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Sustainable operation? Measuring the actual consumption of a hybrid car and determining its consumption curve

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Abstract

Sustainability is one of the most commonly used terms concerning renewable energy, environmental protection and energy management. Without a doubt, understanding its full meaning, it is clear that sustainability is paramount for the quality of life of future generations and for the Earth as a living space. The presented work aims to give an overview of the importance of on-board management in hybrid vehicles as an important tool to increase their contribution to sustainable mobility. Real-world condition measurements were carried out based on the available cognitive features of an average vehicle. Several main consumers were also tested to present their role within cognitive and sustainable mobility. Results show that there is a function between the battery load level and the hybrid vehicle electric power use likeliness. Among the primary but under-addressed concerns today are the uninhibited exploitation of non-renewable energy sources and the avoidance of pollution.

Keywords
sustainability, climate changes, vehicle industry, waste reduction

1 Introduction

The automotive industry is one of the largest emitters during manufacturing, considering any technology, and during the product's life cycle. The car industry is trying to become more sustainable in several ways. These include:

- Electric vehicles (EVs): electric cars are powered by an electric motor instead of a conventional combustion engine. EVs could be environmentally friendly during use, as they do not emit pollutants in the direct exhaust. EVs can reduce greenhouse gas emissions long-term if energy production comes from clean sources.
- Hybrid vehicles: hybrid cars combine internal combustion engines and electric motors. Hybrid systems enable improved fuel efficiency and reduced emissions. Such vehicles can operate quietly and in an environmentally friendly way on short journeys with an electric motor, while on longer journeys, the combustion engine provides the power (*Koller et al. 2022*).
- Fuel cell vehicles: fuel cell cars use hydrogen as fuel, which is converted into electricity in fuel cells. This produces clean water vapour as an emission. Fuel cell vehicles can provide longer range and faster recharging than electric cars (*Chechresaz, 2013*).
- Use of environmentally friendly materials: car manufacturers increasingly use environmentally friendly materials to make cars. For example, they apply more recycled materials, bio-based plastics and lightweight metals, which reduce the ecological footprint of cars.
- Improving the efficiency of manufacturing processes: in the automotive industry, improving the efficiency of manufacturing processes also contributes to bringing the industry closer to sustainability. Using energy, raw materials and waste in manufacturing significantly impacts the environment and society (*Yang et al., 2014*).

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2 Background

Over the last decades, developed countries have taken several measures to reduce emissions of greenhouse gases and soil and groundwater pollutants, mainly for economic reasons but also for human comfort, with varying degrees of success.

The EURO emission standards are widely used, and they are the drivers of drivetrain development regulations in the automotive industry, which are summarised in the list below:

- Euro 1 (1992):
  - For passenger cars-91/441/EEC (*Da Costa et al., 2012*).
  - Also, for passenger cars and light lorries-93/59/EEC.
- Euro 2 (1996) for passenger cars-94/12/EC (96/69/EC)
  - For motorcycle-2002/51/EC (row A)
- Euro 3 (2000) for any vehicle-98/69/EC (*Chehresaz, 2013*)
  - For motorcycle-2002/51/EC (row B)
- Euro 4 (2005) for any vehicle (98/69/EC & 2002/80/EC)
- Euro 5 (2009) for light passenger and commercial vehicles (715/2007/EC)
- Euro 6 (2014) for light passenger and commercial vehicles (459/2012/EC and 2016/646/EU)
- Euro 7 (probably 2025).

The EURO 7 regulation is not expected to introduce any significant tightening compared to the previous stage but puts petrol and diesel cars on an equal footing. As far as we know, this regulation will be in place until the end of 2034, when it will be replaced by new EU legislation from 2035, requiring new cars placed on the market to be zero-emission. Of course, the unplanned development of technology or the insufficient development of the electric grid and, in this case, charging points could mean a postponement of the introduction of the regulation.

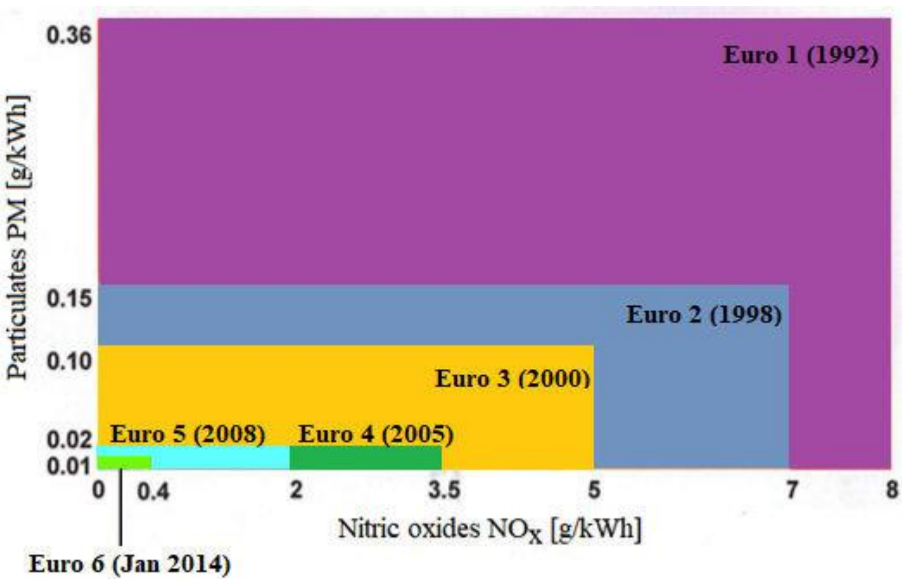

Figure 1. EURO 1–6 emission standards PM/NO_x

Source: Jurchiş, et al., 2018

Sustainability in all areas of the automotive industry is becoming extremely important, and, as a result, the automotive industry is undergoing a radical transformation. Four main trends drive this transformation: electric mobility, shared mobility services, autonomous driving and connected vehicles. The growing interest in electric cars and innovative mobility concepts shows how sustainability has become a key issue. At the same time,

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developers and investors are also paying increasing attention: they want to understand the risks and threats faced by car manufacturers and suppliers and, simultaneously, avoid the loss of prestige associated with non-climate-friendly companies.

This development is being accelerated by both political requirements and changing consumer preferences. Some manufacturers and suppliers have implemented these trends, at least to some extent. For example, they are increasing their fleet of electric vehicles and offering flexible mobility concepts. However, the opportunities are far from exhausted: transforming the automotive industry into a truly sustainable industry is still a long way off (*Zöldy, 2009*).

As far as energy efficiency is concerned, car manufacturers are increasingly improving their energy efficiency. This may include using more efficient machinery and equipment, using renewable energy sources for production processes, and recovering waste heat and wastewater.

Three main themes characterise this development:

1. Climate change and CO_2 emissions

Climate change and its impacts have long been the subject of widespread public debate. As a result, legislators have significantly tightened CO_2 emission standards in recent years. Car manufacturers must reduce CO_2 emissions from vehicle production and the fleet. In this context, using alternative powertrains such as fuel cells, electric drives, and hybrid drives plays an important role.

2. Sustainability of the value chain

As natural resources become scarce, sustainable value chains are becoming increasingly important for the automotive industry. They are based on the principle of resource reuse and recycling. It is particularly important to create transparency along the supply chain. Only then can the origin of components be traced and sustainability ensured along the entire value chain. In this light, car manufacturers and suppliers are working on innovative concepts such as the circular economy, battery recycling, biodegradable components and sustainable processes in research, development and manufacturing.

3. Digital Responsibility

With the increasing uptake of autonomous and connected vehicles, issues such as digital value creation, privacy and data security are coming to the fore. On the one hand, automotive manufacturers and suppliers must define the digital features and technologies needed to deliver sustainable solutions. On the other hand, strict policies are needed to prevent data breaches.

3 Test methods

Our research focused on exploring a solution, the hybrid drive, which is regarded as a sustainable alternative in the short to medium term, both environmentally and economically. Plug-in hybrid drive vehicles (PHEV) are the ones that come close to the desired goals at an affordable price and with lower emissions (*Yang et al., 2014*).

The key of the presented research is to measure the energy flow on the vehicle. There are many different ways and many different methods to determine the consumption of vehicles. The purpose of determining average fuel consumption is to inform the customer of the approximate fuel costs of maintaining the chosen vehicle and to determine the vehicle's emissions based on this value. These theoretical procedures, however, do not consider several factors that may distort emissions and fuel consumption figures in real-life conditions (*Zöldy, 2019*).

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The most commonly used fuel consumption and emission measurement methods are presented in the next chapter. They serve as a benchmark for the test carried out.

The New European Driving Cycle (NEDC) was the first driving cycle model to become widespread. It was developed in the 1970s and updated with empirical knowledge. The last update was in 1997 but was still used in 2019 (*Koller et al., 2022*).

The year-by-year faster development in the automotive industry requires a new measurement model; driving habits have changed, requiring longer distances over a wider geographical area, better quality roads, and larger road networks; average speeds have become significantly higher, and modern cars have become larger and heavier (*Zsombok, Zöldy, 2023*). The NEDC measurement cycle is two-phase: urban and 'extra-urban'. The test assumed an ideal, calm environment, which led to erroneous results.

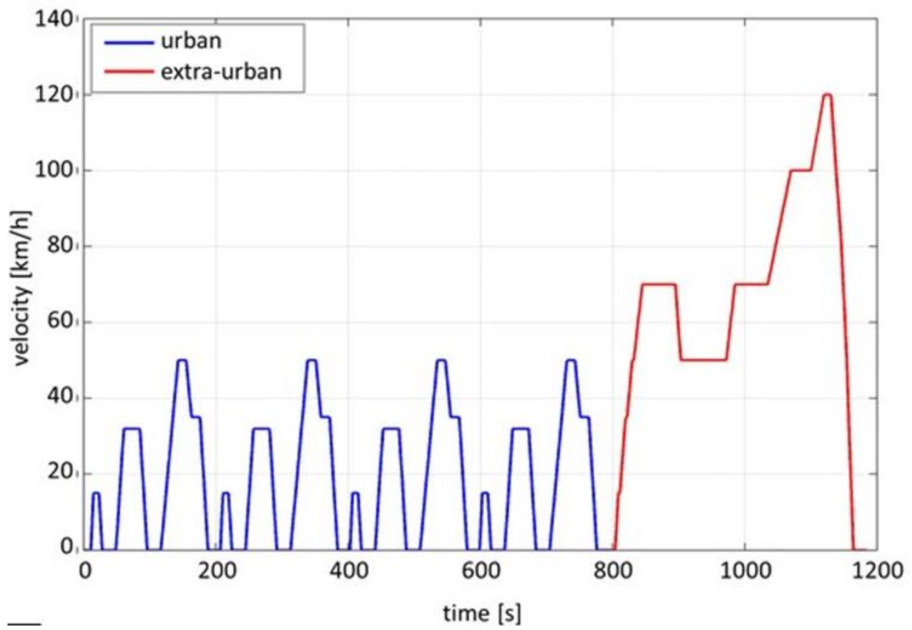

Figure 2. NEDC travel cycle speed-time diagram.

Source: Koller et al., 2022

1. WLTP – Worldwide Harmonised Light Vehicles Test Procedure

By 2015, a new model was born that attempted to eliminate the flaws of the previous NEDC by providing a more realistic test protocol (*Chehresaz, 2013; Williams et al., 2011*). The new cycle is 10 minutes longer (30 minutes instead of the previous 20 minutes), and the speed profile is more dynamic, with higher acceleration and longer braking distances. The average speed increased to 46.5 km/h, and the top speed to 131.3 km/h. The distance covered was 23.25 km, more than double that of the NEDC.

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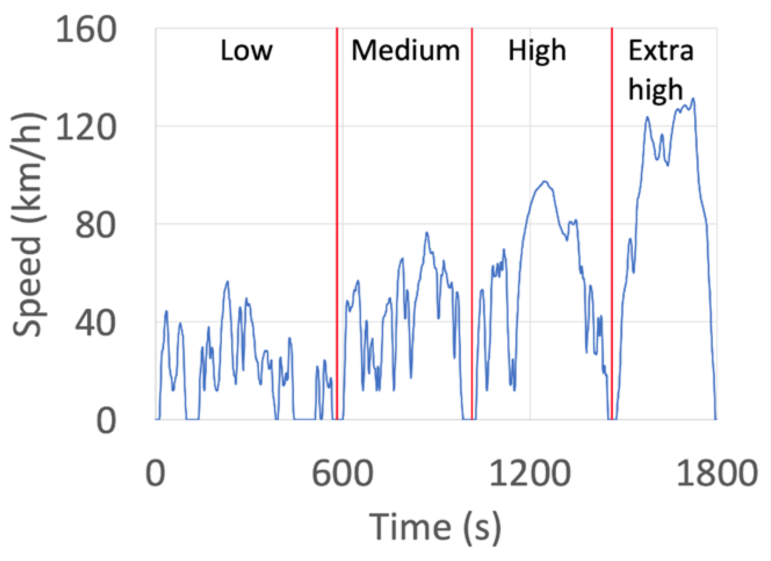

Figure 3: WLTP driving cycle speed-time diagram

Source: Yao, 2019

2. EPA Federal test procedure (FTP-75)

The US Environmental Protection Agency (EPA) standard, also known as FTP-75, is a more complex and, therefore, more realistic set of tests than the two listed above. It is not a new standard, as the first version was published in 1978, and the current one was updated in 2008. The current test cycle consists of 4 parts: urban stage (FTP-75), highway stage (HWFET), aggressive driving (SFTP US06) and optionally air conditioning stage (SFTP SC03). The FTP-75 test consists of 3 parts: cold start, transient phase, and warm start. The warm start phase is a repetition of the cold start, each lasting 505 seconds. To make the brake pad measurement a good approximation of real driving conditions, in 2007, the EPA added two additional tests to the standard. One is the US06, designed to replicate an aggressive driving style: high speeds, strong accelerations, and extreme speed curve changes. The test section lasts 10 minutes, covers 8 miles (13 km), has an average speed of 48 mph (77 km/h) and a maximum speed of 80 mph (130 km/h). The cycle includes four complete stops. The other additional cycle is SC03, the air conditioning phase. During the 9.9-minute stage, 3.6 miles (5.8 km) are covered at an average speed of 22 mph (35 km/h) with five complete stops. Stopping time accounts for 19% of the test.

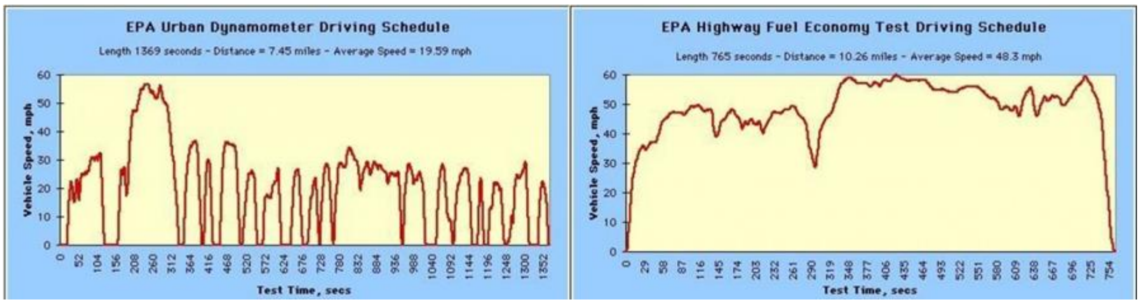

Figure 4: Speed-time diagram of urban and highway sections of the EPA driving cycle

Source: EPA, 2022

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3. UF – Utility Factor

Plug-in hybrid vehicles (PHEVs) can operate in two basic modes: charge-depleting (CD) and charge-sustaining (CS). In CD mode, the vehicle drives the wheels purely electrically, using up the charge of the batteries. In contrast, in CS mode, an internal combustion engine powered by the combustion of various fuels (petrol, diesel, e-fuel) provides the propulsion while generating electricity through recuperative braking. The proportion of the total distance travelled by the vehicle in pure electric mode, i.e. CD mode, is indicated by the Utility Factor (UF) (*Yang et al., 2014*).

In the European Union and in countries where the WLTP standard is still adopted, the UF can be calculated as follows (*Eder et al., 2014*):

$$UF(AER, d_n) = 1 - exp\left[-\sum_{i=1}^{10} c_i \left(\frac{AER}{d_n}\right)^i\right]$$

where,

AER is the pure electric range of the vehicle, according to WLTP;

d_n is the distance, which in Europe is 800 km;

c_i is the i[th] coefficient (*Table 1*):

C_1	C_2	C_3	C_4	C_5
26.25	-38.94	-631.05	5964.83	-25095.60
C_6	C_7	C_8	C_9	C_{10}
60380.21	-87517.16	75513.77	-35748.77	7154.94

Table 1: *i*-th coefficient values
Source: Eder et al., 2014

4 Sustainability concerns for hybrid vehicles

The plug-in hybrid electric drive (PHEV) is a powertrain comprising an electric motor and a conventional internal combustion engine. Their deployment is designed to reduce global greenhouse gas emissions and local air pollution in the least compromised, cost-effective way, but only if the electric drive operates near full capacity. PHEVs comprise around one-third of the global electric vehicle fleet, and their number is expected to grow. There is limited evidence that PHEVs are used as intended in everyday life and that the electric powertrain battery works properly, nor is there any measurement of how much conventional fuel is used. Reports have already been produced, considering user behaviour patterns in different countries. Around 100,000 PHEV vehicles in China, Europe and North America were included in the study (*Plötz et al., 2021*).

In sum, on average, PHEV vehicles' fuel consumption and tailpipe CO_2 emissions under real driving conditions are about four times higher than type-approval values. This value is even more unfavourable when company vehicles are used.

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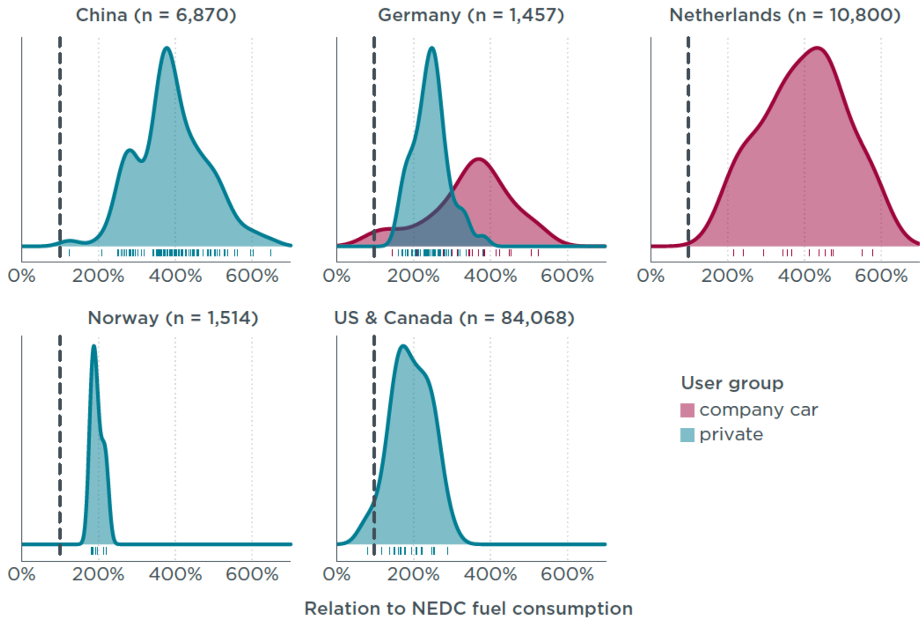

Figure 5: Real-world consumption of PHEV vehicles

Source: Plötz et al., 2021

In our measurement, we explored how the consumption and emissions of PHEV passenger cars evolve under the same traffic conditions, using different driving styles. The focus of the study is the less-researched question of the combined consumption curve of a complex hybrid system (*Zalacko et al., 2020*). From a sustainability perspective, considering the above findings and social research, it would be appropriate to set targets or development paths that end-users can adapt to in all circumstances. If these aspects are not considered, we will only have a semblance of results similar to the PHEV company car application (*Da Costa et al., 2012*).

5 Measurement

A Volkswagen Passat GTE passenger car registered in 2016 with 197,000 km already driven was used for the measurement. The vehicle has an unladen weight of 1765 kg and is equipped in line with the most sold versions. The vehicle is a parallel plug-in hybrid with an internal combustion engine of 1395 cm^3, capable of delivering 115 kW of power according to factory specifications and 250 Nm of torque. The electric motor element of the powertrain has a power output of 85 kW and 350 Nm of torque. According to the manufacturer, the combined power output is 165 kW. The measurement did not consider the reduction in power resulting from the engine's running power.

Basic data obtained via OBD:

- Speed [km/h]
- Pedal position [%]
- Torque of electric motor [Nm]
- Battery voltage [V]
- Battery current [A]
- Electric motor power [kW]
- Battery state of charge (SOC) [%]
- Internal combustion engine speed [rpm]
- Internal combustion engine torque [Nm]
- Internal combustion engine load [%]
- Instantaneous fuel consumption [l/h]

Table 1. Measurement cycle data.

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	Cycle 1			Cycle 2			Cycle 3		
section	**City**	**highway**	**motorway**	**City**	**highway**	**motorway**	**City**	**highway**	**motorway**
passengers	2			2			2	1	
A/C	off			on			on		
mode	normal hybrid			normal hybrid		GTE	GTE	normal hybrid	GTE
average speed	27.49 km/h	49.39 km/h	105.49 km/h	30.23 km/h	49.67 km/h	103.205 km/h	24.48 km/h	48.82 km/h	103.45 km/h
time	752.28 s	656.69 s	580.83 s	682.96 s	653.22 s	593.81 s	849.08 s	661.36 s	592.2 s

The measurement aimed to obtain results comparable to currently available measurement cycles, but in contrast to them, not based on a blueprint, but on real conditions. Like Real Driving Emission (RDE) tests, Real-world Driving Cycle (RWDC) measurements are designed to further understand the unpredictability of traffic and certain vehicle characteristics through different driving styles. The consumption of the Volkswagen Passat GTE used in the measurement was tested on individually created tracks. The author created his measurement track. The evaluation is compared with catalogue data determined in the (WLTP EPA) measurements (Wiki Automative Catalog, n.d.). When designing the measurement route, it was important to ensure that there was a sufficient length of flat, gently sloping expressway section, typical of most large European cities (as industrial centres). The length of the chosen route was planned to be 30-35 minutes, assuming normal traffic conditions and respecting speed limits.

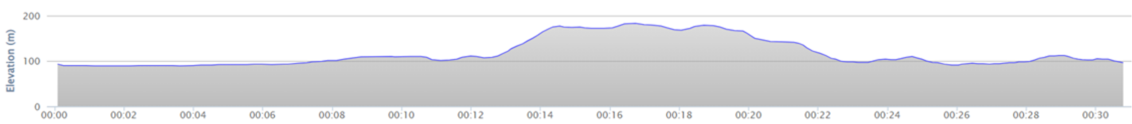

Figure 6. Elevation profile of the test route

In the measurement, we have sought to observe only those variables that are most typical for commuters. These were the air conditioning system, the variable weight, and slightly modifying the air resistance characteristics.

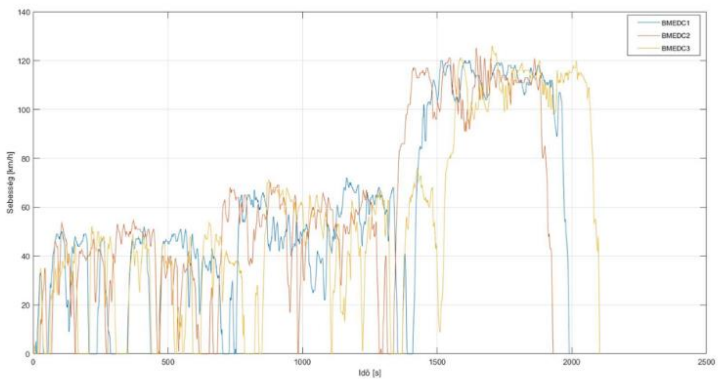

Figure 7. Speed profile during measurements

6 Results

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As shown in the diagram below, the battery usage curve is similar in all three measurements due to the same path, but it can be seen that the system uses the available electrical energy more “bravely” when the charge is higher.

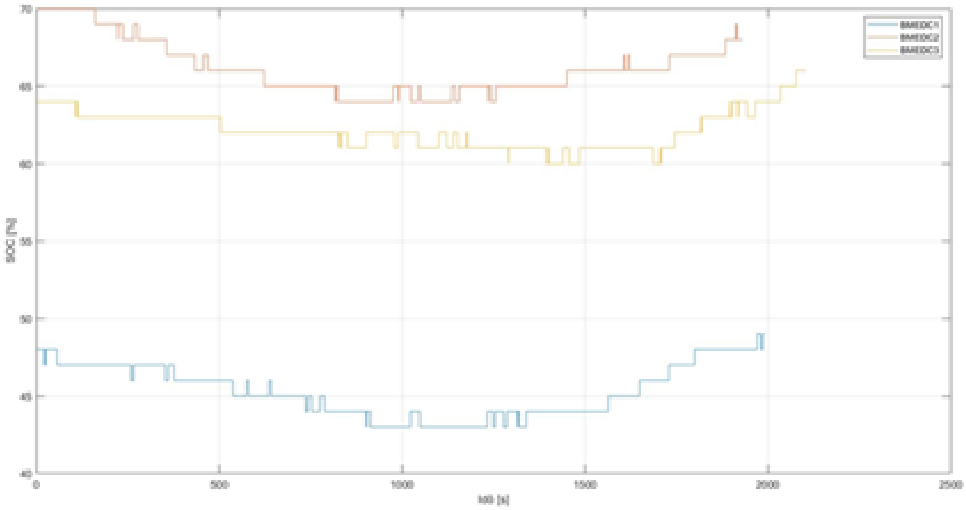

Figure 8. Variation of battery charge level during measurements

To determine the consumption, the instantaneous power of the drivetrain elements as a function of pedal depression was recorded during the measurement. We could also assign a speed to these values to determine the instantaneous consumption Eq. (1).

$$P = M * 2 * \pi * \frac{n}{60}, \quad (1)$$

where

P – power;

n – RPM;

M – torque.

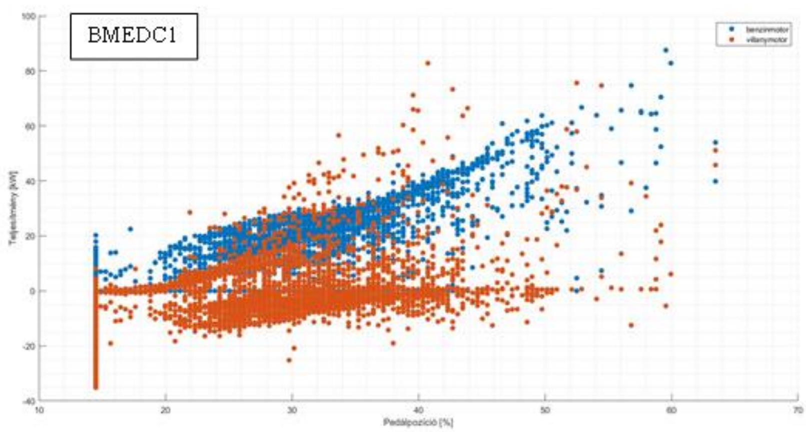

Figure 9. Performance of drive chain elements as a function of pedal position.

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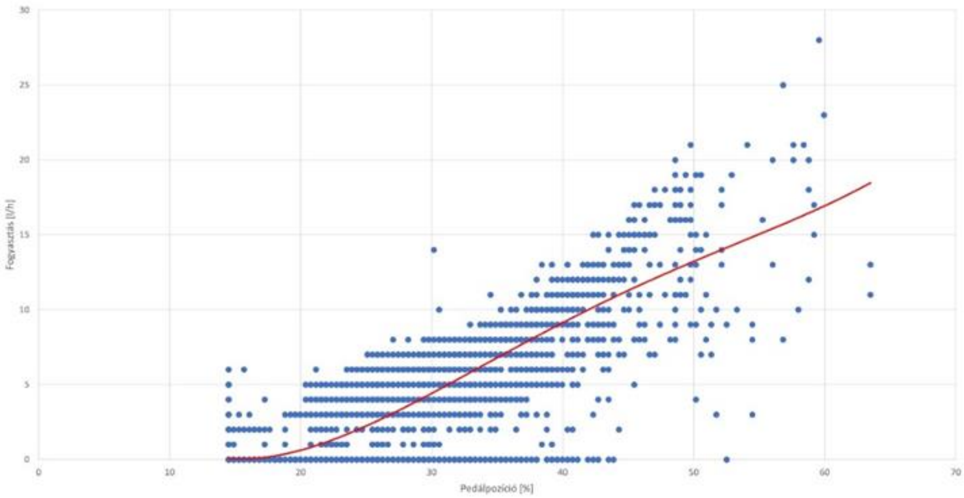

Figure 10. Instantaneous measured consumption.

7 Conclusion

Unfortunately, the energy consumption of the electric motor and the instantaneous consumption of the internal combustion engine could only be monitored separately, so evaluating the measurement and its adequacy would require further measurements. Even though we tried to follow the assumptions of the chassis dyno measurements both in the creation of the cycle and during its execution, the evaluation of the measurement cycles under real conditions provided results that require further investigation and deeper analysis. It can be concluded that, in real conditions, there is a deviation from the theoretical values. Even following the prescribed set of conditions, the vehicle consumption is higher. Hence, the emissions are higher (*Jurchiş et al., 2018*). Comparisons with WLTP or other driving cycle results are not fully possible, but based on the results, the following can be stated: if the battery charge level is higher, the hybrid system supports the combustion engine better, thus lowering consumption and emissions. The measurements show that the continuous utilisation of hybrid vehicles' electric drive in real driving conditions positively affects mobility sustainability.

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