Investigating the Energetics of Electric Vehicles, based on Real Measurements

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Abstract: Electric vehicles can offer a real alternative for mobility in the 21st Century, but the extent of their long-term wear and degradation is unknown. Obviously, both traffic and users have to adapt to the new types of drivetrains, as these cars can be driven optimally in a completely different style. A new measurement and evaluation methodology has been developed, and various tests have been defined to investigate the key questions of electric cars. We showed that energy consumption can be reduced by more than 1/3 at optimum ambient temperatures, compared to 0 °C. We examined the correlation between speed and energy consumption on highway, and found that reducing the average speed from 105 km/h to 85 km/h can increase the range by up to 40%. Finally, we calculated that at 50,000 km of mileage, the battery only degrades by 11%.

Keywords: sustainable mobility; electric vehicles; range; consumption; battery degradation

1 Introduction

Modern mobility is not sustainable in its current form [1], therefore, alternative solutions need to be explored. Increasing recognition of a long-term perspective [2], can be an essential tool for mobility. The international community made several commitments related to transport, but most focus only on road safety or carbon emissions specifically.

Research for alternative solutions has been a popular topic over the past decades, but the global goal has not been achieved. First attempts were made to develop more environment-friendly fuels by reducing the sulfur and lead content [3] [3.1]. Further studies have been done on the possibility of fossil fuel blending with different alcohols [4-8], vegetable oil-based products [9-12], or with rare special blending materials [13-15]. On the technical side, the downsizing of petrol engines has started [16] [17], and for diesel engines, combustion and exhaust gas technologies have been improved [18-20]. At the same time, hybridization was also developed, which had promising results, for further fuel consumption reductions [21] [22].

Regardless of the powertrain type, the role of electricity has increased in vehicles, a modern car including up to 300 electric motors and sensors [24]. This is necessary because of the complexity of drivetrains and the requirement to comply with standards. With the development of safety systems, the vehicle acquires more and more data about its environment [25], which requires high-level data processing [26], artificial intelligence, and fuzzy structures [27] based decision-making in cognitive mobility.

Electric vehicles (EVs) have been a real alternative since the start of motorization. However, the early versions were powered by non-rechargeable primary cells. Over the last 100 years, the evolution of eDrives has been overshadowed by the development of internal combustion engines [23]. The diesel gate and the innovations in battery technology helped start a new era of e-mobility. The electric drivetrain has three main components: the battery, the electric motor, and the inverter.

The high-voltage battery (and its associated auxiliaries) is one of the components of EVs that is much more complex than in internal combustion engine (ICE) cars. The critical dimensions of batteries are: cathode materials (layered compounds, spinel and olivine), anode materials (graphite and lithium titanate), electrolytes, lithium salts, and separators [28]. During the lifetime of a battery, chemical reactions occur that cause it to age; this is the battery degradation. Degradation is a major area of research in lithium-polymer batteries [29].

Several types of electric motors are used in EVs. The proper e-motor selection has a significant influence on the vehicle's efficiency and stability [30]. One of the most preferred options is the Interior Permanent Magnet Synchronous Motor (IPMSM). The researchers focus on the effects of the size and placement of magnets [31].

For the development of inverters, the Hardware-In-the-Loop (HIL) concept is mainly used. This helps speed up the testing process to select the right performance and durability. New research uses the Power-HIL simulation, which can emulate PMSM machines [32].

Summarized the literature review, electric vehicles can be real alternatives for future mobility, which are already part of the transformation nowadays. As e-mobility is a relatively new research area, there are many open points and research orientations. With batteries and charging equipment more reliable and accessible than ever, adoption still depends on tax incentives and infrastructure deployment. Modern, first-generation electric cars are now reaching the average age of vehicles in Hungary, which is approximately 15 years. Utilization point of view, it is essential to be able to predict battery degradation. Our research focuses on the predictability of the degradation of electric vehicle batteries based on field data.

The Test and methods section contains a report on the tests performed, a description of the test vehicle, and the data logging process. The Results and discussion section shows the background calculations for energy consumption, range, and battery degradation. Also, this chapter includes the final outcome of the calculations and possibilities for further improvements. The results are summarized in the conclusion section.

2 Tests and Methods

This article summarizes the results of 3 measurements (Table 1), which are consistently referred to as follows: Normafa winter, Normafa summer, and Balaton challenge. The 2 Normafa measurements compare winter and summer energy consumption on the same route, while the focus is on the range for the Balaton challenge. Furthermore, the battery degradation was determined from the average of the three measurements.

Table 1
The tests performed and the specifications

Test	Date	Road type	Temperature	Repetition	Focus
Normafa winter	2022.03.10	City/Rural	-5 – 0 °C	3	Consumption
Balaton challenge	2022.07.25	Highway-	30 – 35 °C	1	Range
Normafa summer	2022.07.26	City/Rural	25 – 30 °C	3	Consumption

2.1 Test Vehicles

Six electric vehicles were used for the battery degradation test over lifetime. Therefore, vehicles were chosen with lower (~10,000 km) and higher (45,000 km) mileage, which were 4 and 2 years old (these values refer to the first test). There was a 4-month gap between the winter and summer tests, so the mileage in the summer test was already around 5,000 km higher for all cars. These vehicles were rented from a car-sharing company, driven by people with different experiences and driving habits, and often charged on a fast charger. The condition of the batteries was not measured previously; therefore, it was important to test with more vehicles.

First generation Volkswagen e-up! were used in the tests. These cars are not specifically designed with electric platforms, as there are also versions with internal combustion engines. The main details of the vehicles are given in Table 2.

For the e-up!, there are two drive modes: "D" and "B", where the difference between the two modes is the regenerative braking power. In mode "D", the recuperation is manually adjustable from level 0 to level 3, in level 0 there is no energy recuperation. In "B", the strength of recuperation is fixed at level 4, corresponding to ~70 Nm of deceleration torque based on measurements.

Table 2
Test vehicle specifications [33], [34]

Parameter	Value
Curb weight	1,139 kg
Power / Torque	60 kW / 210 Nm
Nominal energy	18.7 kWh
Nominal voltage	374 V
Battery capacity	50 Ah
Battery cell chemistry	Lithium nickel manganese cobalt oxides
Combined Energy Consumption	12 kWh/100 km
Range (WLTP)	133 km

The vehicle has three manually switchable driving profiles: Normal, ECO, and ECO+. In these modes, functions are limited in addition to performance to ensure optimal energy use (Table 3).

Table 3
The impact of e-up! operating modes on performance and functions [34]

System/Driving profile	Normal	ECO	ECO+
Speed limit	130 km/h	120 km/h	95 km/h
Max torque	210 Nm	167 Nm	133 Nm
Peak power	60 kW	50 kW	40 kW
Acceleration (0-100km/h)	12.4 s	14.3 s	-
Accelerator pedal characteristic	Normal	Reduced	Flat
Air conditioning	Normal	Reduced	Deactivated

2.2 Data Logging

There are two options for data logging: use the built-in sensors in the vehicles or install sensors. Modern vehicles are equipped with complex on-board electronics for comfort, safety, and optimal operation. For this reason, we chose the first option, as it avoids disassembling the vehicle and calibrating the sensors.

Electric vehicles are completely different from internal combustion engine vehicles in their powertrains, but their low-voltage systems are nearly the same. There are several CAN buses in EVs for different functions, which are usually connected in a Gateway. Diagnostic CAN, may be used to access the Gateway via the OBD II connector.

The Unified Diagnostic Services (UDS) [35] communication protocol has been implemented for data extraction. The protocol standardizes the communication and the message formats, but the content of the messages is different for each vehicle.

We tested several types of hardware, but finally, Inventure's self-made data loggers were chosen because of their stable operation.

The parameters we have analyzed are shown in Table 4. To investigate the vehicle's energetics, it would be sufficient to monitor only the energy consumption (eConsumption) parameters, but the energy consumption depends on the driving style. The consumption also depends on the route (e.g., road surface, slope), but these are indirectly included in the driving style parameters. The purpose of collecting longitudinal dynamic data is to validate that the drives were done in the same styles. Other data were also examined for future evaluations and to identify potential problems, but the analysis of these data is outside of the scope of this article.

Table 4
List of parameters collected from the CAN bus

Group	Parameter	Unit
eConsumption	Battery voltage	[V]
	Battery current	[A]
	State-of-charge	[%]
Driving style	Speed	[km/h]
	Motor rotation	[RPM]
	Torque	[Nm]
	Brake system pressure	[Bar]
	Accelerator Pedal Position	[%]
Others	Ambient temperature	[°C]
	Adaptive Cruise Control (ACC)	[Off / On]
	Air conditioning (A/C)	[Off / On]

2.3 Test Routes, Measurement Setup

In vehicle life cycle analysis, driving cycles are usually divided into three main groups: city, rural, and highway. Each type has different typical speed and torque values, and in addition, different specific use cases can be defined, e.g., parking in city, overtaking in rural, and emergency stopping on highways.

The energetics of electric cars are most influenced by two important factors related to the route: the slope and the maximum speed allowed. Therefore, an urban section with varied topography and a high-speed highway section were selected.

2.3.1 Normafa Winter and Summer

The city route was selected in Budapest from Móricz Zsigmond square to Normafa hill and back to Móricz Zsigmond square. The total length of the route is 15.4 km, with an elevation gain of 350 meters between the lowest and highest points (Fig. 1).

As the entire route was inside the city, the maximum speed limit was 50 km/h (in some places, it was limited to 30 km/h).

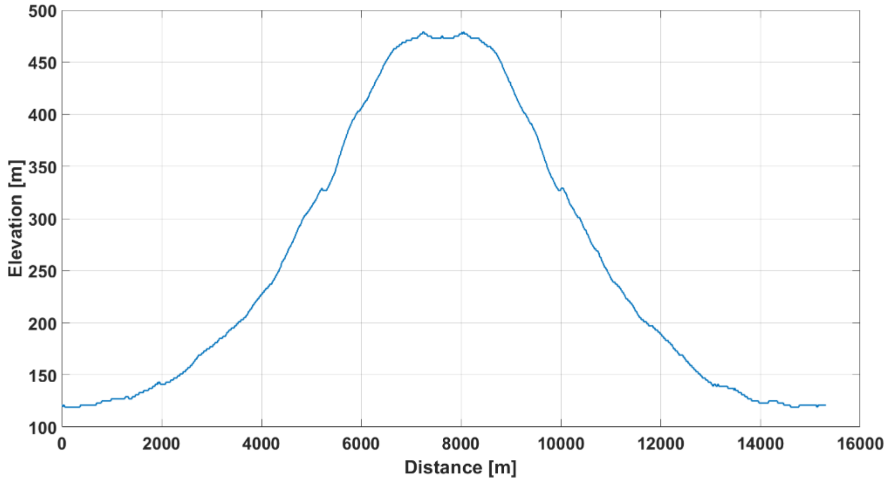


Figure 1
Elevation profile of the Normafa rest route

The tests were done on the same route in winter and summer to investigate the effect of temperature on energy consumption. In the Normafa winter test, the outside temperature was 0 °C, while in summer, it was 30 °C, which is the optimal temperature for the battery (Table 1). The vehicles were stored in an outdoor car park before the tests, so the initial temperatures of each component were nearly the same as the ambient temperature.

We drove in a convoy during the tests to ensure similar driving profiles. The tests were performed in real traffic, so there were differences in driving. To minimize this effect, the tests were done at night, and both tests were repeated three times in a row.

Drive mode "B" was used for the measurements to maximize energy recovery. We chose the Normal operating mode because we needed full power due to the high gradient. The Air Conditioning (AC) was not used, and the Positive Temperature Coefficient (PTC) battery heater is not manually adjustable.

2.3.2 Balaton Challenge

The M7 highway was chosen to test the range, as we thought that an important aspect of testing electric cars would be whether they could get from Budapest to Lake Balaton without charging. The test route is not completely flat due to the environmental conditions, but the slope is negligible (the maximum difference in altitude was 120 meters on the 110 km section). The first 15 km of the route was in the city, with speed limits of 50 km/h, 80 km/h, and 100 km/h. The focus was on comparing different operating modes.

In the measurement, we varied several parameters between vehicles that have an effect on consumption, such as speed and AC (Table 5). The target speeds were chosen to be the highest speeds achievable in the given operating modes. This was complemented by activating Adaptive Cruise Control (ACC) in every second vehicle.

Table 5
The settings used in the test vehicles

	Mode	Speed limit	AC	ACC
Vehicle 1	ECO	120 km/h	Off	Off
Vehicle 2	Normal	130 km/h	Off	On
Vehicle 3	ECO+	95 km/h	Off	On
Vehicle 4	Normal	130 km/h	On	Off
Vehicle 5	ECO+	95 km/h	On	Off
Vehicle 6	ECO	120 km/h	On	On

The measurement was performed only once in this test at an outside temperature of 35 °C. AC was manually set to automatic control and 22 °C in every second car, but the vehicle can override the AC compressor power based on Table 3. The windows were rolled up in all vehicles, as this has a significant effect on air resistance. During the measurement, drive mode "D" with level 0 recuperation was used in all cars to maintain the target speeds more uniformly.

Vehicle batteries could not be discharged to 0% for the following two reasons. In the first place, a vehicle pulling over on the highway can create a dangerous traffic situation. Second, the vehicle automatically switches to another mode to increase the range. At 20% State of Charge (SoC), the vehicle switches to ECO mode, which can be manually switched back to Nominal mode. At 12% SoC, it switches to ECO mode in a non-overrideable way, and at 8% to ECO+ mode.

3 Results and Discussion

In the measurements, vehicles with low mileage were consistently marked with Vehicles 1-3, while vehicles with high mileage were marked with Vehicles 4-6. These numbers also indicate the position in traffic. This is relevant for the Normafa measurements, as we were driving in a convoy there. Therefore, the further back a vehicle was in the convoy, the longer its driving time was. This may slightly increase the consumption.

3.1 Driving Profiles

The comparison of drivers is only relevant for the Normafa measurements, where the same driving style had to be used. Due to the similar route, only the longitudinal dynamics were investigated, which is well characterized by speed, motor torque, and throttle position. The driver can also control his speed with the brake pedal, but this is not included in the evaluation due to drive mode "B". Because of the high recuperation level, the brake pedal had to be used only for stops, which were only 5-7 per measurement. When calculating averages, only values where the speed was greater than 0 were considered.

Figure 2 shows the comparison of drivers for Normafa winter and Normafa summer. It can be seen that the average speeds were approximately the same for both measurements, with a maximum difference of 0.5 km/h.

In the case of Normafa winter, the average torque of Vehicle 4 is slightly higher, but it is only 3 Nm higher than the torque of Vehicle 1. For the Normafa summer, a marginally larger variance is seen for the average accelerator pedal positions, but this may be due to different deceleration strategies. As no outliers were observed for any of the parameters, the drives were considered similar.

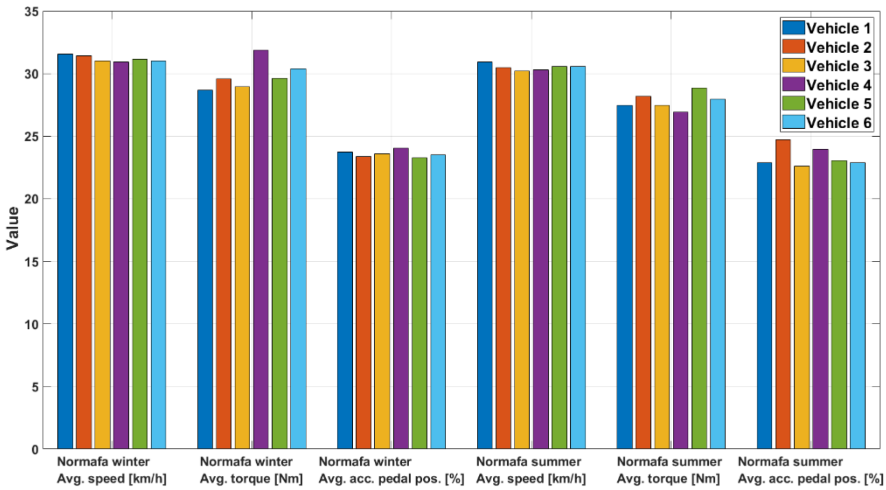


Figure 2
Comparison of driving styles in Normafa summer and winter tests

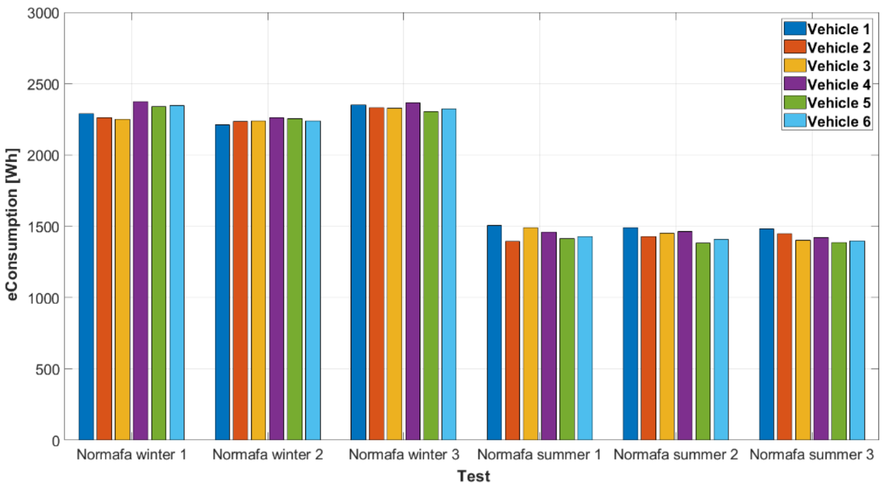
3.2 Energy Consumption

The vehicle's energy consumption is the amount of energy extracted from the battery. Some energy is used for the drive, and some for the power of other consumers. The amount of energy consumed with the measured values can be given by the following equation (Eq. 1):

$$eConsumption = \int W(t)\,dt = \int I(t) * U(t)\,dt \quad (1)$$

Where, W is the instantaneous delivered power, I is the current, U is the battery voltage, and t is the time.

The amount of energy used per test calculated from equation (1) is shown in Fig. 3. The graph clearly shows that while eConsumption was approximately similar in the same tests, consumption decreased significantly in the summer.



The amount of energy used in the tests per vehicle.

It can be seen that there is no significant difference in energy consumption between cars with low and high mileage. There is a minimal difference in the measurement of Normafa winter 1, but this may be due to calculation inaccuracies.

For the analysis of the results, it is important to note that the voltage and current values were recorded with different time stamps due to the CAN bus serial message transmission. Linear interpolation was applied to avoid this, which may result in some inaccuracy.

The averages of the three measurements for winter and summer are shown in Table 6. During the winter test, the average energy consumption was 2294 Wh, compared to 1435 Wh for the same route in summer. This results in a difference of 858 Wh, a 37.5% decrease in consumption in summer when temperatures are optimal.

In Normafa winter, cars with low mileage consumed on average 35 Wh less energy. In the case of the Normafa summer, cars with more mileage consumed 37 Wh less energy. These results imply that mileage does not affect the consumption of vehicles.

Table 6
Average eConsumption and differences between the Normafa winter and summer tests

	Normafa winter	Normafa summer	Difference
Vehicle 1	2,282 Wh	1,493 Wh	789 Wh
Vehicle 2	2,276 Wh	1,423 Wh	853 Wh
Vehicle 3	2,272 Wh	1,447 Wh	825 Wh
Vehicle 4	2,333 Wh	1,446 Wh	887 Wh
Vehicle 5	2,298 Wh	1,393 Wh	905 Wh
Vehicle 6	2,303 Wh	1,412 Wh	891 Wh
Average	2,294 Wh	1,435 Wh	858 Wh

The total length of the route was 15.3 km, from which the average city/rural consumption of the vehicles can be calculated, 15 kWh/100 km in winter and 9.4 kWh/100 km in summer. The manufacturer's specified combined energy consumption is 12 kWh/100 km, which includes highway driving. The air resistance is proportional to the square of the speed, the required power equals the speed multiplied by the drag force, so the energy consumption is proportional to the third power of the vehicle speed; therefore, highway sections increase consumption significantly. The conditions of the manufacturer's measurement are unknown, but it is within our measurement values and is therefore considered acceptable.

3.3 Range

During the Balaton challenge test, we ran into traffic jams on both the 10-15 km and the 21-31 km sections, which made it impossible to keep the target speeds (Figure 4). The real highway speed was only possible on the 32-92 km section. There is also a drop in speed around the 60 km point, but this is an absolutely realistic traffic situation, so we did not want to remove it from the results.

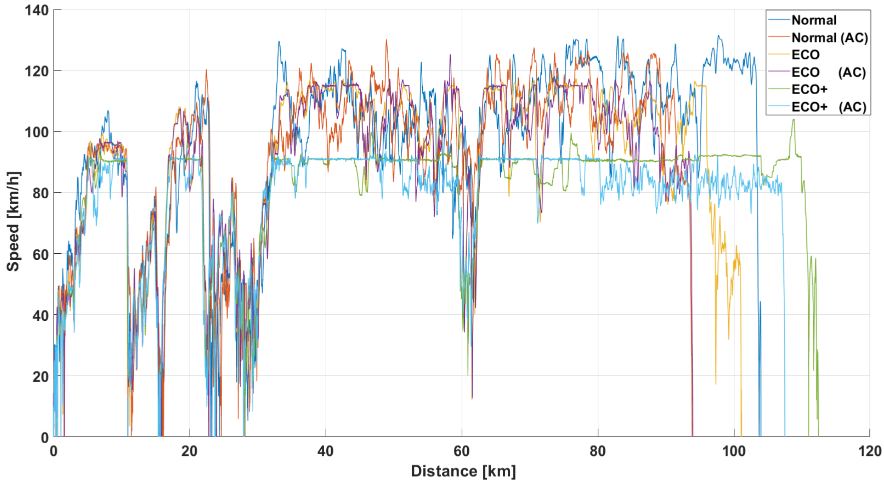


Figure 4

Speed profiles at the Balaton challenge measurement.

Columns 2 and 3 of Table 6 show the average speeds for the total route and the high-speed section, respectively. For both Normal and ECO+ modes, it is visible that the average speed is higher with AC on the total route, while the average speed is higher without AC on the high-speed section. From the perspective of energy consumption and range, the second was relevant for this measurement, so in the further evaluation we limit the route to this 60 km section.

Table 6

The result of speed and consumption in different modes

	Avg. speed	Avg. speed (high-speed)	Standard deviation of speed (high-speed)	eConsumption (high-speed)
Normal	66.4 km/h	106.3 km/h	13.8 km/h	8,151 Wh
Normal (AC)	66.9 km/h	105 km/h	11 km/h	7,980 Wh
ECO	59.8 km/h	101.4 km/h	17.2 km/h	7,967 Wh
ECO (AC)	59.5 km/h	100.6 km/h	17.4 km/h	8,010 Wh
ECO+	59 km/h	86.6 km/h	11.2 km/h	6,251 Wh
ECO+ (AC)	59.1 km/h	85.2 km/h	9.6 km/h	5,838 Wh

Figure 5 shows the consumption trend on the high-speed section. The results indicate that the consumption of 2 vehicles in ECO+ mode is significantly lower than the other four vehicles. Consumption is lower with air conditioning due to lower average speed and lower deviation (Table 6).

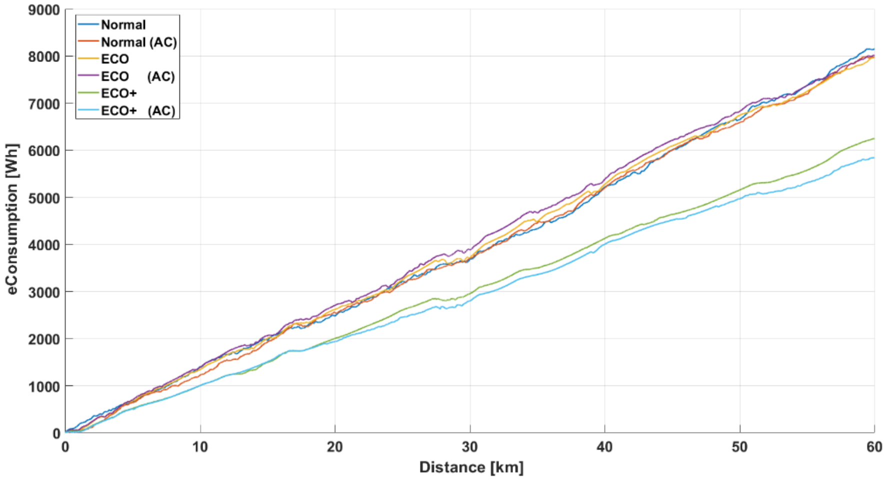


Figure 5
Consumption trends as a function of distance travelled

The consumption of Normal and ECO mode vehicles was approximately the same, although the average speed difference was ~5 km/h. Vehicles in ECO mode had significantly greater deviation in speed, so they slowed down and accelerated more frequently, which increased energy consumption.

The results show that the average speed and deviation of speed have a large effect on eConsumption, while the use of air conditioning is almost negligible. During the test, it was not possible to produce the same values due to traffic. The range on the high-speed section can be calculated from the decrease in charge, assuming that the remaining charge would decrease at the same rate (Table 7).

Table 7
The relationship between calculated ranges and the odometer

	Odometer	**ΔSoC**	**Calculated range**
Normal	18,072 km	52.6 %	114 km
Normal (AC)	50,139 km	58.3 %	103 km
ECO	17,620 km	50.41 %	119 km
ECO (AC)	51,253 km	57.86 %	104 km
ECO+	13,106 km	39.02 %	154 km
ECO+ (AC)	51,057 km	41.64 %	144 km

In all three modes, we obtained significantly longer ranges for vehicles with low mileage than for those with high mileage, by an average of 12 km. This may indicate the degradation of the batteries. Furthermore, if the average speed of 105 km/h is reduced to 85 km/h, the range can be increased by 35-40%.

3.4 Battery Degradation

To investigate the degradation of the battery, the current capacity of the battery can be calculated from the measured consumption and the change in State-of-Charge using the following formula (Eq. 2):

$$Capacity = \frac{100}{\Delta SoC} * eConsumption \tag{2}$$

The average consumption and average △SoC were used for the Normafa measurements. The vehicles were not stopped between the measurements, but the current values were close to 0 A, which would distort the consumption. For the Balaton Challenge test, the results were limited to the high-speed section.

Figure 6 shows the values of the calculated capacities for the three tests and the average of these values, with a black dashed line. The results of the Balaton Challenge measurement are the closest to the average capacities, as expected, as we could discharge the batteries almost completely. It can be observed that while the average for the first three cars with low mileage is about the same as the Balaton Challenge results, the average for the cars with high mileage is slightly lower for all three cars. One of the reasons for this could be the air-conditioning, as it was switched on for these three vehicles. The e-up!s have a high-voltage AC compressor, and its electrical management is not known. Another interesting result is that we got higher battery capacities in summer for five cars. In this measurement, the energy consumption was much lower, and the SoC value decreased less, but not at the same rate.

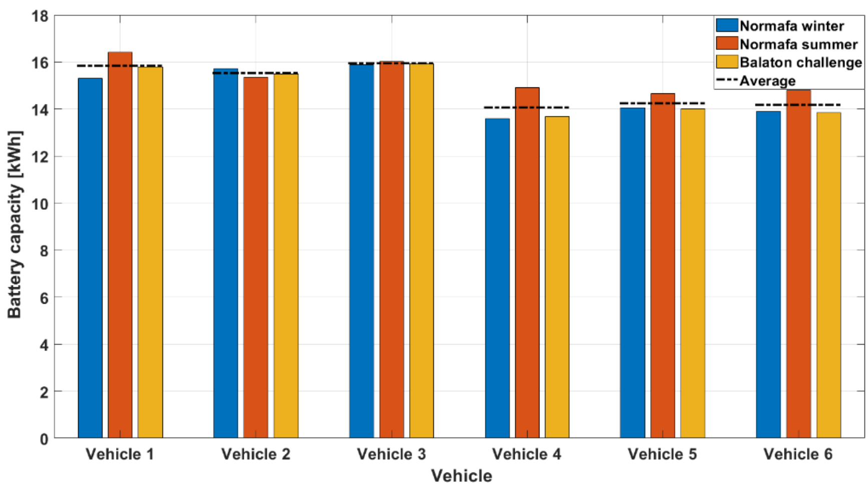


Figure 6

Calculated battery capacities from measurements

Column 2 of Table 8 shows the average battery capacity values, column 3 shows the Odometer values after the third measurement. For e-up!, the usable capacity of the battery is not known, which is usually ~90% of the nominal capacity. An approximate value can be calculated from Table 2, the Combined Energy Consumption is 12 kWh/100 km, while the WLTP range is 133 km, giving a usable capacity of 15.96 kWh. The degradation is the ratio of the average battery capacity to the previous value expressed as percentages.

Table 8
The calculated degradation values for the test vehicles

	Average	**Odometer**	**Degradation**
Vehicle 1	15.84 kWh	17,838 km	0.75 %
Vehicle 2	15.53 kWh	18,304 km	2.69 %
Vehicle 3	15.94 kWh	13,346 km	0.13 %
Vehicle 4	14.06 kWh	50,367 km	11.90 %
Vehicle 5	14.24 kWh	51,301 km	10.78%
Vehicle 6	14.17 kWh	51,471 km	11.22 %

A significant difference in the degradation can be observed as a function of mileage. The average degradation for vehicles with ~16,000 km is 1.19%, while for vehicles with 51,000 km it is 11.3%. For the first, the battery degradation calculated for the second vehicle highly increases the average. Due to the small number of cars, it is not possible to either interpolate or extrapolate the degradation, as the shape of the function is unknown, which would require measuring several vehicles with different mileages.

It is important to underline that although the results show higher degradation, the results are only approximations. The main reasons for this are: measurement accuracy, it is not possible to get more data with the same timestamp in serial communication, the current value can change rapidly with high amplitude, the SoC value is a calculated value, the battery discharge is not linear, driving style/traffic affects the results.

Conclusions

We achieved the following results in this work. We developed a measurement and evaluation methodology for testing the energetics of electric cars, which was tested with six vehicles. In future research, this can be extended with additional vehicles to improve the results. Two measurements were done on the same route, one in winter at 0°C and the other in summer at 35°C. The results showed a 37.5% consumption decrease in summer, under optimal temperature conditions. The third measurement was performed on a highway, where the effect of speed on the range was investigated. If the speed is reduced to 85 km/h, instead of 105 km/h, the range can be increased by 35-40%. Summarizing the results of the three measurements, a battery degradation of 1.2% was calculated for cars with 16,000 km and 11.3% for cars with 51,000 km.

Acknowledgements

Prepared with the professional support of the Doctoral Student Scholarship Program of the Co-operative Doctoral Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.

Project no. 2019-1.3.1-KK-2019-00004 has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the 2019-1.3.1-KK funding scheme.

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