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Determination of Rational Operating Modes for Hybrid Electric Vehicles

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Abstract

Plug-in Hybrid Vehicles (PHEV) are the bridge between Internal Combustion Engine Vehicles (ICEVs), and EVs. This paper describes Energy management, and possible energy management strategies of these vehicles to achieve the desired emission goals.
Environmental pollution is an increasingly significant issue in today's world. Failure to change daily routines- especially transportation habits-this could have severe consequences within a few decades. People are often posing the question about what the optimal balance between our fast-paced modern world could be and minimizing environmental impact, particularly in terms of vehicle selection. The solution may lie somewhere in the middle of the spectrum of regular cars with internal combustion engines (ICE), and pure electric vehicles (EVs). Due to the importance of the topic, this paper delves deeper into plug-in hybrid vehicles (PHEV).

Keywords

PHEV, HEV, energy-management, modelling, simulation

1 Introduction

It is important to highlight the role of transportation in environmental pollution. In Europe, transportation accounts for nearly 33% of total energy consumption and 23% of carbon dioxide emissions (Georgatzi et al., 2020). In recent years, as the greenhouse effect and air pollution have become increasingly severe, green energy has received increasing attention in all areas of life (Shu et al., 2021). The transition to electric road transportation has gained significant momentum in the past decade, facilitated by both technological advancements over the years and growing consumer interest. The compelling force behind the development of clean, efficient, and sustainable vehicles used in urban transportation stems from both environmental and economic considerations (Georgatzi et al., 2020). By 2025, the presence of electric vehicles (EVs) will become mandatory in every country. By 2030, the goal is to achieve carbon neutrality. EVs offer a potential solution to the transportation problems of today, and fortunately, these technologies are developing at an extremely rapid pace.

In 1888, Andreas Flocken built the first four-wheeled EV. However, it did not particularly spread further, as gasoline was considerably cheaper than electric power at that time. However, in the past 10 years, there has been increasing attention towards EVs, which is due to the growing carbon footprint and increased greenhouse effect.

Sziki et al. (2022), and Ádámkó et al. (2022) were investigating electric motor optimization, and vehicle optimization for increasing EV performance. When talking about reducing environmental pollution, it is important to mention the role of artificial intelligence (AI). Based on transportation data, AI helps regulate traffic jams and set traffic lights, and nowadays it is also used for accident prevention (Mahardhika and Putriani, 2023).

While media coverage predominantly focuses on electric vehicles (EVs) and their development, this research has opted to investigate plug-in hybrid electric vehicles (PHEVs). The reason for this is that until battery technology is at a point where it is comfortable to travel up to 500–600 km with a single charge under any climatic conditions, PHEVs can be an extremely good transitional or even permanent solution. Also, battery technology is not yet at a point where high energy density batteries can be manufactured. As a result, the batteries currently in use are not light enough. In the case of PHEVs, dependence on range is eliminated, as the internal combustion engine allows continued operation even when the battery

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is depleted, thus allowing the vehicle to continue driving. Advantages of PHEVs also include that they do not have as large a battery as EVs. This results in benefits such as lower weight and quick rechargeability from the home network. Utilizing a solar panel system can enhance greener and cost-effectiveness of daily transportation. Fig. 1 shows the drive system of a PHEV.

2 Methodology

2.1 Possible approaches and solutions

Numerous possible research methodologies arise in the case of this topic, as detailed below. This reflects the multifaceted nature of the chosen research topic, which can be examined with simpler Excel modeling (Szíki et al., 2014), MATLAB/Simulink® (Matlab/Simulink, 2025), testing under real conditions, or in the lab, testing under the most accurate conditions possible.

In such research, the more closely the situations can be approximated to reality, the more accurate and valuable the conclusions that can be drawn. Furthermore, the advantage of tests under real conditions is the collection of actual vehicle's driving data. However, it is important to mention that in this case too, many factors – the type of roads, the number of passengers, the experience, and habit of the divers, the age of the vehicle, and weather and climatic factors – can influence the research and play a role in the results. It is interesting to examine the phenomenon presented and examined in this paper – energy optimization – on different types of PHEV vehicles for comparison. This allows us to assess which models of which manufacturers perform the best. Furthermore, an important influencing factor is also the age of the PHEV vehicle. For example, a new PHEV recovers energy with greater efficiency thanks to regenerative braking than a PHEV with several years of technology. This comparison also shows how much technology has developed and is developing over time. And how many factors can influence the degree of success of energy management. A test based on the comparison of several vehicles would have been complex, time- and cost-intensive, so a simpler solution for this research has been chosen.

Among the possible and emerging methodologies is modeling in Matlab/Simulink®, which would allow for more detailed modeling of the factors under investigation. This leads to more accurate results that are closer to reality than simpler modeling in Excel. However, the use of Matlab/Simulink is more complex and requires experience, and a high level of programming knowledge.

A suitable toolkit is also available in Matlab/Simulink®. Fig. 2 shows a hybrid drive system in Matlab/Simulink® with the program toolkit. (From Matlab demo)

Weighing the above, simulation modeling proved to be the most efficient approach during the research. The Excel-based model provides an opportunity for a detailed analysis of various energy management scenarios. Its advantage is its ease of use and simplicity of visualization, which helps in interpreting the data derived from the model.

Each of the listed methods has its own advantages and disadvantages. Despite the simplicity and ease of use of Excel, it is limited in terms of complexity. Matlab/Simulink® allows for more accurate modeling, but it is more complex and requires a higher level of expertise. The advantage of simulation modeling is that it allows for the management of a wide range of variables while maintaining flexibility and cost-effectiveness.

As for the test procedures, both the globally harmonized light-duty vehicles test procedure (WLTP) and the New European Driving Cycle (NEDC) can be used during modeling. Calculations using different methods give different results due to different implementations of the test cycle. These two driving cycles are used for both emission and consumption determination. The methodology we choose, comparing the Excel-based model with real driving data, allows for the examination of the main goal of the research – the possibilities of energy optimization – while maintaining comfort and limiting complexity. (Balogh, 2023)

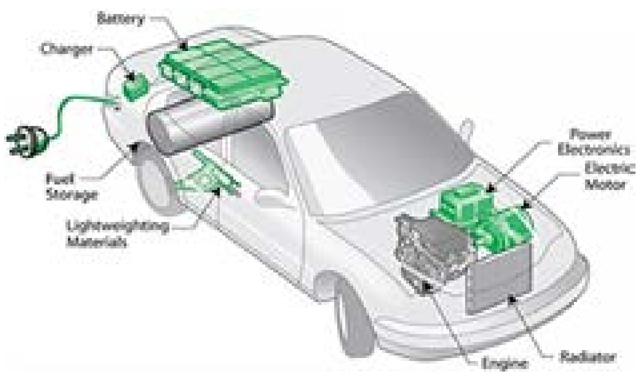

Fig. 1 Plug-in hybrid vehicle drive system (Argonne National Laboratory, 2023)

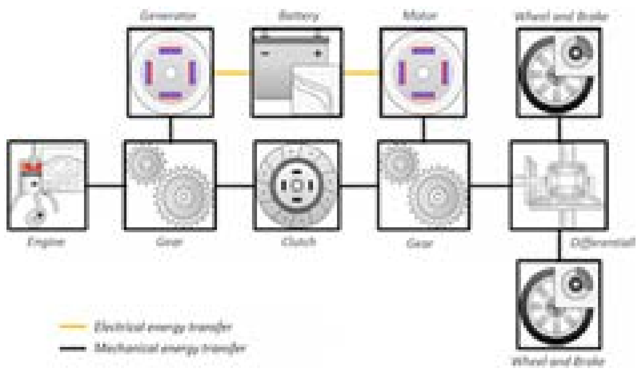

Fig. 2 Hybrid drive system created using Matlab/Simulink® toolkit

2.2 The chosen problem-solving method

In the research, the consumption of a Kia XCeed plug-in hybrid vehicle and a traditional internal combustion engine-equipped Volvo S60 D5 were modeled in Excel, based on the NEDC driving cycle. Three different cases were investigated. For the first time, the PHEV was chosen as its NEDC cycle exclusively with electric drive; followed by the NEDC cycle of the PHEV with hybrid drive; finally, the cycle of a conventional Volvo S60 D5 with an internal combustion engine was tested. The study also includes an ICE powered vehicle because the PHEV cannot drive only in internal combustion mode, but only in EV and hybrid modes. After modeling in Excel, the results were compared with the same strategies in real life. Differences between these are expected, as other factors arising from real driving conditions, e.g., wind or differences in rolling resistance due to road defects, are not included in the calculated data. In research, the NEDC cycle was chosen instead of the WLTP cycle because it is easier to implement both in Excel and in real life. The NEDC driving cycle test process consists of four urban driving cycles (UDCs) and one road-to-motorway higher speed cycle (EUDC).

Table 1 shows details of the first stage of the UDC, which is repeated four times during the NEDC driving cycle before the EUDC cycle. An urban cycle consists of 195 s, and the four urban cycles are a total of 780 s.

Table 1 One of four urban cycles (UDCs) from the NEDC cycle

Section	Task for the NEDC tables
Section 1	Stand for 11 s
Section 2	Acceleration to 15 km/h in 4 s
Section 3	Driving up to 8 s at 15 km/h
Section 4	Slowing down to 0 km/h in 5 s and then stop
Section 5	Stand for 21 s
Section 6	Acceleration to 32 km/h in 12 s
Section 7	Driving up to 24 s at 32 km/h
Section 8	Slowing down to 0 km/h in 11 s and then stop
Section 9	Stand for 21 s
Section 10	Acceleration to 50 km/h in 26 s
Section 11	Driving up to 12 s at 50 km/h
Section 12	Slowing down to 35 km/h in 8 s
Section 13	Driving 13 s up to 35 km/h
Section 14	Slowing down to 0 km/h in 12 s and then stop
Section 15	Stand for 7 s before starting the next cycle

The average speed over the four urban cycles is 18.35 km/h. The road/highway cycle consists of 400 s. It means, the duration of the NEDC cycle is 1180 s. The average speed in this cycle is 62.6 km/h. Table 2 shows the individual stages of the EUDC cycle. The NEDC also specifies that the measurement must be carried out with an additional weight of 100 kg in addition to the vehicle's unladen weight.

Fig. 3 is intended to visualize the NEDC cycle on a graph, depicting the vehicle's speed as a function of time.

Following the representation of the NEDC cycle on the diagram, the data and quantities that are essential for modeling and to be calculated are detailed in Table 3 to determine the energy consumption and the consumption of the internal combustion engine. ***t*** represents the elapsed time in seconds (s), ***v*** denotes the vehicle's velocity in km/h, and in m/s next to it. The latter is equivalent to the distance covered by the vehicle during the given second. The ***a*** is the acceleration of the vehicle in $\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right)$, the **sum *s*** the total

Table 2 The individual stages of the EUDC cycle

Section	Task for the NEDC tables
Section 1	Stand for 20 s
Section 2	Acceleration to 70 km/h in 41 s
Section 3	Driving up to 50 s at 70 km/h
Section 4	Slowing down to 50 km/h in 8 s
Section 5	Driving up to 69 s at 50 km/h
Section 6	Acceleration to 70 km/h in 13 s
Section 7	Driving up to 50 s at 70 km/h
Section 8	Acceleration to 100 km/h in 35 s
Section 9	Driving up to 30 s at 100 km/h
Section 10	Acceleration to 120 km/h in 20 s
Section 11	Driving up to 10 s at 120 km/h
Section 12	Slowing down to 0 km/h in 34 s
Section 13	Stand for 20 s

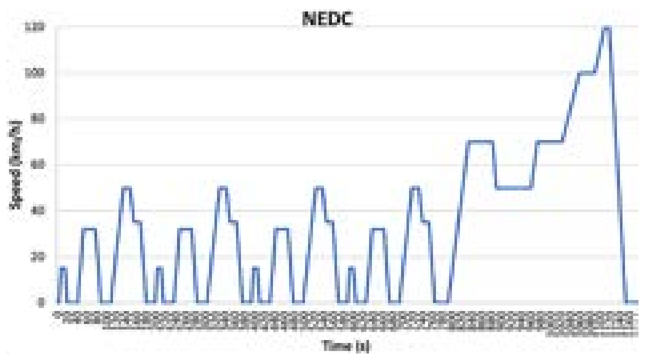

Fig. 3 NEDC cycle velocity-time graph

Table 3 Excel variables for the calculations

Variables, (units)												
t	v	v	a	sum s	F_{drag}	F_{roll}	Sum F	Work	F_{acc}	W_{acc}	F_{brake}	W_{brake}
(s)	(km/h)	(m/s)	(m/s^2)	(m)	(N)	(N)	(N)	(kJ)	(N)	(kJ)	(N)	(kJ)

distance traveled in meters for the given second. In this case F_{air} means the air resistance, which can be calculated based on $F_{air} = \frac{\varsigma_{air}}{2} \cdot c_w \cdot A \cdot v^2$. In this formula the ς_{air}, is the density of air, which was calculated as 1.28 $\frac{kg}{m^3}$ at the modeling. Since the temperature during the real measurement was 4 °C, the temperature of the modeling was also set to this. The c_w is the drag coefficient of the vehicle, which is 0.33 for the PHEV vehicle and 0.28 for the conventional motor vehicle. The ***A*** is the frontal surface area of the vehicle, which is 2.359 m^2 for the Kia, and 2.235 m^2 for the Volvo. The ***v*²** is the square of the velocity.

The rolling resistance, denoted as F_{roll}, is expressed using the formula $F_{roll} = m \cdot g \cdot g_l$, where m represents the mass of the vehicle. For the Kia, this mass is 1745 kg, which is the sum of the vehicle's mass (1565 kg) and the driver + passenger's mass (180 kg). Similarly, for the Volvo, the total mass is 1715 kg (Volvo mass: 1535 kg; driver and passenger's mass: 180 kg). The ***g*** is the gravitational acceleration, which is 9.81 $\frac{m}{s^2}$ where the measurements were made. The g_l is the coefficient of rolling resistance, which in the calculations was determined as 0.02 due to possible road defects, rain and winter tire. The units of air and F_{roll} are (N). The **Sum *F*** is the total running resistance, Sum $F = F_{air} + F_{roll}$. The ***W*** the work required to overcome running resistances in (kJ) at that time. The F_{acc} shows how much force is required to accelerate the vehicle; this is only relevant if there is acceleration. The W_{acc} work due to acceleration up to the given time, also in (kJ). The F_{brake} shows how much braking force is required. Here it is necessary to consider that the running resistances are also brake. This is present when the vehicle is decelerating, i.e., if a < 0. The W_{brake} work of braking until the given date; this is energy that can be stored, i.e., recovered. The calorific value of 1 kg of fuel is 44 MJ/kg for both petrol and diesel.

2.3 The calculations

The environmental aspects of the real driving test are presented below and the basic data of the two vehicles are shown (Table 4).

The test was carried out relatively late, at 11 p.m., in a real traffic situation, minimizing traffic influences and obtaining relevant and comparable results from the measurement.

Table 4 Data of vehicles participating in modelling or testing

Variables	Type of vehicle	
Vehicle parameters	Kia XCeed PHEV	Volvo S60 D5
ICE	1580 cm^3 petrol Max. power: 105 (LE) Max. torque 147 (Nm)	2401 cm^3 diesel Max. power: 185 (LE) Max. torque 400 (Nm)
Electric motor power	Max. power: 60 (LE) Max. torque: 170 (Nm)	-
Combined system power	Max. power: 140 (LE) Max. torque: 265 (Nm)	-
Electric motor battery	Lithium-ion polymer Capacity 8.9 kWh	-
Gear	6 gears dual-clutch (DCT) automatic	6 gears AISIN, hydromechanics automatic transmission
Mass	1565 kg	1535 kg
Tire size	215/50 R18	205/55 R16

Real-life measurements were made under the following environmental factors:

- Outside temperature: 4 °C,
- Precipitation: rain, large puddles on asphalt, water flows occurred,
- 93 %-humidity,
- Wind speed as 25 km/h.

3 Result and discussion

The following are the results obtained by modelling and testing in real driving conditions. First, the Kia XCeed plug-in hybrid vehicle, powered by pure electric power, is modelled and measured in real driving conditions.

3.1 Results obtained by modeling in EV mode

By the end of an urban cycle, i.e., a UDC cycle, the vehicle covered 1.00731 m in 195 s. The rolling resistance of the vehicle is constant 342.37 N. This has no effect when the car stands still. The maximum drag in this cycle was 95.73 N at 50 km/h. The wind intensity has not been defined in the simplified Excel modeling. The combined force of rolling resistance and aerodynamic drag was 438.1 N at a speed of 50 km/h. By the end of the first UDC cycle, the work required to overcome resistance was 395.61 kJ.

Up to this moment, the work needed for acceleration amounts to 268.9 kJ. The braking work performed thus far is 152.31 kJ, which represents recoverable energy. The theoretical efficiency of regenerative braking falls within the range of 60–70%. Considering the conditions during measurements, the calculations were performed using average efficiency, specifically 65%. Upon completing the fourth urban cycle, the vehicle covered 4029.22 m in 780 s. At the end of the cycle, the essential data are as follows: the work required to overcome rolling resistance over the four urban cycles amounts to 1582.43 kJ; the work needed for acceleration during the 780 s is 1075.6 kJ; and the energy recoverable through braking totals 609.26 kJ. These computed values indicate that the cumulative work needed to overcome resistance and achieve acceleration remains significantly greater than the energy reclaimed through braking. In quantitative terms, the implementation of the EDC stage requires 2048.8 kJ of invested energy, which is obtained by adding up the energies needed to overcome driving resistances and accelerate the vehicle, as well as subtracting the energy recovered by regenerative braking. The EUDC stage duration is 400 s covering a distance of 6810.85 m.

The rolling resistance value remains the same, but the maximum air resistance was not surprisingly experienced when reaching and maintaining the top speed at 120 km/h. It has a value of 551.42 N, which is almost six times the air resistance at 50 km/h. At the end of the entire NEDC cycle, the work required to overcome running resistances is 5628.27 kJ and the work invested in acceleration is 2219.81 kJ. With a 65% efficiency of regenerative braking, 1323.7 kJ of electricity can be stored back into the battery by braking over the entire cycle. This means that 6524.38 kJ of energy must be injected by the end of the cycle to complete the NEDC cycle, i.e., during the cycle I consume 1.814 kWh of electricity from the battery. The test cycle takes place over a distance of 10.840 m, resulting in an electricity consumption of 16.734 kWh per 100 km. This translates into an internal combustion engine consumption of about 7 liters. Meanwhile, the battery will be charged at 35 HUF/kWh at best, and 70 HUF/kWh in less favorable. Of course, the most ideal case is to use electricity generated by solar panels to charge the vehicle, since in this case it costs 0 HUF to charge the vehicle. Since the battery has a capacity of 8.9 kWh, a charge calculated with 35 HUF is 311.5 HUF. With this, approximately 53–54 km can be covered. The same case costs 623 HUF at a price of 70 HUF/kWh. The electricity consumption calculated per 100 km is 585.2 HUF, calculated with the more favorable price of 35 HUF/kWh. Nowadays, the price of a liter of petrol is 580 HUF (2023). Based on the previously mentioned consumption of 7 liters, 100 km can be covered from 4060 HUF with a vehicle equipped with an internal combustion engine.

Furthermore, it is important to show what percentage of battery charge is drained and how it behaves during the test cycle. I modeled the percentage-time charge graph in Excel (Fig. 4), which illustrates how much the vehicle's battery has discharged for a given second. It can also be read from the graph that at lower speeds the electricity recovered by regenerative braking is negligible.

This is due to the presence of both rolling and air resistance during braking. At higher speeds, especially when braking from 120 km/h to 0 km/h, the advantage of regenerative braking is striking. The battery of the vehicle used in the test discharged 20.38% (Table 5).

Determination of basic data by modelling and conversion of these works into kWh. This was necessary to calculate the percentage of battery capacity loss during the NEDC cycle.

3.2 Real driving test in EV mode

The test in EV mode was conducted on the Kia XCeed PHEV in real driving conditions. The given driving

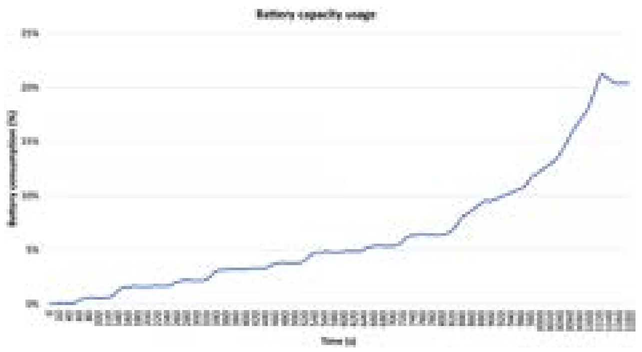

Fig. 4 Battery discharge as a percentage during the test cycle

Table 5 Results obtained at the end of the NEDC cycle in EV mode only

Bottomline of the calculating Excel chart												
sum s	F_{drag}	F_{roll}	Sum F	Work	W	F_{acc}	W_{acc}	W_{gy}	F_{br}	W_{br}	W_{total}	Capacity
(m)	(N)	(N)	(N)	(kJ)	(kWh)	(N)	(kJ)	(kWh)	(N)	(kJ)	(kWh)	(%)
10840,07	0.00	342,37	342,37	5628,27	1.564660	0.00	2219,81	0.617107	0.00	–2036,46	–1.814	20.38

conditions were not the most suitable for the measurement, such as the 4 °C recorded during the test. In the cold, energy consumption is higher, and since it was 4 °C, this did not favor the operation of the battery. Density of air at 4 °C is 1.28 kg/dm^3. Lithium-ion batteries operate most efficiently within a temperature range of 15–35 °C. At lower temperatures, the electrolyte fluid becomes more viscous, slowing down lithium-ion movement, and lithium plating can form on the anode, reducing the battery's capacity and efficiency. Because of this effect, energy production decreases, potentially reducing the range by 20–40%. There may be further measurement inaccuracies, such as not accelerating to the exact speed required or not keeping the speed correct. Freezing road surfaces may require frequent traction control interventions, which increases energy consumption and therefore causes speed fluctuations. Thus, there may be subtle differences in the result. The vehicle is manufactured in 2022, so battery degradation was not considered in the measurement. Results were determined based on battery capacity and the difference in battery levels at the beginning and end of the measurement. When the measurement started, the battery charge was 98%. At the end of the measurement, the vehicle's on-board system indicated a 77% battery charge (Figs. 5 and 6). It is important to mention that in EV mode the vehicle does not provide cabin heating, only seat and steering wheel heating. There is neither a separate fiber heater nor a heat pump heater installed in the vehicle. The vehicle uses heat from the internal combustion engine for heating, just like a conventional internal

Fig. 5 Vehicle battery level at the start of the test cycle (in EV mode)

Fig. 6 Vehicle battery level at end of test cycle (in EV mode)

combustion engine vehicle. For accuracy, the test was conducted without heating, which greatly complicated the viewing conditions.

Based on this, it is possible to calculate the electricity consumed from the battery. In the present case, it is 1.869 kWh; This is how much the vehicle consumed during the test. The electricity consumed per 100 km is 17.241 kWh. In the case of internal combustion engine driven mode, this corresponds to about 7.3 liters of petrol, which is not much different from the modelling figures. The minimal deviation is due to wind and possibly not entirely accurate realization of the cycle.

3.3 Results obtained by modeling in hybrid (HEV) mode

Due to the limitations of the vehicle used for measurement – it automatically switched the electric drive on and off and started and stopped the internal combustion engine itself – I perform the modeling in Excel based on the processed literature, my studies so far and my own experience. I show the most efficient and favorable energy consumption in hybrid mode. The essence of PHEV is to reduce dependence on fossil fuels and also the range dependence that comes from limiting the range of electric propulsion. Based on the literature, my hypothesis is that PHEVs should only be used in electric mode when driving in cities. If you want to travel longer distances, hybrid mode is the most efficient way to get around. It is important to note that in electric mode the vehicle can only accelerate up to 120 km/h, after which the internal combustion engine will also start.

During the modelling, the four urban cycles were electrically driven, and then the 69-s section at 50 km/h in the road/motorway cycle was also electrically driven. In hybrid mode, there is regenerative braking in the same way as in electric mode. In the case of a vehicle powered exclusively by an internal combustion engine, fuel consumption is maintained even when stationary; In hybrid mode, the combustion engine does not operate, only the electric drive system.

The rolling resistance of the vehicle, like the EV mode, is constant at 342.37 N. The resistance required to overcome the maximum running resistance occurs at 50 km/h in the UDC stage. Its value is 438.1 N. From this it is clearly visible that rolling resistance increases consumption much more than this speed. At the end of the first UDC stage of 195 s and 1007.31 m, the work required to overcome the previous running resistances is 395.61 kJ. Until that date,

the work required for acceleration is 268.9 kJ; the braking work, i.e., the energy that can be stored, is 152.31 kJ (still 65% regenerative braking efficiency). The energy invested and used to complete the first UDC cycle is 512.2 kJ. The four identical urban cycles take place in 780 s over a distance of 4,029.22 m. The work required at the end of urban cycles is 2048.8 kJ. The EUDC – the road/motorway cycle – takes 400 s. The first stage of the EUDC is 20 s stationary; Despite the hybrid mode, the vehicle completes this stage exclusively in electric mode. During this period, the energy consumption was negligible, and thus omitted from the calculation. On the entire cycle of the EUDC, maximum air resistance is generated at 120 km/h. Its value is 551.42 N. Compared to air resistance at 70 km/h, this value is almost three times higher, as only a counterforce of 187.63 N is generated here. As previously stated, the 50 km/h section of the EUDC cycle is conducted exclusively in EV mode. Regenerative braking is consistently present throughout the NEDC cycle, as hybrid mode is modeled. Based on modelling, the electricity consumed during the whole NEDC cycle is 1754.2 kJ, which is 0.487 kWh. This represents 5.47% of the battery capacity. The fuel consumption modelling of the internal combustion engine is calculated using the technical data of the internal combustion engine of the plug-in hybrid vehicle, not the total power combined with the electric drive system.

The consumption of the internal combustion engine was calculated with the following values:

Effective power: 77.2 kW,
Mechanical efficiency $\eta_m = 0.8$,
Indicated efficiency $\eta_i = 0.35$,
Calorific value of fuel $H_{petrol} = 44$ MJ/kg.

<u>Which can be used to determine the following calculations:</u>

Effective efficiency: $\eta_{eff} = \eta_m \cdot \eta_i = 0.8 \cdot 0.35 = 0.28 = 28\%$
Effective specific fuel consumption:

$$b_t = \frac{1}{\eta_{eff} \cdot H} = \frac{1}{0.28 \cdot 44 \cdot 10^6} = 8.11 \cdot 10^{-8}\ \text{kg}/(\text{Ws}),$$

$$b_t^h = b_t \cdot \frac{10^3}{10^{-3} \cdot \frac{1}{3600}} = b_t \cdot 3600 \cdot 10^6 = 8.61 \cdot 10^{-8} \cdot 3600 \cdot 10^6 = 292.21 \frac{\text{g}}{\text{kWh}}.$$

In hybrid mode, the work required to overcome running resistances throughout the NEDC cycle is 3619.91 kJ; the value of the work required for acceleration is less, 1144.21 kJ. This means that the work invested by the internal combustion engine is 4764.12 kJ. The result obtained is converted into 1.32 kWh. The result of the effective specific fuel consumption is 292.21 g/kWh, which means that 1 kWh of energy can be produced by burning 292.21 g of petrol. 730 g. The amount of fuel consumed during the NEDC cycle is calculated to be 385.71 g of petrol. This translates into a consumption of 0.528 liters for the duration of the cycle. The average consumption per 100 km can be calculated using a ratio. The ratio is obtained by dividing 100 km by the number of meters travelled during the cycle, which is 10 840.07 m: 100000/10840.07 = 9.225. The average fuel consumption per 100 km is 4.9 liters. Since the vehicle is in hybrid mode, it does not consume fuel when stationary. For this reason, the amount of fuel consumed at idle speed is not counted. In total, a consumption of 4.9 liters per 100 km and a 5.47% reduction in battery capacity are given when modeling in hybrid mode.

3.4 Real driving test in hybrid (HEV) mode

Prior to testing under real driving conditions, the meter has to be reset. By the end of the test, it produced an average consumption of 5.0 liters per 100 km. Also, during the test, there was a 3% decrease in battery capacity (Figs. 7–9). This was verified by arriving at a petrol station at the end of the test and filling up the vehicle, making sure that the vehicle's on-board computer showed the correct consumption value.

The combustion engine-only mode was modeled on another vehicle, as well as the real driving test, as the PHEV cannot be driven exclusively in internal combustion mode.

Fig. 7 Vehicle battery level at end of test cycle (in EV mode)

Fig. 8 Vehicle battery level at end of test cycle (in EV mode)

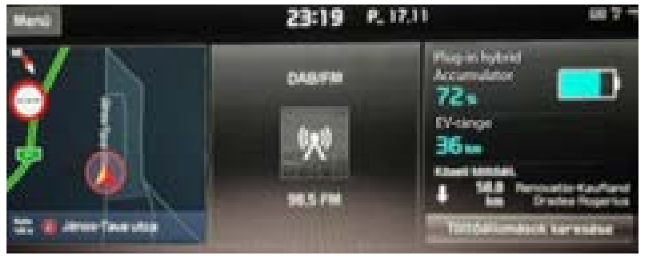

Fig. 9 Battery level in hybrid mode at the end of the test cycle

At the end of the NEDC cycle, the work required to overcome the running resistance is 5188.52 kJ, while the work required for acceleration is 2181.65 kJ at the end of the cycle. The work that can be recovered by braking is 2001.45 kJ. In this case, this becomes mechanical work, i.e., thermal energy, since the vehicle does not have a battery and electric drive. Adding up the work required to overcome running resistance and acceleration, it results in 7370.17 kJ of work. This is 2.05 kWh converted.

Values used for the calculations:

Effective power: 136 kW,

Mechanical efficiency $\eta_m = 0.8$,

Indicated efficiency $\eta_i = 0.32$,

Calorific value of fuel $H_{\text{diesel}} = 44$ MJ/kg.

Which can be used to determine the following calculations:

Effective efficiency: $\eta_{eff} = \eta_m \cdot \eta_i = 0.8 \cdot 0.32 = 0.256 = 25.6\%$

Effective specific fuel consumption:

$$b_t = \frac{1}{\eta_{eff} \cdot H} = \frac{1}{0.256 \cdot 44 \cdot 10^6} = 0.000000088778409\,\mathrm{kg/J}$$

$$= 8.878 \cdot 10^{-8}\,\mathrm{kg/(W \cdot s)},$$

$$b_t^h = b_t \cdot \frac{10^3}{10^{-3} \cdot \frac{1}{3600}} = bt \cdot 3600 \cdot 10^6 = 8.878 \cdot 10^{-8} \cdot 3600$$

$$\cdot 10^6 = 319.603 \frac{\mathrm{g}}{\mathrm{kWh}}.$$

The 319.603 $\frac{\mathrm{g}}{\mathrm{kWh}}$ means that 319.603 g fuel is required to produce 1 kWh energy. Based on 2.05 kWh, the vehicle consumes 655.185 g of fuel over the duration of the NEDC cycle. This is 6044.07 g of fuel consumption per 100 km, divided by the cycle length of 10.840 m. This gives the ratio, which is equal to 9.225. The amount of fuel consumed during the cycle is multiplied by the ratio obtained earlier. The weight of one liter of diesel is 830 g. With the help of data, at the end of modeling, the results indicate that the vehicle's consumption is 7.3 liters per 100 km. To this is added the fuel consumption during standstill according to the cycle. The consumption of the vehicle is 0.9 liters per h. Stand time is 280 s, or 7/90 h. Consequently, the total consumption is calculated to be 7.37 liters per 100 km.

3.5 Real driving test with combustion engine

Before the test in real driving conditions, the meter was reset to zero. By the end of the test, consumption was 7.5 liters per 100 km. At the conclusion of the drive, the vehicle was refueled and the on-board computer was checked for possible measurement errors. The consumption calculated after refueling matched the result obtained through alternative methods. The discrepancy of 0.13 liters may be attributed to measurement inaccuracies and wind gusts, which were not accounted for during the modeling.

4 Conclusion

The aim of the research was to find the most efficient way to improve the energy consumption of plug-in hybrid cars, especially in the NEDC cycle. Based on the results (Table 6) obtained by the modelling, many valuable conclusions can be drawn about the energy management of plug-in hybrids.

The results obtained indicate that even with simplified Excel modeling, fairly accurate results can be obtained compared to tests in real driving conditions. What is even more important to stress is that the results make it clear how plug-in hybrid vehicles should be driven. Based on modelling and real-world tests, it turns out that PHEVs are best used in purely electric mode when driving in cities. However, it should be considered that the tested Kia XCeed PHEV does not have a separate heater, so heating requires the thermal energy of the internal combustion engine, for which it also needs to run the ICE. This makes it impossible to drive in EV mode. According to the owner, this anomaly can be eliminated by turning on the seat and steering wheel heaters, which, according to him, give a pleasant feeling of heat. However, they do not help the more extreme weather conditions that arise during the test. Unfortunately, the windscreen fogs up, which requires the heat of the internal combustion engine to dehumidify, which immediately makes driving in EV mode impossible. It is advisable to cover longer distances in hybrid mode or, if possible, only in internal combustion engine mode. PHEVs are not equipped with a large battery pack, therefore, it is advisable to use this type of motor vehicle in electric mode only in the city.

Table 6 Results obtained at the end of the NEDC cycle only with ICE

Calculated results												
t	v	v	a	sum s	F_{drag}	F_{roll}	Sum F	Work	F_{acc}	W_{acc}	F_{brake}	W_{brake}
(s)	(km/h)	(m/s)	(m/s²)	(m)	(N)	(N)	(N)	(kJ)	(N)	(kJ)	(N)	(kJ)
1180	0.00	0.00	0.00	10840.07	0.00	336.48	336.48	5188.52	0.00	2181.65	0.00	–2001.4

Today's PHEVs are not yet equipped with the most sophisticated artificial intelligence (AI) technologies, so optimal management of energy management is largely the responsibility of the user. Switching between drive modes is possible using a switch. A much more effective solution would be for AI technology instead of the driver to decide on the drive mode based on the analysis of various aspects. This means that the vehicle should be able to decide on the operating mode based on the data provided by the navigation. For example, when I get to town, charge the battery or leave enough charge in the battery to pass through the city.

This would make it possible to minimise local pollution and consumption. In addition, the vehicle could optimize energy consumption even more accurately if it communicated and shared data with the driver's calendar in addition to navigation. By analyzing the data, you would know when and how much to charge your battery based on your next or same day's use. This system can most effectively be complemented by a photovoltaic system to operate the vehicle as economically as possible.

Thanks to their versatile use, PHEVs have the advantages of two different types of vehicles – be it cost reduction, environmental awareness or enabling long-distance driving. Considering a classic household with 2 children as the basis for an imaginary example, then it is not necessarily necessary to have an electric car and an internal combustion engine vehicle separately. Short trips within the city or from the agglomeration to the city are perfectly feasible in electric mode, while longer distances can be driven with the internal combustion engine.

In summary, the most efficient way to drive the PHEV is to drive electrically in the city and activate the hybrid drive only on longer, faster routes. When combined with solar charging, PHEVs can achieve an extremely affordable specific cost. It is also more cost-effective to charge a hybrid battery from a home network than to charge it with the help of an internal combustion engine, using the internal combustion engine as a kind of generator.

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