Theoretical analysis of electric vehicle energy consumption according to different driving cycles

W Gołąbiewski and M Lisowski
West Pomeranian University of Technology in Szczecin
Department of Automotive Engineering
Piastow Avenue 17, 70-310 Szczecin, Poland

Corresponding author: wgolebiewski@zut.edu.pl

Abstract. The paper presents a theoretical analysis of energy consumption according to selected driving cycles. The aim of the study was to analyse the impact of various acceleration and speed values on the energy consumption of an electric vehicle. The object of the study was the Nissan Leaf vehicle, equipped with a synchronous AC electric motor. The research methodology involved creating a mathematical model based on the technical and operational parameters of the vehicle. The characteristics of the torque of the electric motor of the test object were used, the basic and additional resistance values were determined using the vehicle's technical parameters such as: complete vehicle kerb weight plus the mass of passengers and cargo, useful battery capacity, width and height, type of a drive system used, wheel sizes. Finally, the energy consumption for each driving cycle was determined. According to the NEDC cycle, it amounted to a maximum of 15.6 kWh/100 km and was by 4 percent higher than the producer stated.

1. Introduction

The energy consumption of electric vehicles has recently started to play an increasingly important role, mainly due to environmental protection. Comprehensive consideration of this parameter requires the statement that although electric vehicles are considered to be zero-emission during operation in road conditions, they are unfortunately not favourably assessed for pollutant emissions during the well-to-wheel analysis. This is due to the emission of carbon dioxide related to energy consumption, and although during the bench tests, according to research tests, the electric vehicle does not emit this compound to the atmosphere, however, electricity must be generated, predominantly from mine energy carriers [1,2,3]. European Union regulations assume a reduction of carbon dioxide emissions, the expected limits of this compound for 2021 is 95 g/km for the NEDC test or 100 g/km for the WLTP test [4].

Operational tests of energy consumption during the measurements were different due to the different nature of the experiments, the technical parameters of vehicles or different road conditions. And so, during the tests, the energy consumption of an electric vehicle, weighing 1549 kg, powered by lithium-ion batteries was 15 kWh/100 km [5].

The unit energy consumption of an electric vehicle, understood as the ratio of the value of the energy absorbed to the distance put by the vehicle, was also subjected to experiments [5,6].
The measurement results of this indicator of an electric vehicle characterized by a mass of 1360 kg and a coefficient of air resistance $c_x = 0.5$, based on the tests valid in North America, i.e. urban tests - UDDS, extra-urban tests - HWFEDS, also called - HWFET and US 06 (SFTP) corresponded successively to the following values - 137 Wh/km, 165 Wh/km, 249 Wh/km [7, 8]. At a similar level the unit energy consumption of the Zilent Courant electric vehicle was presented, its value ranged from 155 Wh/km to 223 Wh/km [7].

Different vehicles were checked for electrical efficiency according to the NEDC cycle, too. The Nissan Leaf was characterized by the energy consumption at the level of 15 kWh/100 km, Volkswagen e-golf and Renault Zoe's energy consumption was at a similar level. Slightly higher energy consumption had Tesla Model S60, S80 (17 kWh/100km), while Mercedes SLS AMG Coupe Electric 90 - approx. 25 kWh/100 km [9].

The NEDC and WLTP cycles consist of specific time-dependent speed profiles. In publications [10,11] analytical models representing the energy consumption of an electric vehicle during fixed driving conditions (constant velocity values) have been presented. The authors of the publications decided to broaden the subject of the previous articles and take into account the study of energy consumption in stand conditions based on selected driving cycles (NEDC, WLTC). The utilitarian nature of the publication presents a mathematical model that allows to omit tests using a chassis dynamometer, and the adopted model allows to estimate, with an accuracy of up to 4 percent, the value of energy consumption according to driving cycles only on the basis of technical and operational parameters of the selected electric vehicle.

2. Selected driving cycles

The regulations concerning vehicle emission were presented in the European Union for the first time at the turn of the 60s and 70s. At that time, an urban driving cycle (UDC - Urban Driving Cycle) performed in laboratory conditions using a chassis dynamometer, which allowed to determine the emission of toxic compounds, was developed, and the characteristic points of the speed profile test were to reflect urban road conditions. The maximum speed of the research test was 50 km/h [4,12].

At the beginning of the 1990s, this cycle was expanded to include the extra-urban part called EUDC (Extra Urban Driving Cycle). In this way, the NEDC series was created, which consisted of both the urban and extra-urban parts. It was used for many years, while in 2008 studies on an alternative NEDC test that is the WLTP cycle began [13,14,15,16].

2.1. NEDC cycle

NEDC (New European Driving Cycle) was created to assess the level of toxic compounds emission and fuel consumption of passenger vehicles equipped with spark-ignition engines. It had to be representative for the determination of fuel consumption with the typical use of the vehicle in road conditions in Europe. It consists of a fourfold repetition of the UDC - urban driving cycle and EUDC - extra-urban driving cycle (Figure 1).

![Figure 1. NEDC cycle (New European Driving Cycle) [17,18,19]](attachment:figure1.png)

Its implementation is carried out with the use of a test object and a chassis dynamometer in
laboratory conditions. It is performed on an unheated engine at an external temperature from 20 to 30 degrees Celsius and does not take into account the use of air conditioning in the vehicle [18, 19]. It consists of specific values of speed and acceleration performed by the driver at the intended time. The maximum acceleration value during the test is 1.04 \( \text{m/s}^2 \), and the maximum speed 120 km/h. Engine idling time during the test is approx. 25 %.

There is also a certain degree of freedom in determining the weight of the vehicle during the test, which is equal to the weight of the vehicle plus 100 kg. In order to reduce the rolling resistance (affecting the value of fuel consumption), it is possible to optimise the load by the design modifications of prototype vehicles by reducing their kerb weight [18,19,20,21].

The detailed procedure according to which the test should be carried out is recorded in the regulations of UNECE R101. According to those adopted conditions, the measurement of carbon dioxide and fuel/energy consumption as well as the range of vehicles with hybrid drive (internal combustion and electric engines) and an electric drive for vehicles of M1 and N1 categories are carried out [18, 19].

Unfortunately, the test is characterised by an unrepresentative driving style with low values of accelerations, which in real conditions reach much higher values [21]. The cycle is also criticised for the measurement of emission/fuel consumption/power, with the air conditioning turned off or lack of heating glass. Manufacturers use all modifications to reduce fuel/energy consumption. Roof rails and mirrors are pulled off during the test, the tyre pressure is replenished to a value exceeding the manufacturer's recommendations. These activities are aimed at reducing the rolling resistance, and thus reducing the fuel/energy consumption. Critique also involves the lack of an official body that oversees the conditions of tests conducted by producers [22].

2.2. WLTP cycle

The WLTP (Worldwide harmonized Light vehicles Test Procedure) cycle is used to determine levels of pollution and CO\(_2\) emissions, fuel/energy consumption for passenger vehicles and delivery vans. The test procedure provides precise indications regarding test conditions: road load (resistance to motion), gear changes, total vehicle weight (through optional equipment, cargo and passengers), fuel quality, ambient temperature and tire selection and pressure [4,13,14,15,16].

Three different WLTC research tests are used, but before starting the measurements it is necessary to determine to which category the vehicle belongs, wherein the power/weight ratio PWr is being considered, thus the ratio of the vehicle engine power to its kerb weight [4,13,14,15,16]:

- The first class - low-power vehicles PWr<22,
- The second class – vehicles with 22<PWr<=34,
- The third class – high-power vehicles with PWr>34.

In each of the classes there are several driving tests reflecting the real traffic conditions in urban areas, extra-urban areas and on highways. WLTC driving cycle is divided in four parts for Low, Medium, High and Extra High speed. The duration of each part is determined between the classes, and the order of the tests is limited by the maximum vehicle speed. Although the WTLC is improved compared to the NEDC test, the opinion is that it still does not reflect the real road conditions. The acceleration values are unrepresentative, but the test also does not take into account the grade resistance overcome by the vehicles, which can significantly affect the engine load, and thus the value of fuel/energy consumption and toxic compounds emission [4,13,15,16].

Figure 2 shows an example of the WLTC test for the third vehicle class (to which the object of the test belonged).
3. Aim of the study and research methodology

The aim of the research was the theoretical analysis of energy consumption, and the resulting range parameter, of the electric vehicle in accordance with selected driving cycles, which included the NEDC and WTLC tests. The adopted research methodology involved the use of technical-operational parameters of the research object and the creation of a mathematical model describing the aspect of energy consumption in the electric vehicle based on different driving cycles.

3.1. Research object

The object of the study was the Nissan Leaf electric vehicle, its technical data is presented in Table 1. The operational characteristics of the electric motor under research are shown in Fig.3. Using the research object and the adopted research model, the characteristics of the simulated energy consumption of the vehicle for selected driving cycles were determined.

| Table 1. Technical parameters of the Nissan leaf vehicle [23,24,25] |
|---|---|---|
| **Vehicle data** | **Value/Description** | **Unit** |
| Max engine power | 109/ 80 | KM/kW |
| Rotational speed of max power | 3000-10000 | [rpm] |
| Max engine torque | 254 | [Nm] |
| Rotational speed of max torque | 0-3000 | [rpm] |
| Usable electric capacity of batteries $E_e$ | 21.3 | [kWh] |
| Type and transmission of the drive | Locked front-wheel, no clutch, cylindrical gear fixed position, 7.9377:1 | - |
| Vehicle weight $m$ | 1550 | [kg] |
| Height $H$ | 1.549 | [m] |
| Width $B$ | 1.770 | [m] |
| Aerodynamic resistance coefficient $c_d$ | 0.28 | - |
| Wheel size | 205/55R16 | - |
4. Mathematical model of energy consumption

The authors of the publication used a mathematical model on the basis of publications [10,11]. After identifying the data and defining the limits, the purpose function was presented, based on which the analysis of the Nissan Leaf energy consumption for selected driving cycles was carried out.

4.1. Data identification

The technical parameters of the vehicle (in accordance with Table 1) were used for simulation tests and the following traffic conditions were adopted:

a) rolling resistance coefficient of tyres = 0.012 – F class of tyres,
b) mass of passengers and cargo – 100 kg,
c) air density = 1.177 kg/m$^3$,
d) external pressure = 100 kPa,
e) external temperature = 23 Celsius degrees (296 K),
f) battery load (in relation to 1s): maximum - vehicle control systems, lighting, radio, GPS, maximum air conditioning/heating - 2 kW; medium - vehicle control systems, lighting, radio, GPS, economical mode of using air conditioning/heating - 1 kW; minimal - vehicle control systems, lighting, radio, GPS, disabled air conditioning/heating - 0.3 kW.

4.2. Definition of limitations

For the adopted mathematical model of energy consumption the limitations were used [24,25]:

a) the power of the electric motor - $0 < P^e \leq 80$ [kW],
b) efficiency of the electric motor - $0.85 \leq \eta^e \leq 0.95$
c) efficiency of the main gear - $0.85 \leq \eta^FD \leq 0.95$
d) coefficient of rotating masses – 1.04,
e) efficiency of the energy recovery system – 0.6,
f) vehicle speed $0 \leq v \leq 130$ km/h,
g) acceleration of the vehicle $0 \leq a \leq 1.6$ m/s$^2$

The efficiency value of the electric motor was determined on the basis of the torque value and the rotational speed.

4.3. Purpose function

The purpose function was the general energy consumption of an electric vehicle. The record of the energy transport structure was made based on the transport energy graph (Fig. 4).
The energy recovered during the vehicle braking is described by the relation of rotating masses

\[ E = \frac{E_v + E_{ac} - E_{reg}}{1000 \cdot 3600} \]  

(1)

where: \( E_m \) – energy of motion [Ws], \( E_v \) – energy consumption while driving the vehicle at a constant speed [Ws], \( E_{ac} \) – energy consumption of the vehicle during acceleration [Ws], \( E_{reg} \) – energy recovery (recuperation) [Ws].

Energy consumption during the vehicle is moving at a constant speed is determined by the following formula:

\[ E_v = P_h \cdot t = \frac{P_d}{\eta_M} \cdot t = \frac{P_w}{\eta_M \cdot \eta_{FD}} \cdot t = \frac{F_R}{\eta_M \cdot \eta_{FD}} \cdot \frac{v}{t} = \frac{(F_{RR} + F_{DR}) \cdot v}{\eta_M \cdot \eta_{FD}} \cdot \frac{v}{t} = \frac{[f_i \cdot (m_1 + m_2) \cdot g + \frac{\rho}{2} \cdot c_d \cdot A \cdot v^2] \cdot v}{\eta_M \cdot \eta_{FD}} \cdot \frac{v}{t} \]  

(2)

where: \( P_h \) – power consumption of high-voltage battery [W], \( t \) – time [s], \( P_d \) – the power of the electric motor [W], \( P_w \) – power of movement resistance [W], \( \eta_M \) - efficiency of the electric motor, \( \eta_{FD} \) - efficiency of the main gear, \( F_R \) – resistance to motion [N], \( v \) – vehicle speed [m/s], \( F_{RR} \) – rolling resistance [N], \( F_{DR} \) – air resistance [N], \( f_i \) – rolling resistance coefficient, \( m_1 \) – curb weight of the vehicle [kg], \( m_2 \) – mass of passengers and cargo [kg], \( g \) – acceleration of gravity [m/s^2], \( \rho \) – air density [kg/m^3], \( c_d \) – air resistance coefficient, \( A \) – the frontal area of the vehicle [m^2]

The energy consumption during acceleration of the vehicle was described by the following relationship:

\[ E_{ac} = \int_{v_1}^{v_2} \frac{F_R \cdot v}{\eta_M \cdot \eta_{FD}} \cdot t \cdot dv = \int_{v_1}^{v_2} \frac{(F_{RR} + F_{DR} + F_{ac}) \cdot v}{\eta_M \cdot \eta_{FD}} \cdot t \cdot dv = \int_{v_1}^{v_2} \frac{[f_i \cdot (m_1 + m_2) \cdot g + \frac{\rho}{2} \cdot c_d \cdot A \cdot v^2 + \delta \cdot (m_1 + m_2) \cdot \frac{v}{t}] \cdot v}{\eta_M \cdot \eta_{FD}} \cdot t \cdot dv \]  

(3)

where: \( v_1 \) – initial speed [m/s], \( v_2 \) – final speed [m/s], \( F_{ac} \) – resistance of inertia [N], \( \delta \) - coefficient of rotating masses = 1.04.

The energy recovered during the vehicle braking is described by the relation [26]:

\[ E_{reg} \]

The part of general energy consumption was energy of motion determined from the following relationship [10,11]:

\[ E_m = \frac{E_v + E_{ac} - E_{reg}}{1000 \cdot 3600} \]  

(1)

\[ E_{ac} \]

\[ E_{reg} \]

\[ \eta_M \]

\[ \eta_{FD} \]

\[ F_R \]

\[ F_{RR} \]

\[ F_{DR} \]

\[ f_i \]

\[ m_1 \]

\[ m_2 \]

\[ g \]

\[ \rho \]

\[ c_d \]

\[ A \]

\[ v_1 \]

\[ v_2 \]

\[ v \]

\[ F_{ac} \]

\[ \delta \]
\[ E_{\text{reg}} = \int_{v_1}^{v_2} F_e \cdot v \cdot t \cdot \eta \cdot dv = \int_{v_1}^{v_2} (F_{\text{IR}} + F_{\text{DR}} + F_{\text{RR}}) \cdot v \cdot t \cdot \eta \cdot dv \]  

(4)

where: \( \eta \) - efficiency of the energy recovery system.

General energy consumption determined on the basis of the equation (1), related to the distance the vehicle travels, according to the selected driving test has been determined on the basis of the equation:

\[ E = \frac{100(E_m + E_e)}{s} \]

(5)

where: \( E \) - general energy consumption of the vehicle [kWh/100 km], \( E_e \) – energy of receivers [kWh], \( s \) – the distance travelled by the vehicle during the cycle [km].

The range of the vehicle \( d \) was determined based on the useful capacity of the electric battery and the overall energy consumption of the vehicle:

\[ d = \frac{100 \cdot E_e}{E} \]

(6)

where: \( E_e \) – useful electric capacity of the battery [kWh].

5. Energy consumption of electric vehicle

On the basis of (5) and (6) the energy consumption and the range of the electric vehicle for selected driving tests was determined.

5.1. NEDC cycle

Figure 5 below presents the energy consumption and the range for the NEDC cycle.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Energy consumption and range of the electric vehicle according to the NEDC cycle

Based on Fig. 5, it can be concluded that the UDC urban cycle (considering only the issue of the vehicle drive) is characterized by lower energy consumption compared to the EUDC extra-urban cycle \( (E_{\text{UDC}} = 8.48 \text{ kWh/100 km}, E_{\text{EUDC}} = 10.25 \text{ kWh/100 km}) \), which results in a greater range of the vehicle \( (d_{\text{UDC}} = 251.19 \text{ km}, d_{\text{EUDC}} = 207.82 \text{ km}) \). In the extra-urban cycle, energy consumption is about 21% higher. This may be caused by low values of acceleration and speed in the urban cycle and a much larger share of air resistance during significant speed in the extra-urban cycle. During the minimal use of vehicle electric loads, the energy consumption, compared to this parameter during the drive, increases \( (E_{\text{UDC}} = 10.11 \text{ kWh/100 km}, E_{\text{EUDC}} = 10.73 \text{ kWh/100 km}) \) and the range of the vehicle is reduced – \( d_{\text{UDC}} = 210.59 \text{ km}, d_{\text{EUDC}} = 198.54 \text{ km}) \). The situation begins to occur unfavourably during the medium and maximum use of electric loads. Then the energy consumption can increase up to \( E_{\text{UDC}} = 19.38 \text{ kWh/100 km} \) (range of 109.92 km).
Energy consumption according to the NEDC cycle ranged from 9.61 to 15.61 kWh/100 km, which was equal to the range from 221 km to 136 km.

5.2. WTLC cycle

Fig.6. presents energy consumption and range for the WLTC cycle. It can be seen that the extra high phase is characterized by the lowest energy consumption (E drive = 6.64 kWh/100 km, E min = 7.17 kWh/100 km, E medium = 8.41 kWh/100 km, E max = 10.17 kWh/100 km) compared to the other phases (low, medium, high), which equals the greater range of the vehicle (d drive = 480.8 km, d min = 447.9 km, d medium = 386.1 km, d max = 322.5 km). As in the case of the NEDC cycle, the use of electric loads has a large impact on energy consumption (for example for the low phase: E = 7.33 kWh/100 km, E max = 16.32 kWh/100 km it is more than twice as high energy consumption, so half size of the vehicle range, from d min = 290.50 km to d max = 130.52 km).

**Figure 6.** Energy consumption and range of the electric vehicle according to the WLTC cycle

The energy consumption according to the WLTC cycle was from 6.22 to 10.53 kWh/100 km, which was equal to the range from 341.91 km to 202.33 km.

5.3. Comparison of energy consumption in tests

Considering the general energy consumption according to the NEDC and WLTC cycles, the values of this parameter were compared for the drive phase without the use of electric loads, as well as for the drive phase using a different strategy of power reception. Based on Figure 7, it can be seen that the energy consumption according to the NEDC cycle could be even 54% higher in relation to the WLTC cycle.

**Figure 7.** Percentage comparison of energy consumption according to NEDC and WLTC cycles
6. Model validation
The mathematical model presented was used to assess energy consumption according to different driving cycles. Two research tests were used, the NEDC and WLTC cycles. The values of energy consumption and vehicle range for each sub-cycle of the selected test were presented. The results of the simulation give the maximum energy consumption according to the NEDC cycle, which equals 15.6 kWh/100 km. The producer gives a value of 15 kWh/100 km [27] so it can be said that the presented model maps the energy consumption according to the NEDC cycle with an accuracy of 4 percent. The comparison of energy consumption for the WLTC test was not possible due to the lack of manufacturer data.

7. Conclusion
The theoretical analysis of the electric vehicle's energy consumption in accordance with the applied mathematical model made it possible to draw the following conclusions:

- The energy consumption according to the NEDC cycle was from 9.6 to 15.6 kWh/100 km, which was equal to the range from 221 km to 136 km,
- the power consumption according to the WLTC cycle was from 6.22 to 10.53 kWh/100 km, which was equal to the range from 341.91 km to 202.33 km,
- energy consumption according to the NEDC cycle could be even 54% higher in relation to the WLTC cycle,
- the important issue is the distribution of energy in the context of electric loads, which has a very significant impact on the overall energy consumption,
- the presented model, with accuracy to 4 percent, allowed to map the energy consumption values in the laboratory conditions.

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