manual. toyota-tech.eu (accessed on 03.10.2024).

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