# INFLUENCE OF BATTERY VOLTAGE ON HYBRID VEHICLES PERFORMANCES

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## ABSTRACT

*It is known that the maximum efficiency of the electric motors is increased when the power voltage go higher. But, is this a condition to improve the global efficiency for a hybrid-electric powertrain? Anyway, more and more producers of hybrid cars try to proceed to higher voltage of their electric part of powertrain.*

*This paper try to point out which are the advantages of raising the nominal voltage of a hybrid-electric system from 180V to 324V, using the AMESim software. For this reason, the watched parameters are fuel consumption for NEDC cycle, the autonomy in pure electric drive at 50 km/h and 90 km/h, maximum speed for pure electric drive and the acceleration time from 0 to 90 km/h.*

**Keywords**: hybrid car, electric car, alternative powertrain, AMESim, simulation,

## 1. INTRODUCTION

After nine years of the 21$^{th}$ century, when the internal combustion engines pollutant emissions have been stageworthy reduced, the main negative impact of vehicles exhaust gases became the greenhouse effect. Therefore, all producers from automotive industry try now to reduce the fuel consumption, being known that the $CO_2$ gas emission, which have the most important contribution in greenhouse effect, is directly proportional with engine fuel consumption. Till the batteries technologies will be enough improved to make possible the implementation in pure electric drive vehicles, which are the most “clean” and very efficient, hybrid powertrains are an intermediary step.

## 2. GLOBAL VEHICLE MODEL AND PARAMETERS

Using AMESim software tool, work of realizing models for simulations is simplified by choosing one of the submodels from various libraries. Figure 1 shows the sketch for the model used for numerical simulations. Each icon cover a fragment of C code, written using the specific equations for the system.

For analyzing the raising of voltage from 180V to 324V, the model of battery is important. It is an internal resistance model, which characterizes the battery with a voltage source and an internal resistance. The battery output voltage is calculated as follows:

$$U = U_0 - R \cdot I \tag{2.1}$$

where: $U_0$ is the open circuit voltage in V, $R$ is the equivalent internal resistance in Ω, $I$ is the input current in A, Figure 2, Figure 3.

The battery consists of banks in serial and parallel arrangements; each battery bank consists of cells. Battery bank used for simulations is presented in The arrangement of 180V is reached by organizing 5 banks of 30 cells in series and 5 in parallel.

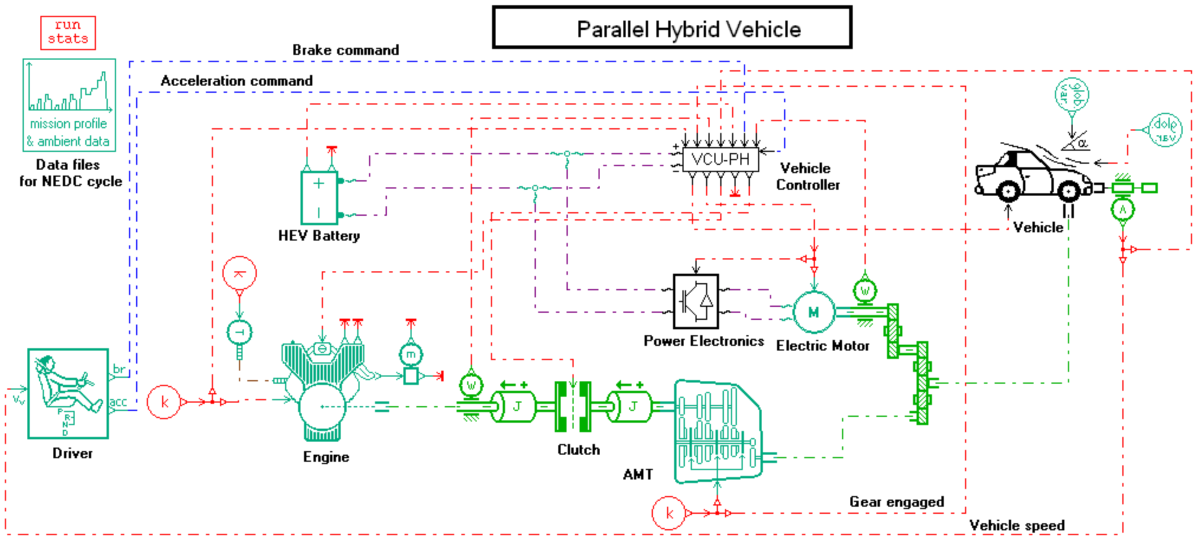


**Figure 1 – Model sketch of hybrid car**

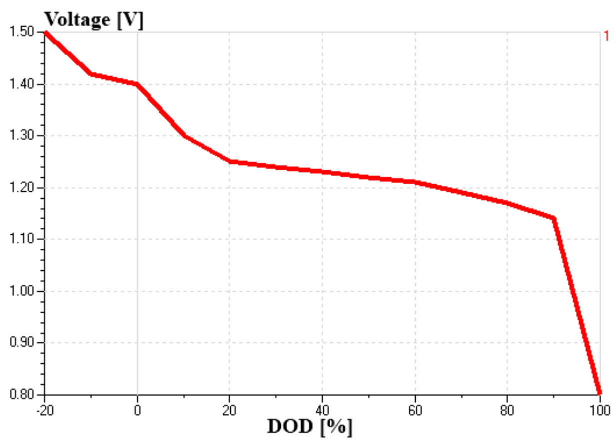


**Figure 2 – Open circuit voltage for cell battery**

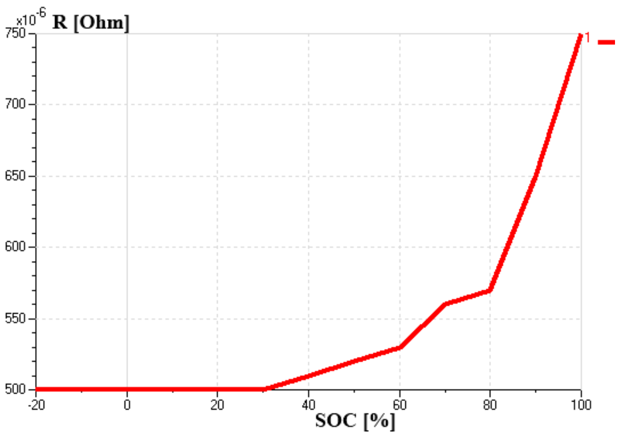


**Figure 3 – Internal resistance for cell battery**

If the nominal capacity of one bank formed from 30 cells in series is 3,2 Ah [4], then the nominal capacity of 180V arrangement is 16 Ah (5 x 3,6 Ah) and for the 324V arrangement (9 banks in series and 3 in parallel) this is 9,6 Ah (3 x 3,2 Ah).

The depth of discharge DOD is used as an input to read the open circuit voltage data file and the internal resistance data file too. The depth of discharge is expressed in per cent and it is computed as follows:

$$DOD = \frac{q}{C_{nom}} \cdot 100 + DOD_0 \quad (2.2)$$

where: $q$ is the charge used by the load [As], $C_{nom}$ is the rated capacity [As], $DOD_0$ is the depth of discharge at the beginning [%].

The battery pack open circuit voltage (output at port 3) is computed as follows:

$$U_{oc} = U_{file} \cdot N_{cell} \cdot S_{bank} \ [V] \quad (2.3)$$

where: $U_{file}$ is the open circuit voltage read in the file [V], $N_{cell}$ is the number of cells in series per battery bank, $S_{bank}$ is the number of battery banks in series.

The parameters used in simulations are centralized in Table 1 and Figure 4. Values for car parameters, gearbox and engine was obtained from Citroen C1, [5].

**Table 1 - Parameters values for simulations**

| Submodel | Parameter | Value / Unit |
|---|---|---|
| Vehicle | Kerb weight | 790 kg |
| | Wheel Inertia ( 4 wheels) | 2,5 kg·m$^2$ |
| | Rolling radius | 0,283 m |
| | Maximum brake torque | 1000 Nm |
| | Drag coeficient | 0,31 |
| | Frontal area | 1,97 m$^2$ |
| | $f_0$ coeficient | 0,01 |
| | $f_1^*$ coeficient | $5 \cdot 10^{-6}$ h/km |
| Gearbox | Final drive gear ratio | 3,55 |
| | Final drive efficiency | 0,97 |
| | 1$^{st}$ gear ratio | 3,545 |
| | 2$^{nd}$ gear ratio | 1,913 |
| | 3$^{th}$ gear ratio | 1,31 |
| | 4$^{th}$ gear ratio | 1,027 |
| | 5$^{th}$ gear ratio | 0,85 |
| | Gearbox efficiency | 0,97 |
| Engine | Type | ICE – spark ignition |
| | Maximum power | 50kW / 6000 rev/min |
| | Maximum torque | 93 Nm / 3600 rev/min |
| | Hot Idle consumtion | 500 g/h |
| | Displacement | 998 cm$^3$ |
| Electric motor | Nominal voltage | 156 – 312 V |
| | Continous torque | 31,3 – 35 Nm |
| | Continous shaft power | 15 – 20 kW |
| | Peak shaft power | 35 – 47 kW |
| | Peak efficiency | 85 – 87 % |
| | Weight | 40 kg |

| | | |
|---|---|---|
| Battery pack | Nominal capacity | 16 - 9,6 Ah |
| | Nominal voltage | 180 – 324 V |
| | Cells number per bank | 30 |
| | Parallel displacement of banks | 5 - 3 |
| | Series displacement of banks | 5 - 9 |

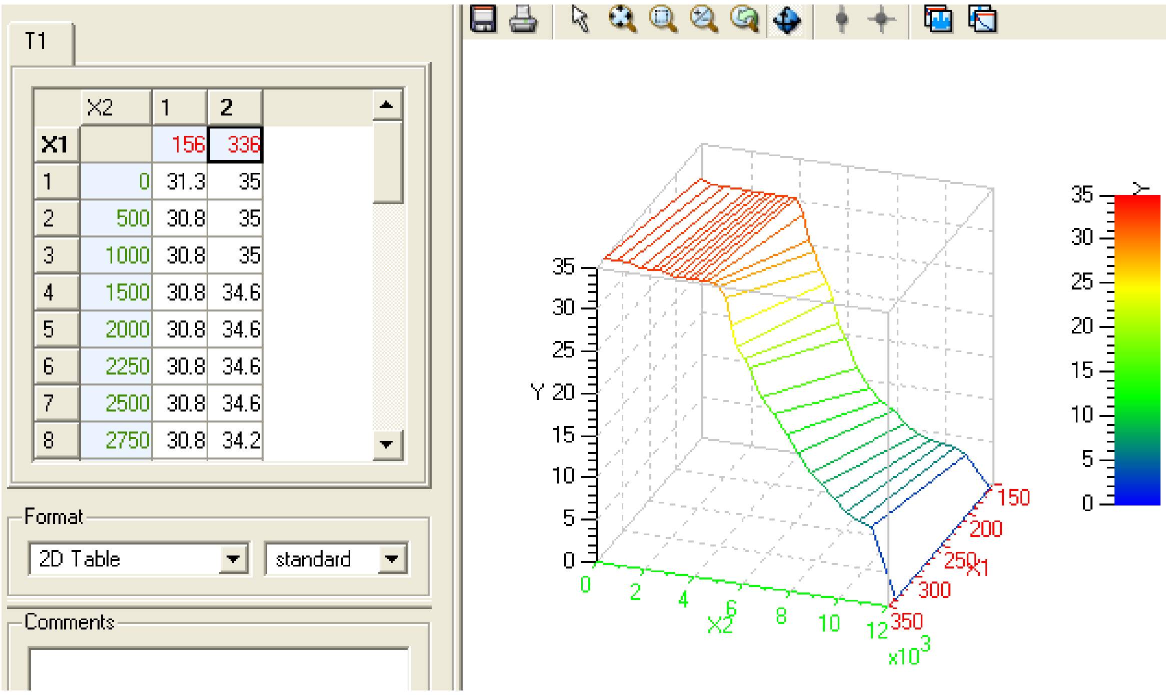


**Figure 4 – Torque for electric motor [Nm] vs. revolution speed and voltage**

## 3. SIMULATION AND RESULTS

For a minimum degree of validation for model used, Figure 5 and Figure 6 presents a good approach of real speed of vehicle and control speed and a normal scale for rotary speed of engine and electric motor. Also, it is visible that the engine starts just when the vehicle speed exceed the value of 10 m/s (hybrid drive) and it charge the battery during traction.

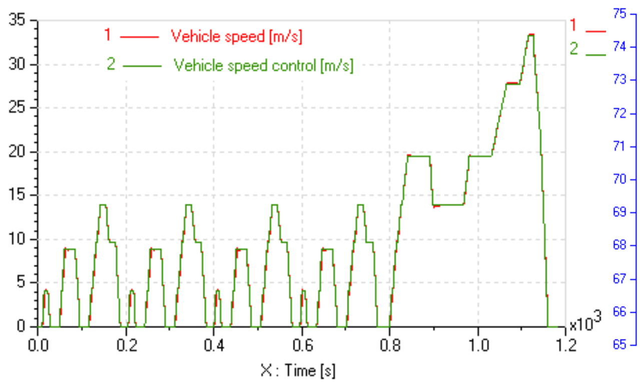


**Figure 5 – Vehicle speed and control speed**

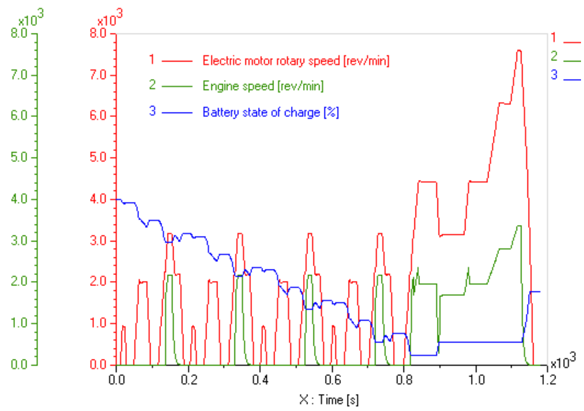


**Figure 6 – Engine speed, electric motor speed and SOC[%]**

3.1 Fuel consumption

Because the SOC of battery at end of cycle can influence the fuel consumption (by stocking some energy), simulation was run for 10 NEDC consecutive cycles. In this way, the SOC of battery at end have a minimum influence for fuel consumption. Obtained values are presented in table 2 and fig. 7.

**Table 2 – Calculation of average fuel consumption for different range of battery capacity usage**

| | Range of battery capacity used [%] | Distance [km] | Total fuel consumption [g] | Initial SOC [%] | NEDC Fuel Consumption [l/100km] | Average fuel consumption [l/100km] |
|---|---|---|---|---|---|---|
| **180 V** | 80% - 60% | 109.2 | 2985.9 | 80 | 3.65 | **3.47** |
| | 80% - 60% | 109.2 | 2564 | 100 | 3.13 | |
| | 80% - 40% | 109.2 | 3001.2 | 60 | 3.66 | |
| | 90% - 80% | 109.2 | 2809 | 95 | 3.43 | |

| | Range of battery capacity used [%] | Distance [km] | Total fuel consumption [g] | Initial SOC [%] | NEDC Fuel Consumption [l/100km] | Average fuel consumption [l/100km] |
|---|---|---|---|---|---|---|
| **324 V** | 80% - 60% | 109.2 | 2779.19 | 80 | 3.39 | **3.41** |
| | 80% - 60% | 109.2 | 2563 | 100 | 3.13 | |
| | 80% - 40% | 109.2 | 3053.5 | 60 | 3.73 | |
| | 90% - 80% | 109.2 | 2783 | 95 | 3.40 | |

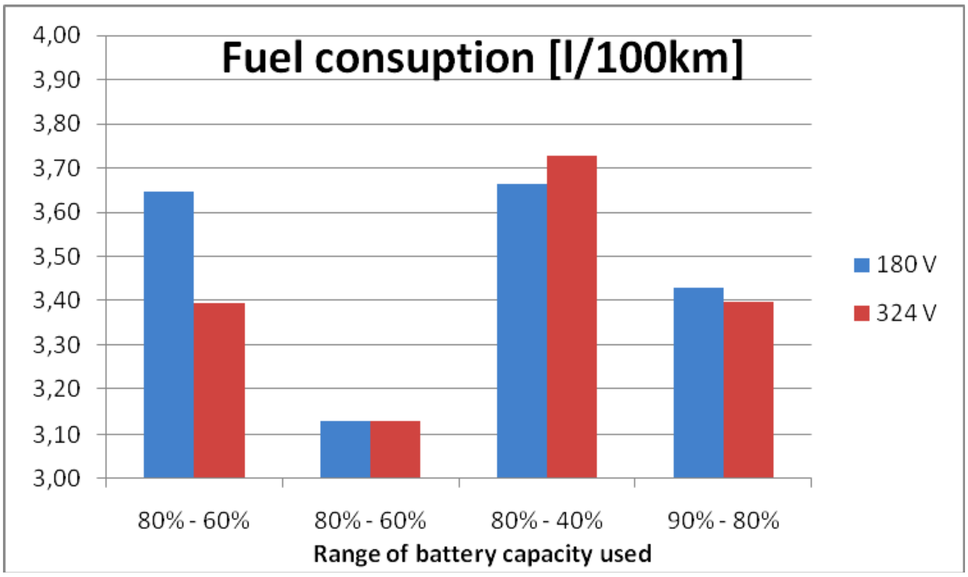


**Figure 7 – Fuel consumption values for the voltages analised**

3.2 The driving range autonomy

Running again the simulations for different values of constant speed of vehicle, the driving range calculated is presented in Figure 8 , for speed of 90 km/h, and in Table 3 (and fig.9) also for 18 km/h. Values of driving range for 180V voltage have been corrected by factor of capacity (which take into account the different number of banks in battery packages), computed as follows:

$$k_{range} = \frac{N_{324}}{N_{180}} = \frac{27}{25} = 1,08 \quad (3.1)$$

where: $N_{324}$ , $N_{180}$ are the numbers of total banks in 324V, respectively 180V configuration.

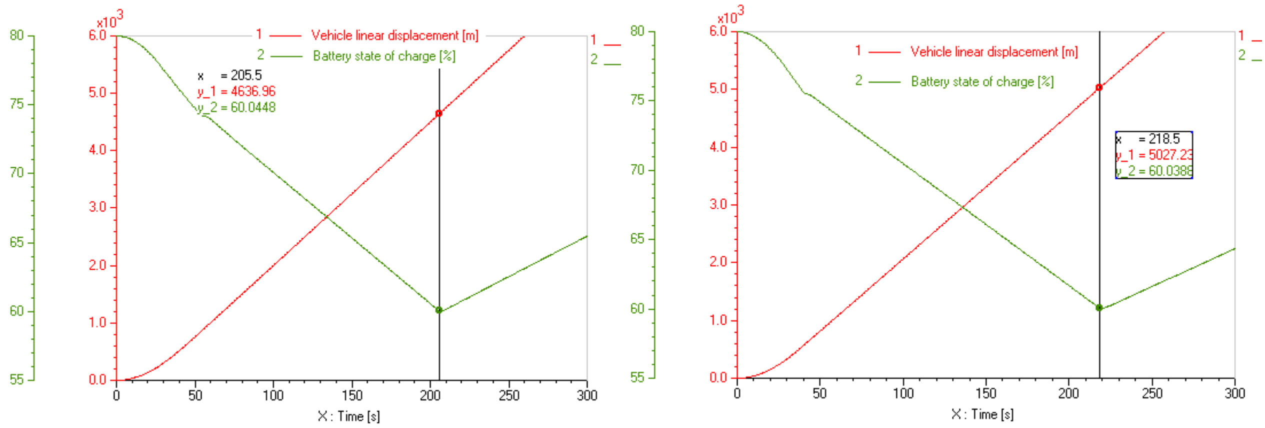


**Figure 8 – Driving range at 90 km/h constant speed for 180 V, respectively 324V**

**Table 3 – Driving range**

| | Constant speed [km/h] | Range [km] |
|---|---|---|
| **180V** | 90 | 5.008 |
| | 18 | 15.137 |
| **324V** | 90 | 5.027 |
| | 18 | 14.995 |

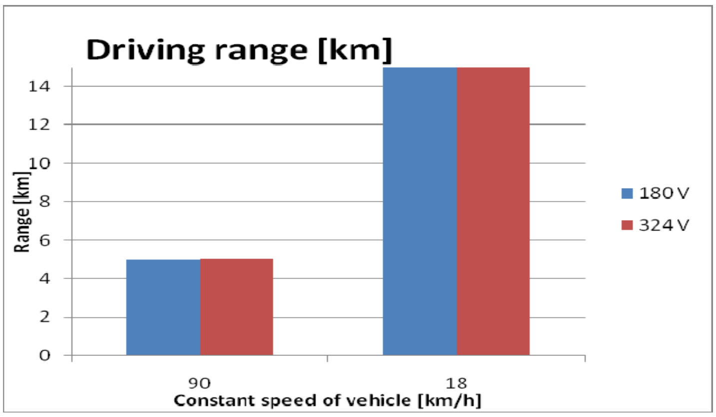


**Figure 9 – Driving range for 90 and 18 km/h**

3.3 Dynamic performances for pure electric drive

Analyzing the curves from Figure 10, it can be observed the maxim speed of **27 m/s** for 180 V system and **30 m/s** for 324 V system. For acceleration time from 0 to 25m/s, it can be observed a value of **50,2 s** for 180V system and **39,1 s** for 324 V system.

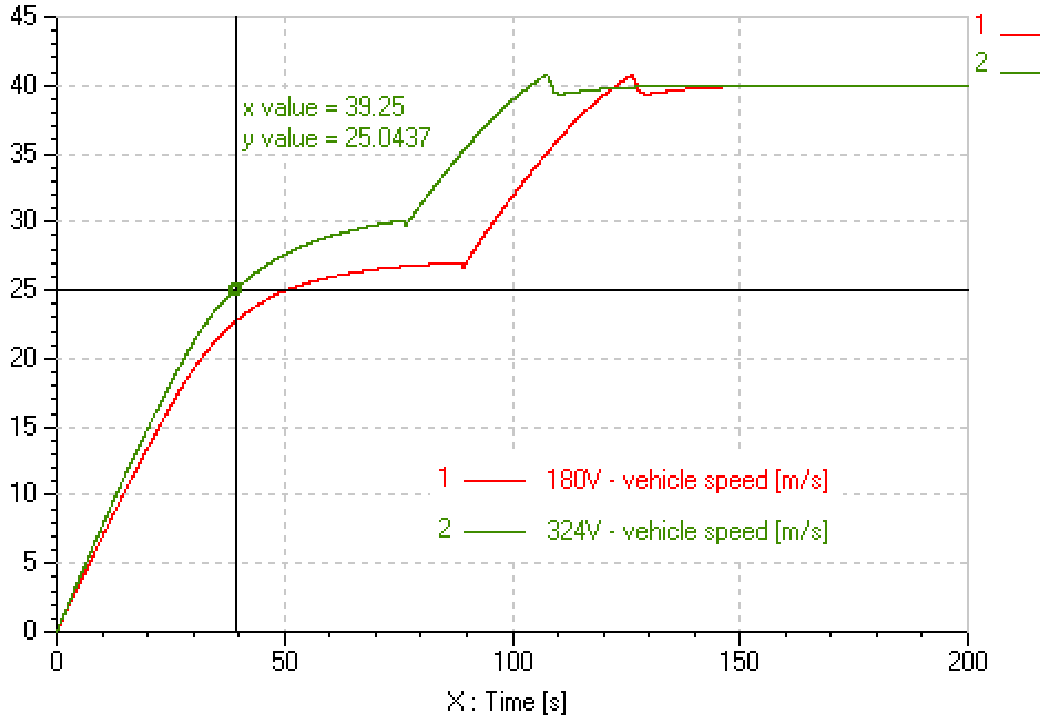


**Figure 10 – Acceleration (pure electric drive) for 180V and 324V battery**

## 4. CONCLUSION

Analyzing the results of this work it is visible that the voltage of electric system from a hybrid powertrain have a major importance just in case of dynamic parameters (maximum speed and acceleration time at pure electric drive). Using the electric motor at high voltage, the raised mechanical power will be capable to drive the vehicle with 10% faster (**108 km/h** confronted by **90 km/h**). Also, the acceleration time from 0 to 90 km/h at pure electric drive is 22% better.

Taking into account the ease of obtaining a battery package with higher voltage from battery banks formed by cells, is making sense why more and more automotive producers try to increase the nominal voltage of their hybrid powertrains, even when the fuel consumption of internal consumption engine is not significantly reduced and not even the driving range at pure electric drive is not improved.

## 5. ACKNOWLEDGEMENT

This work was supported by CNCSIS Romania through project ID_1091 (contract number 166/01.10.2007) and POSDRU/6/1.5/S/19 contract, ID_7713/2007.

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## 7. GLOSSARY

*NEDC*: New European Driving Cycle

*SOC*: State Of Charge [%]

*DOD*: Depth Of Discharge [%]