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A comparison of the battery electric TU/e Lupo EL and VW Lupo 3L diesel

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Abstract

To gain more insight in different aspects of electric vehicles, the Dynamics and Control group of the Eindhoven University of Eindhoven has developed the Lupo Electric Lightweight (EL) as a research platform for electric mobility. A model of the powertrain of the Lupo EL is created and gives fairly accurate indications of the real-life performance of the Lupo EL. The deviation between the model and DC measurement results is less than 10%. According to the measurements results, the electric Lupo EL has significant lower carbon dioxide emissions than the Lupo 3L equipped with a diesel engine. The difference in CO₂ emissions between the EL and 3L at constant speed is at least 8.9%. Batteries make the vehicle more expensive and result in additional CO₂ emissions during production. The break-even distance is 82300 km for the CO₂ emissions and 326400 km for the investments, if normal power grid electricity is used. If solar energy is used, the break-even distance would be 38600 km for the CO₂ emissions and 243600 km for the investments. The range of the Lupo EL is between 150 and 200 km, depending on the driving conditions. Comparing the Lupo EL with other electric vehicles, like the Nissan Leaf and Smart ForTwo, the energy usage is fairly low.

Keywords: Lupo EL, electric vehicle, energy, battery, life cycle analysis

1 Introduction

According to different studies the world climate is rapidly changing. Several studies show a connection between global temperature rise and increase of carbon dioxide emissions. Reconstructions of climate data over the past 1000 years show an increase in global temperature since the beginning of the 20th century. Analyzing this data, it can be concluded that the sudden temperature rise cannot be explained by natural variations alone, but must be caused by human activity in particular CO₂ emissions. A big part of the worldwide CO₂ emissions is contributed by the transport sector. In 2008 a total of 29381.4 million tonnes CO₂ was emitted worldwide. Transportation emissions contributed 23% to the total CO₂ emissions in 2008. With an estimated annual growth of 3.4% of the world stock of vehicles, it is necessary to reduce the emission per vehicle. On the route towards efficient vehicles

with low emissions car manufactures are looking for new, or renewable, energy sources to power the vehicle like electric energy [6] [7] [8].

To gain more insight in different aspect of electric vehicles, the Dynamics and Control group of the Eindhoven University of Eindhoven has developed the Lupo Electric Lightweight (EL) as a research platform for electric mobility. The vehicle is designed on the basis of a VW Lupo 3L, which is thoroughly optimized to have a low weight. The resulting battery electric Lupo EL achieves a unique combination of interior space (4 seats), weight (1060 kg) and battery capacity (27 kWh) [2]. The Lupo EL is equipped with several new components compared to the Lupo 3L. A list of the important new components is given in table 1.

The initial design goal of the Lupo EL was to have a similar performance as the Lupo 3L, with a charging time of 8 hours or less on a standard power socket [2]. The top speed of the Lupo EL

is electronically limited to 130 km/h and it is able to accelerate from 0 to 100 km/h within 12 seconds. A hill climb, including start-stop maneuver, of 30 % has been executed without any problems at the RDW proving grounds in Lelystad, The Netherlands.

In this paper a powertrain model is proposed to calculate the energy usage of the VW Lupo EL. This model is validated and evaluated for different driving conditions. This paper is based on a graduation research project, which is described in a master thesis [1].

Table 1: Component specifications [2]

charger	3.3 kW, 260-520 V DC out
HV batteries	91 cells in serie, 27 kWh, 273 kg, cell: 90Ah, 3.3 V, LiFePO ₄
motor	24 kW/ 80Nm (nominal), 50 kW/270 Nm (peak), AC induction, 10500 rpm max.

2 EV powertrain modeling

A good and useful modeling practice consists of breaking down the vehicle powertrain in various subsystems, as shown in figure 1. The model is calculated in a backward order. In the backward calculation the vehicle speed is the input and subsequently the battery power is the output.

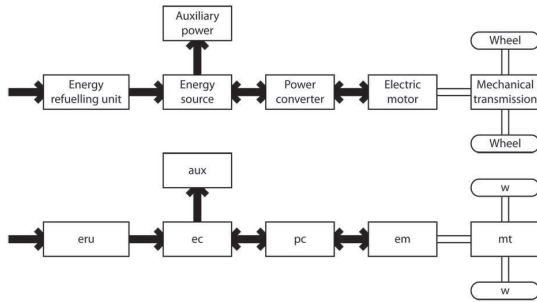


Figure 1: Simplified powerflow model

2.1 Road load and mechanical transmission

The first submodel of the system to be considered is the road-load and mechanical transmission model. The wheels transform the momentum and rotational speed, which is provided by the electric motor, into a forward velocity and traction force. The inputs and outputs of this submodel are:

Inputs:

- Vehicle speed (v) [m/s]

- Road slope (α) [$^\circ$]

Outputs:

- Angular wheel velocity (ω_{em-mt}) [rad/s]
- Wheel moment (T_{em-mt}) [Nm]

The elementary equation that describes the longitudinal dynamics of a road vehicle without rotational inertia has the following form:

$$m_v \frac{dv}{dt} = F_t - (F_a + F_r + F_g) \quad (1)$$

where m_v is the vehicle mass including driver and cargo [kg], F_a is the aerodynamic drag [N], F_r the rolling resistance [N] and F_g is the force caused by the gravity when driving on non-horizontal roads [N]. The traction force F_t is the force generated by the prime mover minus the force that is used to accelerate the rotating parts inside the vehicle and minus all friction losses in the powertrain [3].

The equations for calculating F_a , F_r and F_g are described as:

$$F_a = \frac{1}{2} \rho_a A_f c_d (v - w)^2 \quad (2)$$

$$F_r = c_r m_v g \cos(\alpha) \quad (3)$$

$$F_g = m_v g \sin(\alpha) \quad (4)$$

In these equations, ρ_a [kg/m³] is the density of ambient air, c_d [-] is the aerodynamic drag coefficient, A_f [m²] is the frontal area, w is the windspeed in the forward direction of the vehicle [m/s] (positive for tail wind), c_r [-] is the tyre rolling resistance coefficient and g [m/s²] is the acceleration due to gravity [3]. The wind speed in the direction of the vehicle can be calculated with the next equation:

$$w = W \cdot \sin(\psi_{car} - \psi_{wind}) \quad (5)$$

where W is the absolute wind speed [m/s], ψ_{wind} is the wind direction [$^\circ$] and ψ_{car} is the direction of the vehicle [$^\circ$], with the northern direction as 0 $^\circ$. The change of aerodynamic drag coefficient due to cross wind is neglected due to a lack of data.

The traction force is generated by the prime mover, the electric motor. This traction force is a result of the wheel torque and the tyre radius. Thereby the forward velocity is a result of the angular velocity and the tyre radius. Therefore the traction force and vehicle velocity can be rewritten as:

$$T_{mt-w} = F_t R_e \quad (6)$$

$$\omega_{mt-w} = \frac{v}{R_e} \quad (7)$$

Where R_e is the effective rolling radius of the tyre [m].

2.1.1 Wheel and drivetrain inertia

When the vehicle is moving, the electric motor is driving both the traction forces F_t , and the inertia's and transmission resistance of the transmission:

$$T_{em-mt} = r_d(T_{mt-w} + T_{fr}) + 4r_d\dot{\omega}_{mt-w}J_w + \frac{\dot{\omega}_{mt-w}}{r_d}J_{em} \quad (8)$$

$$\omega_{em-mt} = \frac{\omega_{mt-w}}{r_d} \quad (9)$$

This results in the next equation for calculating the torque which the electric motor has to provide:

$$T_{em-mt} = r_dT_{fr} + 4r_d\dot{\omega}_{mt-w}J_w + r_dR_e(m_v\frac{dv}{dt} + F_a + F_r + F_g) + \dot{\omega}_{mt-w}\frac{J_{em}}{r_d} \quad (10)$$

In these equation r_d is the gear ratio [-], J_w is the wheel inertia [kg m²], T_{fr} is the friction moment in the bearings of the wheels and motor [Nm] and J_e is the motor inertia [kg m²].

2.1.2 Tyre rolling resistance

The rolling resistance is an important factor which influences the energy usage of a vehicle. Especially at lower speeds, the rolling resistance losses are dominant. The rolling resistance is depending on the tyre inflation pressure, p_i , the normal force F_z and the ambient temperature T . A tyre's rolling resistance can be described by the following equation [1]:

$$c_r = c_{rnom}(\frac{P_i}{P_{nom}})^\alpha(\frac{F_z}{F_{znom}})^\beta 1.006^{27-T} \quad (11)$$

where c_{rnom} is the rolling resistance under normalized conditions [-], p_i is the tyre inflation pressure [Pa], F_z is the vertical force on the tyres [N] and T is the ambient temperature [°C]. For an average passenger car tyre $\alpha \approx -0.4$ and $\beta \approx 0.85$ [4].

2.2 Electric motor and power converter

Due to the fact that the electric motor of the VW Lupo EL is an AC induction motor, the motor has a high-voltage three-phase input. The currents and voltage which drive the electric motor are only measurable with advanced and expensive sensors and systems. To simplify the model the electric motor and power converter can be combined in one subsystem calculation.

The input of the power converter (inverter), and therefor the output of the backward calculations, is the power from the battery pack. The output of the electric motor (AC induction motor) is the torque (T_{em-mt}) and shaft speed (ω_{em-mt}) going into the mechanical transmission.

Inputs:

- Angular engine velocity (ω_{em-mt}) [rad/s]
- Engine momentum (T_{em-mt}) [Nm]

Outputs:

- EM battery power (P_{pc-em}) [W]

For the VW Lupo EL an empirical equation has been derived from the motor characteristics provided by the manufacturer. The equation consists of an efficiency due to the electrical resistance $A=0.28$ s/Nm, the power of the engine $B = 0.09$, a constant resistance torque $C=1.8$ Nm and a constant loss in the inverter P_{inv} [W].

$$P_{pc-em} = T_{em-mt}\omega_{em-mt} + P_{loss} \quad (12)$$

$$P_{loss} = A \cdot T_{em-mt}^2 + B \cdot T_{em-mt}\omega_{em-mt} + C\omega_{em-mt} + P_{inv} \quad (13)$$

2.3 Auxiliary power

Next to the electric motor, the vehicle auxiliaries require energy from the HV batteries. The high voltage (HV) battery power is converted with a DC-DC converter to low voltage (LV) power which is used to power the auxiliaries and charge the 12V battery. The total power which is used by the DC-DC converter is the output of the auxiliaries block and has to be added to P_{ec-pc} to calculate the total desired battery power.

Outputs:

- Auxiliaries battery power P_{ec-aux} [W]

The total power demand of the auxiliaries is depending on the components that are turned on, eg. lighting, heating and the 12V power supply of the inverter. The heater of the VW Lupo EL consists of two components which can be turned off or on individually. These components demand 330 W and 660 W respectively. During driving the daylight running lights are always powered and consume 13.9 W. If a higher light intensity is needed, the daylight running lights are switched off and the high beam Xenon headlights are turned on which consume 62 W. The efficiency of the DC-DC converter is measured to be 72%. The total amount of 12V power which is used by the auxiliaries is 100 W with the daylight running lights on and no Xenon lightning, and 150 W with the Xenon lighting on and no running lights as shown in figure 2 [2]. With an

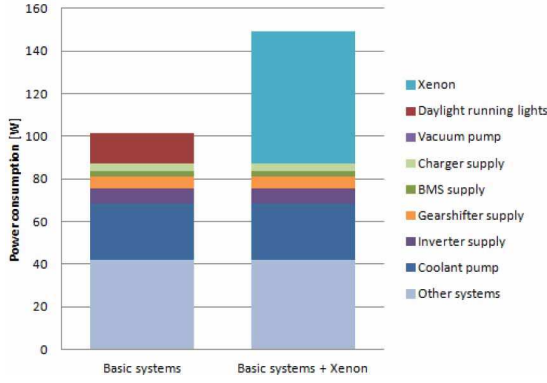


Figure 2: Auxiliary energy consumption breakdown [2].

efficiency of 72%, this results in a HV power demand of 139 and 208 W respectively. This figure will obviously rise considerably when the heating system is turned on.

Test results show a higher HV power demand during stand-still than is expected from the auxiliaries power. It is expected that this power usage is caused by the inverter. If the EV is in driving mode, the HV power demand during stand-still is 450 W even with no torque demand. If the vehicle is in neutral mode, the total HV power demand is 50 W, which indicates that some auxiliaries are turned off. For modeling purpose, a constant HV auxiliary power demand of 450 W will be used.

2.4 Batteries

The focus of this section will be on modeling a Li-ion battery. Although some statements may be applicable for other battery technologies, it may not be applied to other batteries technologies in general. Within the battery model block, the input is the sum of the powers which are needed to drive the electric motor and auxiliaries. The output of the block is the electrical power which is received from the charger.

Inputs:

- Auxiliaries battery power (P_{ec-aux}) [W]
- EM battery power (P_{ec-pc}) [W]

Outputs:

- Charger energy (E_{eru-ec}) [kWh]

The start-point of the simplified model is the battery equilibrium voltage. The equilibrium voltage, i.e. Electro-Motive Force (EMF), of the Li-ion battery is the difference between the equilibrium voltage of the positive and negative electrodes [5]. The equilibrium voltage of a battery is the theoretical voltage of the battery when the C-rate is zero, so when the current is zero. To find the equilibrium voltage the battery is discharged with a decreasing amount of C-rate until the EMF-line can be accurately estimated, results

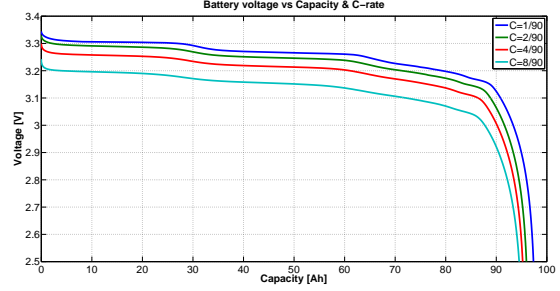


Figure 3: Discharge characteristics Lupo EL battery (LiFePO4).

are shown in figure 3. The total battery overpotential (V_t) is the difference between the equilibrium voltage V_{bat}^{eq} and the battery output voltage V_{bat} [5].

$$V_t = V_{bat} - V_{bat}^{eq} \quad (14)$$

The battery overpotential consists of the sum of the (1) diffusion limitation in the electrode(s) (V_{ed}) [V], (2) the diffusion and migration limitations in the electrolyte (V_{el}) [V] and (3) ohmic voltage drop in the electrodes and current collectors (V_{Ω}) [V] which can be calculated according to [5]:

$$V_t = V_{el} + V_{ed} + V_{\Omega} \quad (15)$$

$$V_{\Omega} = I \cdot R \quad (16)$$

When models are available for V_{el} [V] and V_{ed} [V] the evolution of the battery voltage can be found [5]. This results in a overall resistance term for the entire battery:

$$V_t = V_{\Omega} = IR \quad (17)$$

In (14), V_{bat} refers to the desired battery voltage [V], i.e. the sum of the the electrical motor and auxiliaries battery power (18), divided by the battery current (18). Within (16), I is the battery current [A] and R is the ohmic resistance inside the battery [Ω]. Note that by definition $I > 0$ during the charge and $I < 0$ during the discharge [5]. Both the battery EMF and the ohmic resistance are depending on battery temperature.

The total amount of power taken from the battery is the summation of the power demands of the power converter and the auxiliaries:

$$P_{bat} = V_{bat}I = P_{ec-aux} + P_{ec-pc} \quad (18)$$

To calculate the battery efficiency it could be useful to re-write (14) in the following form, by using the general equation for electrical power $P = I \cdot V$:

$$V_t I = V_{bat} I - V_{bat}^{eq} I \quad (19)$$

or:

$$R I^2 + V_{bat}^{eq} I - P_{bat} = 0 \quad (20)$$

Using the quadratic equation, the next formula can be derived for the output current:

$$I = \frac{-V_{bat}^{eq} \pm \sqrt{V_{bat}^{eq2} + 4P_{bat}R}}{2R} \quad (21)$$

By definition P_{bat} , R and V_{emf} are positive and I is negative for discharging, so the plus-minus sign of (21) must be negative. This results in the next equation for calculating the battery output voltage:

$$V_{bat} = \frac{P_{bat}}{I} = \frac{P_{bat}2R}{-V_{bat}^{eq} - \sqrt{V_{bat}^{eq2} + 4P_{bat}R}} \quad (22)$$

The discharge efficiency can be written as:

$$\eta_{discharge} = \frac{P_{bat}}{V_{bat}^{eq} I} \quad (23)$$

The discharge energy which has been taken from the battery pack between t_0 and t_e can be written in the next equation, where t is the driving time.

$$E_{bat-d} = \int_{t_0}^{t_e} (V_{bat}^{eq} I) dt \quad (24)$$

For charging the battery with a low C-rate (approx $C < 5$), the battery resistance R for charging can be assumed constant compared to the battery resistance for discharging. Because the maximum C-rate is 2 during driving and 0.1 during charging, R is constant and the next equation is valid:

$$RI^2 + V_{bat}^{eq} I = V_{charge} I \quad (25)$$

Where $I > 0$ for charging. So the total charge energy is:

$$E_{eru-ec} = E_{ch-bat} = \int_{t_0}^{t_{max}} (V_{charge} I) dt \quad (26)$$

Modern technologies provide electric and hybrid vehicles the opportunity to regenerate energy from braking. The current regenerative braking control strategy increases the deceleration of the vehicle at a certain brake pressure as is depicted in figure 4. In case of zero throttle input, the electric motor decelerates the vehicle by 0.5 m/s^2 . The deceleration due to regenerative braking increases linearly with brake pressure up to 2 m/s^2 at 10 bar in addition to the deceleration due to the hydraulic braking system. Up to 20 bar, the regenerative braking deceleration is constant. Between 20 and 70 bar, the regenerative braking deceleration decreases again linearly to 0 m/s^2 . The power which is recovered due to regenerative braking is then:

$$P_{regen} = m_v a_{regen} v \quad (27)$$

Where a_{regen} is the fraction of the total deceleration attribute to regenerative braking [m/s^2].

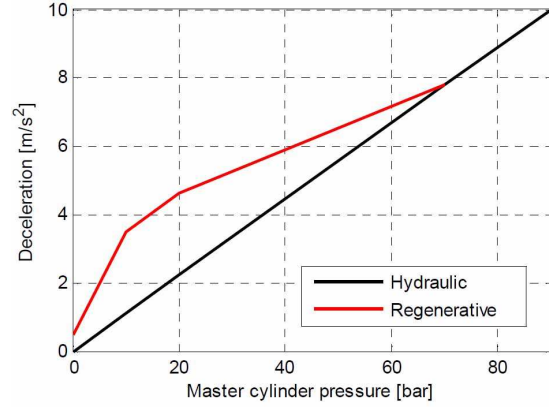


Figure 4: Regenerative braking Lupo EL [2]

2.4.1 Battery resistance

The resistance of the battery is depending on the temperature of the Lupo EL battery pack. An empirical equation from test data has been obtained:

$$R = 4.7810^{-4} T_{bat}^2 - 0.0206 T_{bat} + 0.388 \quad (28)$$

Where T_{bat} is the battery pack temperature [$^{\circ}\text{C}$] and R is the battery pack resistance [Ohm].

2.4.2 Battery warming

According to the equations mentioned above, the battery has losses, which are related to the battery internal resistance R . Due to this battery resistance, a part of the battery energy is wasted to heat the battery, while the main part is used to power the vehicle. With a constant speed test, the battery pack temperature development can be described by the thermodynamic equation as is described by:

$$M c_b \frac{dT_{bat}}{dt} = Q_{in} - Q_{out} \quad (29)$$

with

$$Q_{out} = \lambda_v (T_{bat} - T_{env}) \quad (30)$$

So:

$$\frac{dT_{bat}}{dt} = \frac{Q_{in} - \lambda_v (T_{bat} - T_{env})}{M c_b} \quad (31)$$

Where M is the mass of the battery pack [kg], c_b is the specific heat capacity [$\text{J/kg}^{\circ}\text{C}$], λ_v is the heat transfer coefficient of the surrounding of the battery pack [J°C], Q_{in} is the battery pack power losses [W], T_{bat} is the battery pack temperature and T is the ambient temperature [$^{\circ}\text{C}$]. The specific heat capacity of a LiFePO_4 battery is estimated to be $955.4 \text{ J/kg}^{\circ}\text{C}$ [1]. The specific heat capacity of air is $1.0035 \cdot 10^{-3} \text{ J/kg}^{\circ}\text{C}$. Due to the fact that the batteries are in a metal battery box, the potential heat energy is able to dissipate through the box. Due to this reason the average heat capacity drops slightly. According

to the test results at cold weather conditions the specific heat capacity of the batteries and battery box is $600 \text{ J/kg}^\circ\text{C}$. The heat transfer coefficient (λ_v) to the surrounding of the battery pack is estimated to be $5 \text{ J}^\circ\text{C}$.

2.5 Charger

A charger functions as a AC-DC converter which provides the batteries with a constant current up to a certain battery voltage. If the battery pack reaches a certain threshold value, the battery is charged with constant voltage. The charger can be modeled as a constant resistance where energy is lost between the power socket and the batteries. The input of the charger model block is the energy which is stored in the batteries. The output of the block is the energy which has been taken from the power socket.

Inputs:

- Charger energy (E_{eru-ec}) [kWh]

Outputs:

- Power socket energy (E_{ps}) [kWh]

The power which is provided by the power socket is limited by (1) the maximum voltage of the power supply, (2) maximum fuse current and (3) maximum charge current of the vehicle. Because the voltage of the power socket and the current are constant during most of the charging time, the charger is assumed to have a constant efficiency. This means that the next equation holds:

$$E_{ps} = \frac{E_{eru-ec}}{\eta_{ch}} \quad (32)$$

In this equation, η_{ch} is the charger efficiency and is determined to be 89.6% for the Lupu EL charger. E_{ps} is the energy which is taken from the power socket [kWh].

3 Validation of Lupu EL model

In the previous section a simulation model is described in order to predict the energy usage of the Lupu EL. Some parameters which are used for modeling the vehicle are obtained by dedicated tests. In this section the accuracy of the model and parameters selection will be discussed. Some parameters are determined beforehand, others are obtained from testing results. The main parameters are listed in table 2.

3.1 Rolling and air drag resistance

For determining the rolling and air drag resistance several roll-out tests have been performed. For the roll-out test the car is accelerated on a flat road up to 120 km/h. After reaching this speed, the motor was turned off so the vehicle could decelerate freely up to 70 km/h. This procedure was

Table 2: Lupu EL Parameters [1]

Parameter	Value	Unit
g	9.81	m/s^2
r_d	0.1156	-
R_e	0.27855	m
m_v	$1060 + m_{pass}$	kg
J_w	0.75	$\text{kg} \cdot \text{m}^2$
$J_e m$	0.0384	$\text{kg} \cdot \text{m}^2$
T_{fr}	4.25	Nm
$A_f \cdot c_d$	0.5319	-
c_r	0.0105	-

repeated for a deceleration from 70 to 50 km/h and 50 to 0 km/h. All test were performed in both western and eastern direction to eliminate the effects of wind and height. The air-density during the roll-out test was 1.2387 kg/m^3 with $T_{amb} = 17.5 \text{ }^\circ\text{C}$. The results of a roll-out test with the tyres inflated to 3 bar, are depicted in figure 5. A rolling resistance of $c_r = 0.0105$ and a air drag resistance of $A_f \cdot c_d = 0.5319$ give the best results for these roll-out tests.

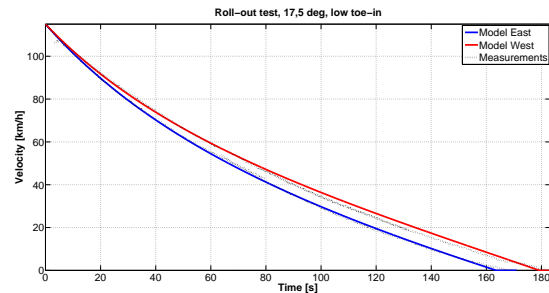


Figure 5: Roll-out test 26-03-2012, tyre inflation pressure 3 bar, zero road slope.

3.2 Electric motor and power converter efficiency

The equation for calculating motor-converter losses (13) is determined empirically according to motor measurements supplied by the manufacturer. The vehicle has been tested at the Test Centre Lelystad (TCL) of the Dutch roadworthiness authorities (RDW) and local roads. The tests were performed with constant speed and the results are compared with the simulation results with the above mentioned parameters and are shown in figure 6 & figure 7. From the constant speed test it can be concluded that the empirical determined equation (13) and values for the motor-converter combination has a fairly good agreement with the test results. The small deviation in the top-speed part can probably be explained by the difference in air-density during the test-event due to temperature and humidity fluctuations.

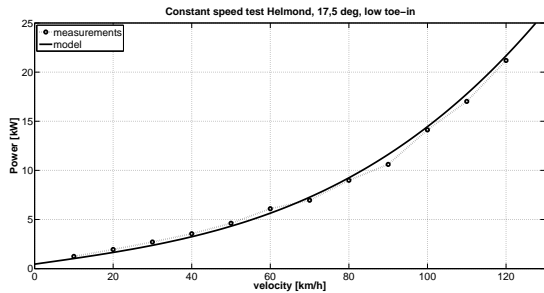


Figure 6: Battery power at constant speed test 26-03-2012, tyre inflation pressure 3 bar.

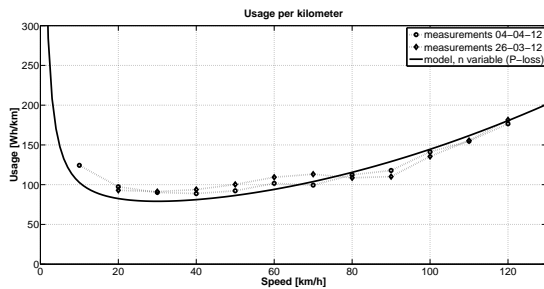


Figure 7: DC Energy usage at constant speed test 26-03-2012, tyre inflation pressure 3 bar.

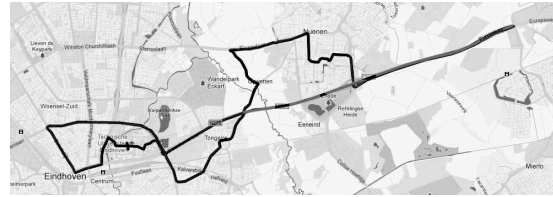


Figure 8: Drive cycle Mierlo, Helmond and Eindhoven.

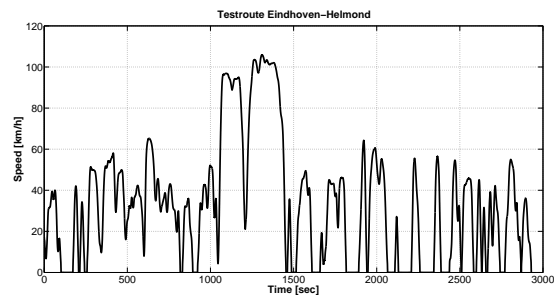


Figure 9: Test route speed.

3.3 Dynamic performance

A driving cycle is performed to analyse the dynamic accuracy of the model, now including acceleration and regenerative braking. A pre-defined route through Mierlo, Helmond and Eindhoven was developed and is shown in figure 8. The most important data of the Lupo EL was logged and compared with the model. The velocity profile at this route is shown in figure 9. Due to the fact that the vehicle speed is measured discontinuously, the differentiated acceleration profile gives very incorrect results in backwards calculations. To counter these peaks, the speed signal is filtered with a 2^{nd} order Butterworth filter with a cutoff frequency of 0.1 rad/sec. The power profiles of the model and the real-time measurements are shown in figure 10. The energy consumption is the integral of the power demand over time and is shown in figure 11. It has to be stated that the depicted energy consumption is the integral of the powerflow into and out of the battery. It can be seen in figure 11 that the difference between the measurements and the model is approximately 8.5%. This difference can be explained by (1) the potential difference in measured and real velocity, (2) insecurity in the total weight of the vehicle, passengers and instruments, (3) difference in wind speed, (4) accuracy of regenerative braking and (5) the assumption that there is a no-slip condition between the tyres and the road.

At the fifth of November 2011, the Eindhoven University of Technology participated in the Future Car Challenge. In this trip, the Lupo EL has driven from Brighton to London as efficient

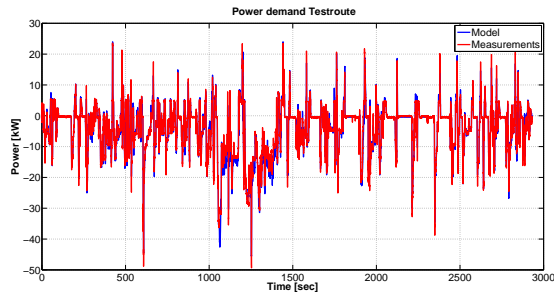


Figure 10: Power demand.

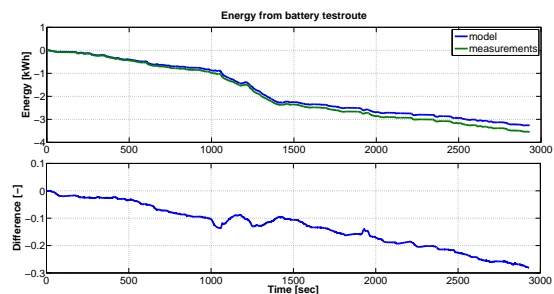


Figure 11: Battery energy consumption test route Eindhoven-Helmond.

as possible. The height and speed profile of the challenge are depicted within figure 12. During the future car challenge the VW Lupo EL finished at the 10th place out of 39 participants. The energy consumption of the Lupo EL was 13 kWh/100km, which is much lower than the average 24 kWh/100km of all participants.

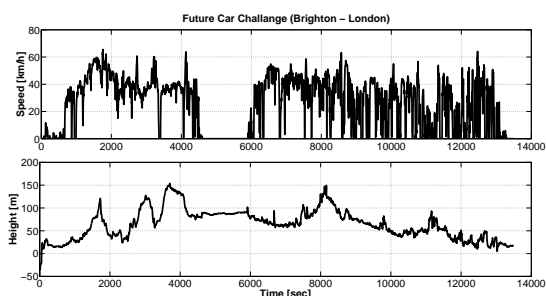


Figure 12: Speed and height profile Future Car Challenge (Brighton to London).

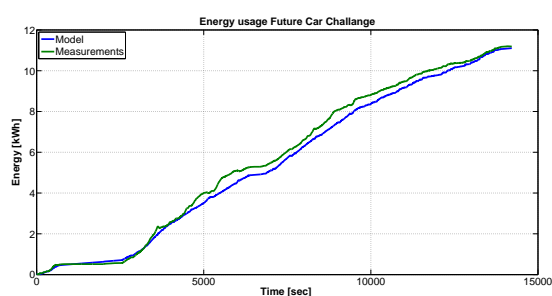


Figure 13: DC Energy usage Future Car Challenge (Brighton to London).

Comparing the difference of energy measurement results and model results of the London-Brighton challenge and the Eindhoven-Helmond route shows an inconsistency in accuracy. The main reason for this inconsistency is the most likely measuring inaccuracy of the GPS system. Figure 13 shows the increasing difference of energy consumption at the moment that the height difference is maximum, the difference between the measurement data and the model is 7.8%, compared to the final measured energy usage. At the end of the challenge, as the height difference is relatively small, the difference between measured energy usage and the model is 0.5%. The differences in these results can be explained by (1) lack of accurate information about the route height and (2) uncertainty about the passengers weight, temperature and the wind speed and direction.

3.4 Battery heating

The batteries used within the Lupo EL are based on the LiFePO₄ chemistry. The influence of pack temperature on battery pack resistance is tested during a constant speed test at 100 km/h. The start temperature of the constant speed test was

7°C. The battery pack temperature increases linearly during the test due to the heat produced by the batteries. The relation between measurement results and battery resistance model is depicted in figure 14.

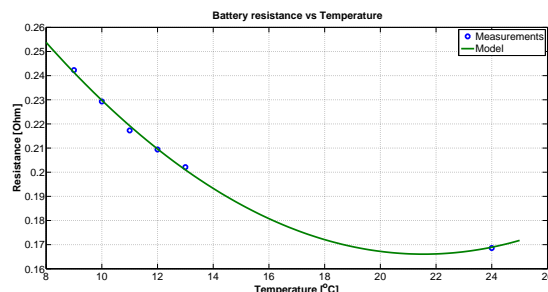


Figure 14: Battery pack resistance vs temperature.

The influence of the battery pack temperature is implemented in the model. For validating the relation between battery resistance and battery temperature, a simulation is performed for driving 100 km/h with an ambient temperature of 7 [°C] during a period of 5010 sec (the length of the cold-weather test). The simulation represents the constant speed test of 100 km/h with an ambient temperature of 7 °C and a changing battery pack temperature due to energy losses in the batteries. The results are compared with the measurements results and depicted in figure 15 and figure 16. The difference in battery voltage (figure 15) can be explained by (1) the difference in battery pack voltage at a certain SOC and (2) start-up problems to get cruise-control engaged.

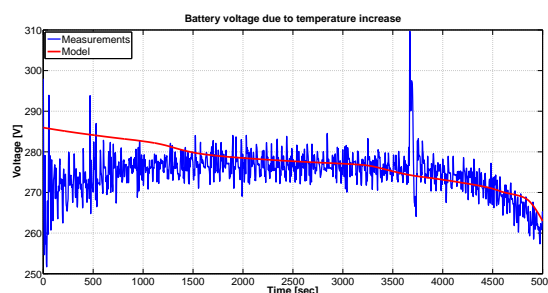


Figure 15: Battery voltage during a cold-weather 100 km/h test drive.

4 Vehicle comparison

4.1 Lupo EL vs Lupo 3L

In order to be able to compare diesel and battery electric driving, two similar vehicles will be compared on their cost and CO₂ emissions. The Eindhoven University of Technology owns two Volkswagen Lupo's of which one is powered by an electric motor (Lupo EL) and the other by a diesel ICE (Lupo 3L). The VW Lupo 3L has a 45 kW TDI engine and weighs 840 kg. According to the vehicle information, an average usage

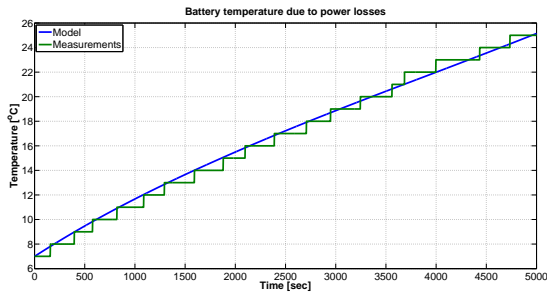


Figure 16: Battery temperature during a cold-weather 100 km/h test drive.

of 3L diesel per 100 km is assumed. Test results show that this assumption is slightly lower than real-life consumption [1].

To compare the diesel and electric powertrain, a carbon dioxide and costs comparison can be made. The fuel and electricity usage are tested in constant speed tests under comparable conditions. The inflation pressure of the tyres was 3 bar for both vehicles and the temperature of the tests varied between 15 and 25 deg. For calculating the carbon dioxide emissions the equivalent emissions for electricity (500 g/kWh) and diesel (3100 g/L) are used. The costs of electricity and diesel are 0.22 euro/kWh and 1.499 euro/L [1]. The energy taken from the power socket is used to calculate the emissions and costs of electric driving. In figure 17 the CO₂ emissions from both propulsion systems are depicted for constant speed driving. It is clear that for all speeds, the Lupo EL has lower CO₂ emissions than the Lupo 3L. The smallest tested emissions difference between the Lupo 3L and Lupo EL is 8.9% at 120 km/h. The driving costs for both vehicles are depicted in figure 18. The difference in operational costs between the Lupo EL and Lupo 3L are bigger than the difference in emissions. The minimal costs difference between the EL and 3L is 58% at 120 km/h.

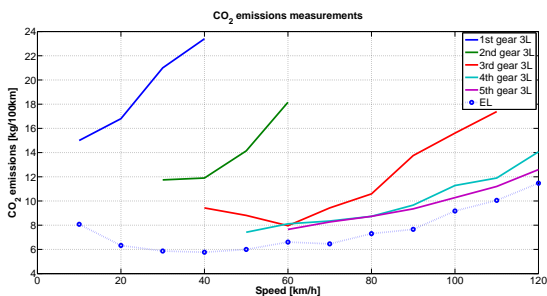


Figure 17: CO₂ emissions at constant speed

A simulation of a NEDC drive cycle is performed for the Lupo 3L and EL. For the Lupo 3L, the most efficient gear shifting strategy is used over the entire cycle. The results of the NEDC cycle simulation are listed in table 3. Next to the simulation, a real-life test is performed with the Lupo EL and Lupo 3L. The drive cycle between Eindhoven, Nuenen and Helmond, as described in above, is driven multiple times with both vehi-

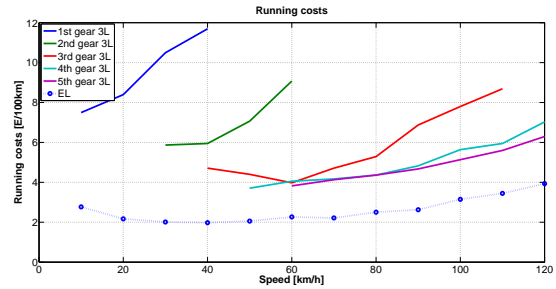


Figure 18: Energy costs at constant speed

cles. The AC average energy usage of the Lupo EL over 5 repetitions was 4.8 kWh/lap. The total fuel usage of the Lupo 3L over 3 repetitions was 3.62 liter. The resulting fuel usage, CO₂ emissions and driving costs are listed in table 3.

Table 3: Fuel usage, CO₂ emissions and driving costs Lupo 3L and Lupo EL (usage: [l/100km], CO₂: [kg/100km], Costs: [euro/100km])

Test	Usage	CO ₂	Costs
NEDC 3L	3.2 [L]	9.9	4.80
NEDC EL	13.6 [kWh]	6.8	2.99
Eind-Helm 3L	4.36 [L]	13.5	6.54
Eind-Helm EL	17.3 [kWh]	8.7	3.81

From the dynamic tests, it can be concluded that the running costs and emissions of the Lupo EL are significantly lower than those of the Lupo 3L. Nevertheless, the Lupo EL has higher starting costs and CO₂ emissions than the Lupo 3L. The production of the batteries are estimated 12.5 kg CO₂ per kg battery [10]. The costs of the batteries are 300 euro/kWh [2]. To encounter the emissions and costs for the electric motor and other systems, a 10% overhead is added to the costs and emissions of the batteries. This means that the Lupo EL has 8910 euro higher starting costs and 3623 kg more CO₂ emissions for the production than the Lupo 3L. The energy used for the production of the Lupo 3L base vehicle was 17.04 MWh [14]. Because the cost and emissions of the Lupo EL base vehicle is equal to the cost and emissions of the Lupo 3L, these numbers are left out of the break-even calculations.

The costs and emissions of electric energy mentioned above is focused on electric energy from the power grid. To check more environmental friendly options, the emissions and costs of charging the vehicle with solar power is calculated. The average sun energy in Eindhoven is between 0.7 kWh/m²/day (winter) and 4.2 kWh/m²/day (summer). The average solar energy in Eindhoven is 2.7 kWh/m²/day [11]. With a typical solar panel (poly crystalline silicon) efficiency of 15%, the average daily solar energy is 0.405 kWh/m²/day. The average daily distance traveled in Dutch passenger cars

is 36.5 km [15]. This results in a daily energy usage of 6.31 kWh with an average energy usage of 17.3 kWh/100km. So to be able to load the Lupo EL on an average day, 15.6 m² of solarpanels is needed. The commercial costs of a kind of solarpanels are estimated to be 375 euro/m², so the total costs of the batch solarpanels would be 5850 euro [12]. If for the installation and overhead (eg. DC/DC converter, batteries, cables) additional costs of 20% are used, the total investments would be around 7020 euro. For the production of the solarpanels 60.1 kg/m² CO₂ is emitted [13]. This results in a total emission of 938 kg CO₂ for the production of the solarpanels. For the energy storage system of the solar panels and overhead the amount of CO₂ emitted is raised with 20%. So in total 1130 kg of CO₂ is emitted for the solar panels and overhead.

The break-even points of the CO₂ emissions between electric grid and diesel power are 129400 km for the NEDC cycle and 82300 km for the testroute, as shown in figure 19. The total costs of the Lupo EL are lower than the Lupo 3L after 492300 km for the NEDC cycle and after 326400 km for the testroute, as shown in figure 20. Using solar power would rapidly decrease the break-even point of the CO₂ emissions, but would still increase the break-even distance of the total costs. The break-even point of the CO₂ emissions of the Lupo EL which is powered by solar energy, and the Lupo 3L is at 48000 km for the NEDC test and at 35200 km for the Eindhoven-Helmond testroute. The payback time before driving costs of electric on solar energy is lower than driving the 3L is 331900 km for the NEDC test and 243600 km for the Eindhoven-Helmond testroute, as is listed in table 4 and table 5.

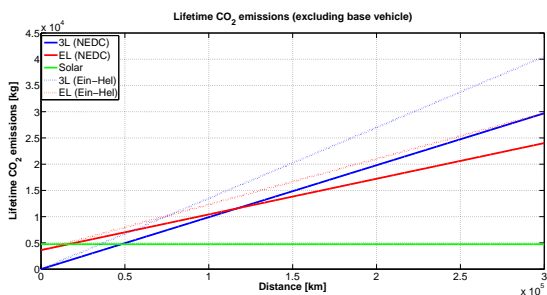


Figure 19: Life time emissions

Table 4: Break-even distance CO₂

Energy source	NEDC	Ein-Helm
Electric grid	129400 [km]	82300 [km]
Solar	48000 [km]	35200 [km]

Under normal conditions, the energy usage of the Lupo EL is 14.5 kWh/100km DC at constant

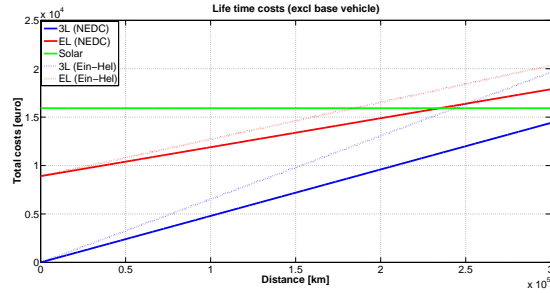


Figure 20: Life time costs

Table 5: Break-even distance costs

Energy source	NEDC	Ein-Helm
Electric grid	492300 [km]	326400 [km]
Solar	331900 [km]	243600 [km]

driving conditions of 100 km/h. This is the total energy taken from the battery, so including discharging losses and losses in the motor and inverter. The total amount of energy which can be stored within the Lupo EL battery pack is 27 kWh. Due to cycle life reasons, only 80% of this energy is used. Therefore, the maximal energy usage of the Lupo EL is 21.6 kWh. This results in a constant speed radius of 149 km at 100 km/h. For the NEDC driving cycle the driving range would be 199 km and the Eindhoven-Helmond testroute gives a range of 156 km [1] with an assumed overall charger and battery charging efficiency of 85%.

4.2 Lupo EL vs other electric vehicles

Comparing the Lupo EL with other electric vehicles, as is shown in figure 21, it can be seen that the energy usage is comparatively low. At low speeds and part load the efficiency is suffering from the usage of an induction motor, compared to the permanent magnet motors used in the other vehicles.

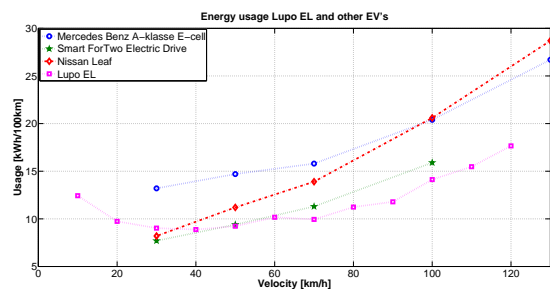


Figure 21: Lupo EL vs current electric vehicles [9]

5 Conclusions and outlook

The first iteration of the Lupo EL powertrain model gives already fairly accurate numbers of the real-life performances of the Lupo EL. The deviation between the model and DC measurement results is less than 10%.

According to the measurements results, the Lupo EL has significant lower carbon dioxide emissions than the Lupo 3L. They can be even reduced further by using energy from solar panels. The additional CO₂ emissions from the battery production can be completely compensated during the life of the vehicle, in the case of solar panels even within 35000 to 50000 km.

The energy costs of driving the electric Lupo are always lower than for the diesel car. But it is questionable if it is possible to reach the breakeven point over the life of the vehicle, when the additional costs of the batteries are taken into account. This is also the case when using solar panels.

Over the past 1.5 year the Lupo EL has driven over 6000 km without any problems or failures. It appears to be surprisingly reliable for a prototype vehicle. The practical driving range of the Lupo EL is between 150 and 200 km, depending on the driving conditions.

Although the powertrain model, which is created to estimate the energy consumption of the Lupo EL, works rather well, it has to be optimized for future research. Extra attention should be paid to the battery model and resistance in order to increase the accuracy of the dynamic response. Especially the battery behavior at the charging stage has to be investigated more in detail.

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