

Evaluating the TU/e Lupo EL BEV performance

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Abstract

The TU/e has developed a battery electric vehicle (BEV) using a VW Lupo 3L as donor platform. The differences between the initial design calculations and actual vehicle performance are analysed. Battery charging and discharging efficiency, acceleration performance and top speed are as expected. The range at low, constant speeds is less than expected, due to a higher rolling resistance and lower power train efficiency at reduced power levels. The Lupo EL can nevertheless compete with electric vehicles offered by different car manufacturers today and has an attractive set of specifications. Both energy consumption and range appear to be quite good in comparison, due to the combination of low vehicle mass, good aerodynamic properties and large battery capacity. The donor vehicle, a VW Lupo 3L diesel, can be considered as one of the most fuel efficient vehicles being mass produced and is indicative for internal combustion cars of the future. The low fuel consumption has been confirmed by tests. In a direct comparison, the electric variant still has 30 to 50% lower CO₂ emissions when using electricity from the grid in the Netherlands. These advantages disappear when including the CO₂ emissions of battery production. Depending on the electricity price and driving conditions, the energy costs per kilometre are 25% to 70% lower compared to the Lupo 3L diesel.

Keywords: BEV, energy consumption, LCA, simulation, range

1 Introduction

In 2009 the TU/e started the development of a battery electric vehicle, using a VW Lupo3 L as donor platform [1]. This vehicle is known as the TU/e Lupo EL, where EL is the abbreviation for Electric Lightweight. During spring 2011 the vehicle was finished and got a type approval allowing it to drive on the public road. Since then almost 10000 km have been travelled, various experiments have been executed and much experience was gained regarding various aspects of electric driving [2]. More recently improved instrumentation was added, allowing a precise

monitoring of various vehicle signals and of the power train in particular.

This paper will evaluate the performance of the TU/e Lupo EL in three different ways. In section two the actual vehicle performance will be compared to initial estimates and assumptions made at the start of the project. In particular battery charging, energy consumption, range and acceleration properties are considered.

In section 3 a comparison will be made with other electric vehicles on the market today and near future. It will be shown that the design choices made for the Lupo EL are still valid today and that

the vehicle can compete with the electric vehicles offered by major vehicle manufacturers.

Finally a comparison is made with the donor vehicle in section 4. The Lupo EL is based on a VW Lupo 3L diesel, which is considered to be one of the most fuel efficient production cars ever produced. Can an EV conversion built with a limited budget compete with this vehicle in terms of costs and CO₂ emissions? A back to back comparison is done to assess this.

2 Performance analysis

2.1 Electric power train

A schematic overview of the power train is shown in Figure 1, as presented in [1]. In the next sections various parts will be discussed and measurement results will be used to verify for example the 80% efficiency claims, energy consumption and range for various operating conditions. The aim of this paper is to model the power train as simple as possible, nevertheless aiming to achieve a reasonable accuracy.

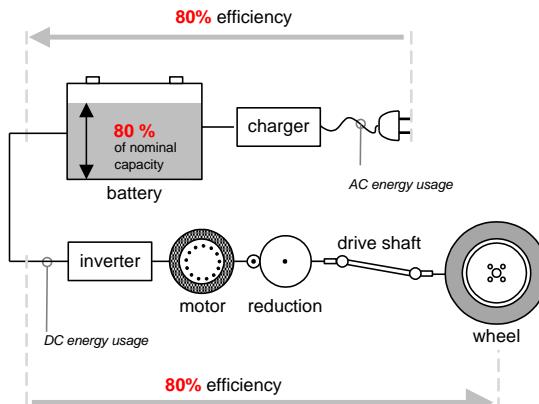


Figure 1: Electric vehicle power train [1].

2.2 Battery charging

Energy is stored in a battery, which provides DC electricity to propel the vehicle and provide energy for various 12 V systems in the car via a DC-DC converter. The battery is charged using AC electricity from the grid. In the Lupo EL the battery consist of 91 LiFePO₄ cells with a nominal capacity of 90 Ah and nominal voltage of 3.3 V, resulting in a capacity of 27 kWh and nominal voltage of 300 V. Based on the recommendations of the battery manufacturer, only 80% of this capacity will be used (21.6 kWh) to ensure sufficient cycle life [3]. According to the manufacturer 80% of the

battery capacity will still be available (17.3 kWh) after 2000 cycles. In real life the situation is even better, as normally the battery is depleted less. The cycle life increases for example to 3000 cycles when using 70% of the nominal battery capacity [3]. So far no degradation of the battery has been observed.

To determine the overall battery charging and discharging efficiency, the following procedure is followed:

- the battery is charged to 100% according to the battery management system (BMS).
- the car is being driven and the DC energy extracted from the battery E_{DC} is determined by integrating the recorded DC power P_{DC} .
- the battery is charged again to 100% and the required AC electricity E_{AC} is determined by integrating the recorded AC power P_{AC} .

The combined battery/charging efficiency η_{bc} calculated as:

$$\eta_{bc} = \frac{E_{DC}}{E_{AC}} = \frac{\int P_{DC} dt}{\int P_{AC} dt} \quad (1)$$

Some measurement results are listed in Table 1.

Table 1: Measured discharging and charging energy.

date	E_{AC} [kWh]	time [h:mm]	E_{DC} [kWh]	η_{bc} [-]
2013/05/06	27.86	7:52	22.56	0.810
2013/05/21	18.05	5:06	14.84	0.822
2013/05/22	21.39	6:11	17.46	0.816
2013/05/27	20.46	5:48	16.55	0.809
2013/05/28	16.81	4:44	13.74	0.817
2013/05/30	14.31	4:04	11.88	0.830
2013/06/05	6.87	1:58	5.13	0.746
2013/06/06	7.02	2:00	5.25	0.748
2013/06/17	22.93	6:30	18.41	0.803

Based on the results listed in Table 1, an efficiency η_{bc} of 80% may be sufficiently accurate as a first approximation, which is exactly the same as the initial assumption illustrated in Figure 1. This simple approach disregards the decrease in battery efficiency with increasing current, as reported in [2]. So aggressive driving may result in a lower efficiency. The regenerative braking power is handled with 100% efficiency when using equation (1), which is not realistic. This leads to lower values of η_{bc} for trips made on 2013/06/05 and 2013/06/06, which consist of irregular city driving. A more refined model can be developed to address these issues.

Furthermore the energy consumption of auxiliaries is taken into account while charging the battery, e.g. the water pump, fan, daytime running lights, PLC controller, dashboard. So for example charging under hot conditions will result in a slightly lower efficiency, as the cooling fan will be running more frequently.

The average AC charging power equals 3.52 kW. The average DC power from the charger equals 3.18 kW, so the charger itself has an efficiency of 90.3%.

2.3 Coast down test

To determine the efficiency of the power train, the DC energy (or power) extracted from the battery needs to be known, as well as the mechanical energy (or power) to propel the vehicle. The DC part can be measured easily, the mechanical properties of the vehicle are determined in a coast down test.

The corner mass of the Lupo EL is listed in Table 2. The total vehicle mass, including some data logging equipment and charging cables, is 1071.5 kg. The driver and ballast accounted for 150 kg. Furthermore the rotational inertia of the wheels, motor and gearbox has to be taken into account. This was calculated to be 6% of the vehicle mass.

Table 2: Measured vehicle corner mass.

	left	right
front	309.5 kg	311.5 kg
rear	228.5 kg	222.0 kg

During a coast down test the vehicle is brought up to speed and all propulsion is removed, allowing the vehicle to roll freely until standstill. The following differential equation then holds for the vehicle velocity V on a level road surface:

$$((1 + \alpha)m_{car} + m_{load})\dot{V} = -F_{rr} - F_{aero} \quad (2)$$

With F_{rr} the rolling resistance force:

$$F_{rr} = f_{rr}(m_{car} + m_{load})g \quad (3)$$

and F_{aero} the aerodynamic drag force:

$$F_{aero} = \frac{1}{2}\rho A C_d V^2 \quad (4)$$

The following parameters are used: $m_{car} = 1071.5$ kg, $m_{load} = 150$ kg, $\alpha = 0.06$, $g = 9.81$ m/s², $A = 1.97$ m², $C_d = 0.30$. In the approach presented here, the rolling resistance coefficient f_{rr} also includes friction losses in wheel bearings, brakes and other power train

components. Tyre rolling resistance is dependent on many factors like for example tyre inflation pressure, road conditions and temperature. The effect of temperature is shown in Figure 2.

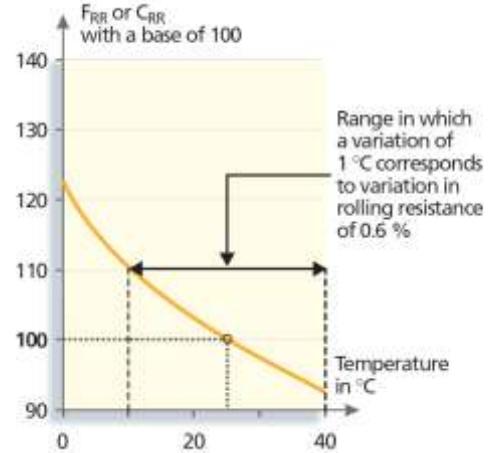


Figure 2: The effect of ambient temperature on rolling resistance for passenger car tyres, [4].

The air density ρ is also not constant and depends on the ambient temperature and pressure as illustrated by Figure 3. Humidity has a minor influence on the air density at higher temperatures. For the test conditions the air density has a value of approximately 1.16 kg/m³.

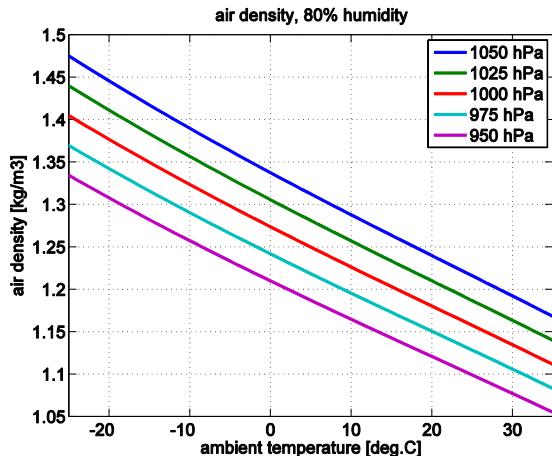


Figure 3: Air density as a function of ambient temperature and pressure.

A comparison of model results and actual coast down tests is shown in Figure 4. It can be seen that the measurement can be represented accurately by the simulation model, with the exception of very low speeds. Furthermore a large difference exist between the rolling resistance seen on the highway (smooth asphalt) $f_{rr} = 0.011$ and Rijtvenweg (coarse rural road) $f_{rr} = 0.017$. Coast down tests

executed on the Park Forum road showed a rolling resistance of 0.013. More details on the various roads are given in section 4.2.

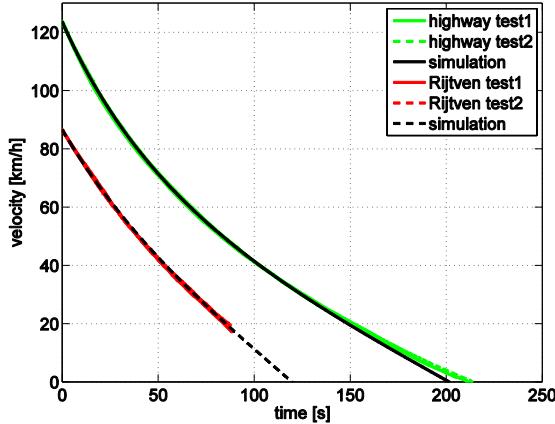


Figure 4: Coast down test and simulation.

2.4 Constant speed driving

To analyse the energy consumption and power train efficiency during constant speed driving, the power extracted from the high voltage battery is measured, P_{DC} . The mechanical power P_{mech} required to overcome rolling resistance and aerodynamic drag at a certain speed can be calculated using results from the coast down test. It is defined as:

$$P_{mech} = (F_{rr} + F_{aero})V \quad (5)$$

Next to the mechanical power needed to move the vehicle, the auxiliary power P_{aux} has to be considered. The auxiliary power is needed for controllers, dashboard, water pump, etc. and is independent from the vehicle velocity. Furthermore the power train is not 100% efficient, which is obvious as a cooling system is required, resulting in an additional power loss P_{loss} . Based on energy conservation we may write:

$$P_{DC} = P_{mech} + P_{loss} + P_{aux} \quad (6)$$

In the initial stages of the design of the Lupo EL, a constant drive train efficiency η_d was assumed, resulting in:

$$P_{DC} = \frac{P_{mech}}{\eta_d} + P_{aux} \quad (7)$$

For the drive train efficiency a value of 0.81 was used combined with an auxiliary power of 200 W [1]. Unfortunately this approach appears to be too simplistic and does not give accurate results. The following empirical model for the power train loss is proposed:

$$P_{loss} = c_1 T_m^2 + c_2 T_m \omega_m + c_3 \omega_m \quad (8)$$

In this equation T_m equals the motor torque and ω_m the angular velocity of the motor. The motor angular velocity is related to the vehicle forward velocity V , assuming a no slip condition:

$$\omega_m = \frac{V}{R_e} i_{gear} \quad (9)$$

With R_e equal to the tyre effective rolling radius (0.275 m) and i_{gear} the reduction ratio between motor and wheels (8.654). The motor torque is calculated as:

$$T_m = \frac{(F_{rr} + F_{aero})R_e}{i_{gear} \eta_{gearbox}} \quad (10)$$

The gearbox efficiency $\eta_{gearbox}$ is introduced to reflect losses in the gearbox. The car is equipped with a two stage, fixed reduction gearbox and $\eta_{gearbox}$ is assumed to be 0.95.

The constants in the empirical equation (8) have been determined by manual tuning, in order to make the calculated right hand side of expression (6) best match the measured left hand side DC power. The final values are: $c_1=0.25$ 1/Nms, $c_2=0.04$ and $c_3=2.2$ Nm. The auxiliary power P_{aux} equals 150 W. The power as a function of forward velocity is presented in Figure 5, showing that the model gives a fairly accurate representation of the measurements.

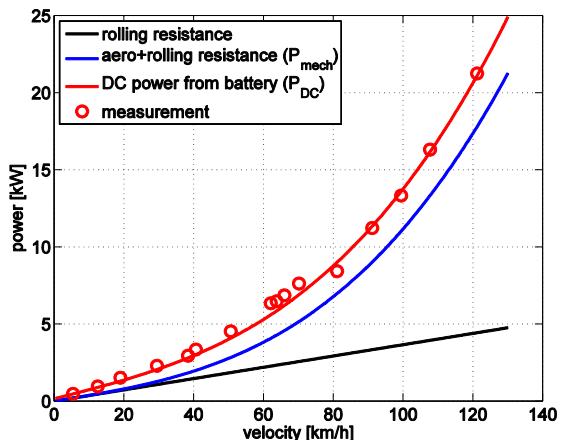


Figure 5: Constant speed power.

Using equation (7), the drive train efficiency η_d can be calculated for different forward velocities, the result is shown in Figure 6. So this picture makes clear that the efficiency ranges between 65 and 85%. In particular at lower power levels the

efficiency of the AC induction motor apparently drops and the initially assumed value of 0.81 cannot be justified.

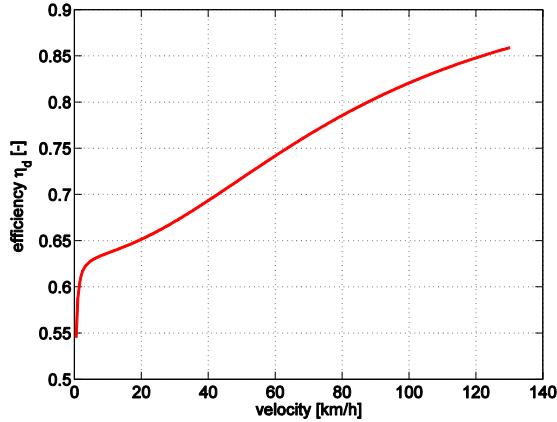


Figure 6: Constant velocity drive train efficiency.

The DC energy consumption of an electric vehicle is often expressed in the units Wh/km. As 1 Wh/km is equal to 3.6 Ws/m or 3.6 N, it actually represents a force. Using the constant velocity measurements and dividing the power by the velocity, Figure 7 can be obtained. The measurements show a discontinuity between 70 and 80 km/h. This can be explained as the tests below 70 km/h were executed at Park Forum and the tests of 80 km/h and above were executed on the highway. Based on the results of coast down tests, the Park Forum road has a higher rolling resistance (0.013) compared to the highway (0.011). Including this difference in the model, the accuracy for each velocity range improves.

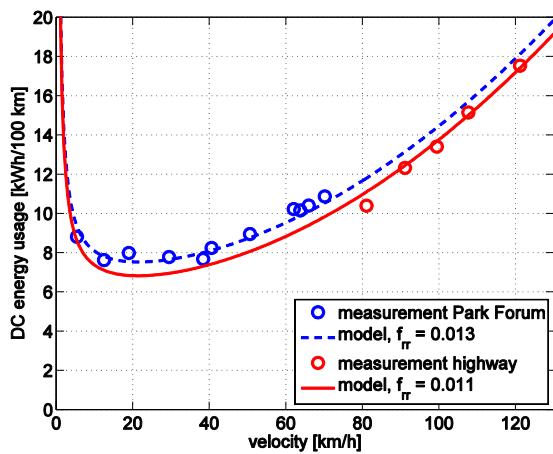


Figure 7: Constant velocity energy consumption.

Finally the constant velocity range is considered. With a usable battery capacity of 21.6 kWh and knowing the DC energy consumption, the range for different constant velocities can be

calculated. The results are shown in Figure 8. Also a comparison is made with the initial calculations presented in [1]. Two factors contribute to the major reduction in range at lower speeds: in the initial calculations a rolling resistance coefficient of 0.0085 was assumed, whereas a value of at least 0.011 appears to be more realistic. The second major contribution is a reduced efficiency of the drive train at reduced power levels as already illustrated by Figure 6. A range comparison with other electric vehicles will be made in section 3.2.

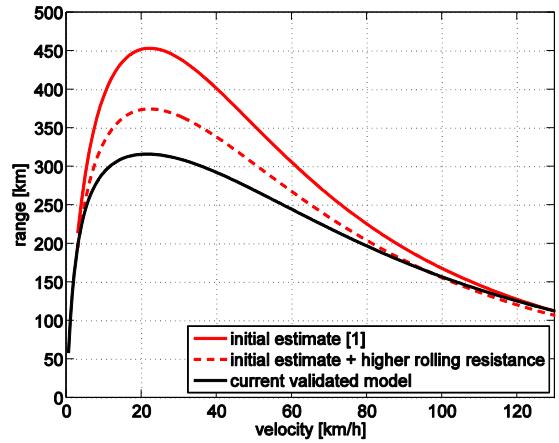


Figure 8: Constant velocity range.

2.5 Acceleration performance

The acceleration properties of the vehicle are shown in Figure 9. A velocity of 100 km/h is reached in about 13 seconds for a vehicle loaded with 150 kg. The velocity profile can fairly easily be simulated assuming a constant motor power of 50 kW, an initial acceleration capability of 4.1 m/s^2 and other parameters presented in this paper. Tyre grip limits the acceleration during the first three seconds.

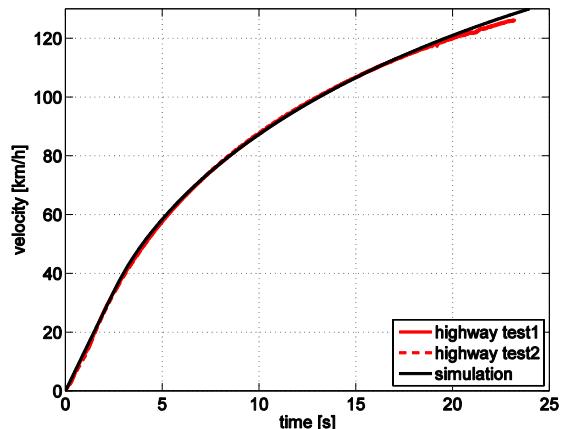


Figure 9: Lupo EL acceleration performance.

3 Comparison with other electric vehicles

3.1 Vehicle mass and battery capacity

One of the design goals of the Lupo EL was to build a vehicle with a low mass and large battery capacity in order to maximise the range. A comparison is made with other electric vehicles to see to which extent this goal has been achieved. An overview of different electric vehicles is given in Table 3. The overall vehicle length is specified in order to get an impression of the vehicle size. In the next column the vehicle mass is specified, data is obtained from reference [5] and manufacturer specifications. For the i-Miev, Lupo EL, Leaf and Model S the mass was determined in our Automotive lab.

The manufacturer specifies a nominal battery capacity, but this figure does not necessarily reflect the usable battery capacity of the vehicle. Furthermore, as already explained in section 2.2 charging losses have to be taken into account. So three values are specified in Table 3: the nominal battery capacity C_{batt} , the usable battery capacity $C_{batt,u}$ and the energy E_{charge} (AC electricity) required to recharge a fully depleted battery. For many vehicles the data is taken from reference [5] while charging at 20 °C ambient temperature, as this reflects the conditions for indoor charging of the Lupo EL best. From Table 3 it can be observed that for many vehicles the nominal battery capacity specified only loosely reflects the usable battery capacity. Combined with the specific DC energy consumption [Wh/km], the usable battery capacity will determine the vehicle range.

Charging and battery losses are reflected by the ratio between $C_{batt,u}$ and E_{charge} . For the Mercedes A class E-cell and Smart ED the charging efficiency is clearly below 80%, 76% and 77% respectively. In order to have a fair comparison between different electric vehicles, the charging losses should be taken into account. This is even more true when comparing different types of vehicle propulsion, e.g. diesel versus electric as will be discussed in section 4. It is noted that the difference between AC and DC energy consumption is quite often not clearly made and this distorts the discussion on energy consumption and costs per kilometre. Typically the AC energy consumption (and costs) will be 25% higher than the DC energy consumption.

Table 3: Electric vehicle characteristics.

	length [m]	mass [kg]	C_{batt} [kWh]	$C_{batt,u}$ [kWh]	E_{charge} [kWh]
Smart ED	2.695	1010	17.6	17.8	23.0
i-Miev	3.475	1132	16.0	14.8	18.3
Lupo EL	3.529	1071	27.0	21.6	27.0
E-up!	3.540	1185	18.7	?	?
A E-cell	3.883	1635	36.0	34.7	45.7
BMW i3	3.999	1195	22.0	?	?
Zoe	4.084	1468	22.0	?	?
Leaf	4.445	1540	24.0	19.4	24.2
Model S	4.970	2159	85.0	?	100.4

When reviewing Table 3 it is clear that the Lupo EL has competitive specifications: a large usable battery capacity, given the vehicle size, combined with a low vehicle mass and efficient charging.

3.2 Constant velocity driving

Typically a driving cycle, like the NEDC, is used to assess vehicle energy consumption, but we prefer to compare the specific energy consumption at constant velocities. There are several reasons for this: many of the available driving cycles don't faithfully represent daily driving conditions and have a too low average velocity, acceleration and/or deceleration. Furthermore for a battery electric vehicle the range becomes really important for highway driving, when the battery is depleted comparatively fast. Highway driving is mostly done at fairly constant speeds. Finally constant velocity driving is a simple and easy to execute experiment.

Figure 10 shows a comparison of the DC energy consumption of a number of electric vehicles. The Lupo EL data originates from measurements on the public road, for the other vehicles measurement data from reference [5] is used. From Figure 10 it is clear that the DC energy consumption of the Lupo EL at low velocities is fairly similar to other small electric vehicles. For higher velocities the results are even better, most likely due to a lower aerodynamic drag. In particular the Smart is known not to have good aerodynamic properties. Its drag coefficient C_d equals 0.35 and the frontal area A is 2.06 m². Combining these DC energy consumption figures with the usable battery capacity, gives the constant speed range, as shown in Figure 11. It can be observed that the Lupo EL has pretty good range, due to the comparatively large usable battery capacity, low vehicle mass and good aerodynamic properties. The maximum distance driven on a single charge so far equals 229 km, with an average velocity of 69 km/h. In that case 83.6% (22.56 kWh) of the nominal

battery capacity was used, which is a little over the recommended 80% (21.6 kWh) as explained in section 2.2.

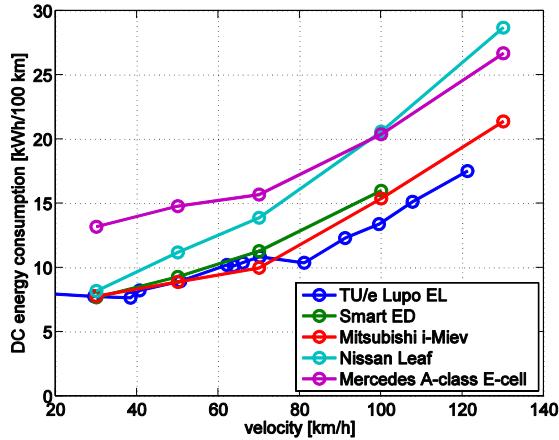


Figure 10: Constant velocity DC energy consumption.

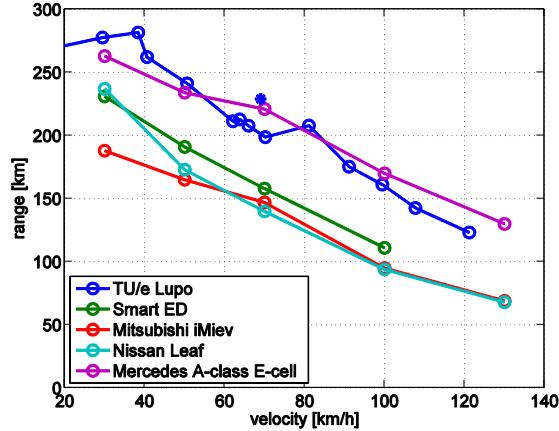


Figure 11: Constant velocity range.

3.3 Charging time

The charging times on a single phase 230 V 16 A connection for a fully depleted battery are listed in table 4, again using measurement data from reference [5]. As can be seen from this table, only the Nissan Leaf and Lupo EL use the maximum power available, reducing the charging times by 20% compared to the other vehicles.

Table 4: Electric vehicle charging.

	E_{charge} [kWh]	P_{charge} [kW]	time [h:mm]	fast charging
Smart ED	23.0	2.9	7:52	no
i-Miev	18.3	3.0	6:10	Chademo
Lupo EL	27.0	3.5	7:40	no
A E-cell	45.7	3.0	15:06	no
Leaf	24.2	3.6	6:38	Chademo

Furthermore it can be noted that the Japanese electric cars (Mitsubishi i-Miev and Nissan Leaf)

offer Chademo DC fast charging with a power of 50 kW, which greatly reduces charging times. Other recent developments, particularly in Europe, focus on three phase charging with high power. An example is the Renault Zoe, which is equipped with a 43 kW three phase charger. Starting in 2013 the Nissan Leaf can also be ordered with a 7.2 kW single phase charger. At the time the Lupo EL was conceived in 2009 these components were not yet available on the market. A 3.6 kW Brusa charger was selected back then, but today also a 22 kW three phase version exists.

Although there are quite some developments ongoing to reduce charging times, it is believed that the majority of vehicle charging will be “slow”. There is still no definite answer on the impact of fast charging on the life of the batteries and also charging efficiency has not been addressed enough. As long as slow charging can be executed within 8 hours, it may not interfere too much with human activities like sleeping and working. Fast charging is considered to be the “range extender” for the relatively few times that a long journey has to be made. In order not to affect the overall travelling time too much, a charging time of less than 20 minutes would probably be acceptable for these conditions.

3.4 Some final notes

As can be seen from the results presented here, it appears that the Lupo EL has favourable characteristics in comparison to other electric vehicles on the market today. It should however not be forgotten that it is a one-off prototype vehicle, built with a limited budget. The Lupo EL is not equipped with power steering, electric windows or air conditioning, things customers have become to expect from a modern car. Also the interior heating during winter time can be at best called marginal.

Nevertheless the vehicle clearly demonstrates that an interesting set of performance characteristics can already be achieved today by combining “medium tech” lithium iron phosphate (LiFePO₄, 100 Wh/kg) batteries with a lightweight, “high-tech” chassis. Perhaps even more than for a conventional internal combustion car, it pays off to reduce the weight of the chassis to compensate for the limited energy density of batteries. Similar reasoning has been applied to the BMW i3, which employs a carbon fibre body shell on an aluminium subframe carrying the power train.

4 Diesel versus electric

4.1 Introduction

The donor vehicle of the Lupo EL is the VW Lupo 3L diesel, which was built between 1998 and 2005. It is a remarkable vehicle with respect to fuel consumption. Volkswagen has gone great lengths to optimize the vehicle and achieve a fuel consumption of 3.0 L/100 km on the NEDC cycle; in real life an average fuel consumption of 3.7 L on 100 km can be achieved [6].

As shown in the previous section, the Lupo EL can be considered a representative and efficient electric vehicle. An obvious question is what is achieved by exchanging the power train: what will be the impact on for example CO₂ emissions and costs? Several trips have been made with both vehicles at the same time to compare the energy consumption, as illustrated by Figure 12. A brief overview of the some vehicle characteristics is given in Table 5.



Figure 12: Lupo EL and 3L used in comparative tests.

Table 5: Vehicle characteristics

	Lupo 3L diesel	Lupo EL battery electric	
mass	847	1071	kg
top speed	165	130	km/h
0-100 km/h	14.5	13.0	s
power	45	50	kW
torque	140	180 (270)	Nm
energy storage	34 L	27 kWh	

4.2 Measurement procedure

As both vehicles are available at the same time, a route is driven with one vehicle following the other. To precisely assess the diesel fuel consumption, the diesel car has been equipped with a second fuel tank, see Figure 13. This fuel tank has a capacity of 7 litres and is equipped with quick disconnect couplers, allowing it to be removed from the vehicle and weighted before and after a trip. Furthermore electronically

operated valves have been introduced to allow on-the-fly switching between the main fuel and second tank.

The second fuel tank also serves some educational purposes, as it is indicative for the amount of energy stored in the battery pack of the Lupo EL. The battery pack has a volume of about 180 L, a mass of 273 kg and a usable capacity of 21.6 kWh. Assuming a drive train efficiency of 80%, 17.3 kWh will be available at the wheels. The mass of the second diesel fuel tank is 8.6 kg when completely filled with 7 litres of diesel and this represents a 64 kWh of energy. Assuming a not unrealistic 25% efficiency for the diesel power train, 16 kWh will be available at the wheels.



Figure 13: Second fuel tank installed in the Lupo 3L.

The electric vehicle is fully charged before the start of the trip. On returning it is fully charged again, mostly the next day. The energy consumption is calculated by integrating the AC charging power recorded on-board. Cross checks with a high precision measurement device confirmed that the numbers obtained are accurate within 0.2%.

The difference in mass of the drivers and the presence of a second fuel tank in the diesel car is compensated by ballast. The test conditions reflect a vehicle with 150 kg cargo, or 2 people of 75 kg. Both vehicle use fairly new Michelin tyres, with a mileage of less than 10000 km. The tyre pressure on both vehicles was checked consistently and equals 3.0 bar for all four tyres.

Both vehicles are equipped with a cruise control, in the Lupo EL it is a self developed system. For the Lupo 3L an aftermarket system is used, as a cruise control was never offered officially by VW. The Lupo 3L diesel is not equipped with a start-stop system as this feature is not available in combination with electric power steering.

The tests executed can be split into three parts:

- *highway driving*

A route from the TU/e campus to junction Ewijk and back was driven (highway A50). On the highway a constant speed is selected using the cruise control. The total distance equals 114 km and includes 14 km off highway driving on a 70 km/h road with a single traffic light.

- *constant velocity tests*

Low, constant speed tests were executed near Eindhoven airport at Park Forum development area. This is an almost circular track with a length of 1.8 km and little traffic.

- *city driving*

A trip is made through Eindhoven city, fairly randomly selecting streets and junctions. Instructions were given to never exceed 50 km/h. Both test drivers felt that it was representative for city driving and includes traffic lights and speed bumps.

4.3 Energy consumption and range

The tests were executed in the period between May 21 and July 16, 2013. Testing was always done under dry weather conditions, with temperatures in the range of 15 to 25°C. In Table 6 the raw measurement results are listed.

Table 6: Test results.

V_{cr} [km/h]	dist. [km]	time [s]	V_{avg} [km/h]	diesel [L]	AC el. [kWh]
highway					
120	114.0	3696	111.0	4.684	22.93
110	114.0	4017	102.2	4.213	20.46
100	114.0	4360	94.1	3.842	18.05
90	114.0	4648	88.3	3.587	16.81
80	114.0	5122	80.1	3.130	14.31
constant velocity					
65	38.6	2166	64.1	1.002	4.77
50	71.5	5085	50.6	1.666	7.82
35	61.3	5794	38.1	1.326	5.78
city driving					
-	47.7	7690	22.3	1.869	6.87
-	49.6	7975	22.4	1.882	7.02

In this table V_{cr} represents the target speed for the cruise control. On the highway runs the average speed V_{avg} is lower due to the 70 km/h connection road, changing the driving direction at the Ewijk junction and interactions with other traffic. Furthermore it can be noted that the majority of the measurements took between one and a little over two hours and covers a distance of at least 50 km. This was necessary to have a

significant consumption of diesel and to reduce the mass of the second fuel tank.

Table 7: Normalised energy consumption and range.

V_{avg} [km/h]	diesel [L/100 km]	range [km]	AC electricity [kWh/100 km]	range [km]
highway				
111.0	4.11	828	20.1	134
102.2	3.70	920	17.9	149
94.1	3.37	1009	15.7	166
88.3	3.15	1080	14.6	179
80.1	2.75	1238	12.5	207
constant speed				
64.1	2.60	1309	12.4	215
50.6	2.33	1459	10.9	243
38.1	2.16	1573	9.4	283
city driving				
22.3	3.92	867	14.4	201
22.4	3.80	895	14.2	204

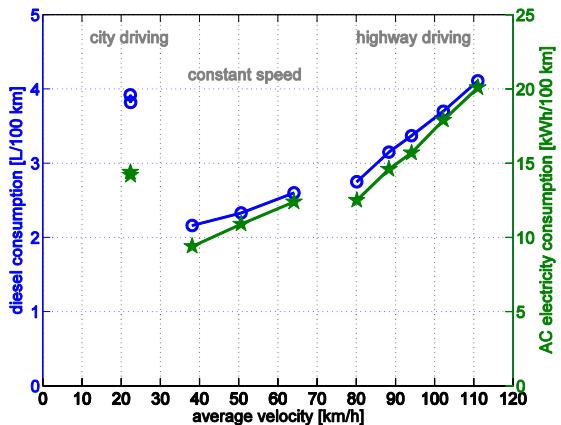


Figure 14: Energy consumption Lupo 3L (blue) and Lupo EL (green).

The normalised results are listed in Table 7 and are shown in Figure 14. The first conclusions are very obvious: the energy consumption will increase when driving faster and for city driving with many start-stop events the both vehicles are less efficient. When looking more in detail, it can be observed that the energy consumption of the electric car is slightly more progressive with velocity, but it has to be said that the behaviour for constant speed and highway driving appears to be surprisingly similar. In advance it was expected, based on VW documentation [1], [7], that the fuel consumption of the diesel car would increase for speeds below 50 km/h. For both cars there seems to be some discontinuity, between 65 and 80 km/h which must be due to the different roads being used, as already mentioned in section 2.4 and a slightly different test procedure. When taking constant speed driving as a reference, it can be observed that for city driving the electric car is clearly more efficient. The absence of engine

idling when the vehicle is standing still and regenerative braking will be the main factors contributing here.

In Table 7 also a calculated range is provided. For the Lupo 3L diesel the full capacity of the tank is used (34 L) and for the Lupo EL the DC energy consumption has been determined and is combined with the usable battery capacity. It is clear that the range of the electric car is much smaller: a factor 4.5 (city driving) to 6 (constant speed/highway driving).

During execution of the experiments it also became clear that for city driving simply no range problem exists. To deplete the battery and travel about 200 km, almost 9 hours of continuous driving is necessary, which is rather unlikely occur in practice. Perhaps the available hours of driving can also be a useful metric to make people familiar with the capabilities of the car. This is illustrated by Figure 15.

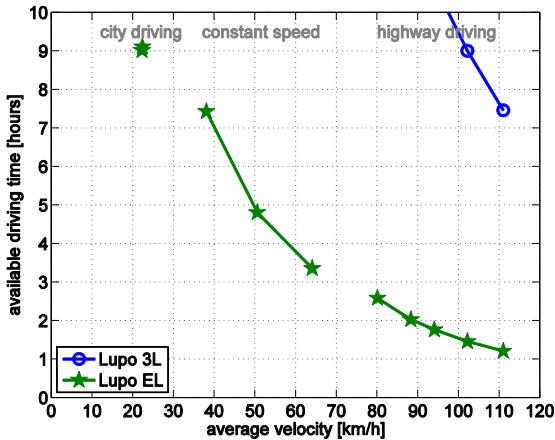


Figure 15: Available driving time.

4.4 Energy costs

A comparison of the energy costs has to start with the price per unit. An historic overview of the relevant energy prices in the Netherlands over the past five years is shown in Figure 16. Since the beginning of 2009 the price of diesel and petrol has increased by approximately 40% and seems to be levelling off. The price of electricity appears to be less volatile and does not show the upward trend since 2009. In the comparison a price of 1.40 euro/L for diesel, 0.22 euro/kWh for private users and 0.11 euro/kWh for business users will be used. When applying these factors to the results shown in Table 7 and Figure 14, Figure 17 can be obtained. It appears that electric driving is about 25% to 40% cheaper

for private drivers and 60% to 70% for business users.

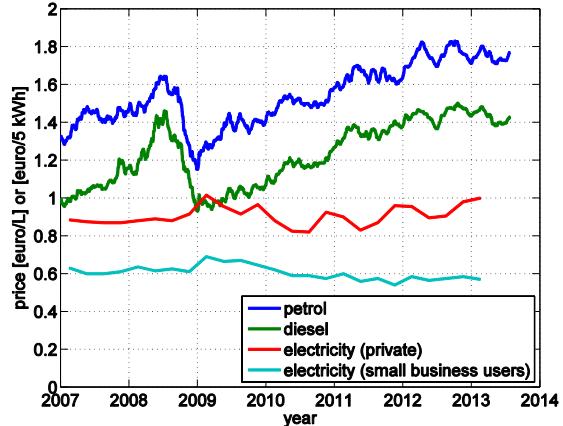


Figure 16: Historic overview of energy prices in the Netherlands, data from [8].

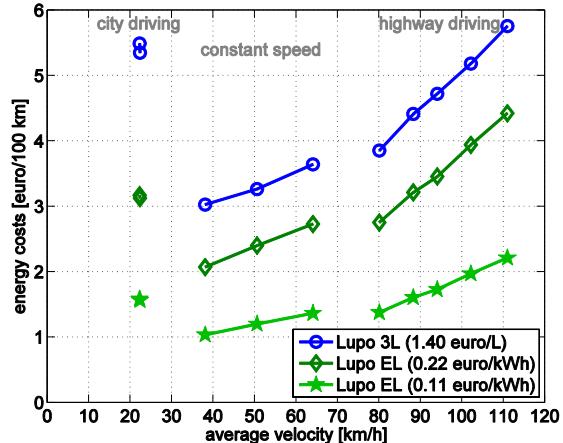


Figure 17: Energy costs per 100 kilometer.

It is well known that fossil fuels are taxed heavily by the government and that this potentially provides a cost advantage for electric driving. In the Netherlands in 1996 an additional energy tax was introduced, which is more than 0.11 euro/kWh for private users. Consider a household that increases their electricity usage by switching to an electric car. In that case 0.15 euro/kWh of the price of 0.22 euro/kWh is actually tax, so almost 70% [10]. In the case of diesel 0.68 euro/L of the 1.40 euro/L is tax, almost 50% [9]. When taking the average of the city and highway driving tests, a fairly representative consumption of 3.5 L/100 km and 15.5 kWh/100 km are obtained. So per 100 km the diesel car is then taxed with 2.38 euro and for the electric car this number equals 2.33 euro. So in this scenario the tax revenues are almost equal. Following the same approach, for business users driving an electric car the tax revenues will definitely be reduced compared to diesel driving.

Obviously many other aspects could be considered in the cost comparison, like purchase price, depreciation and maintenance. Since the Lupo EL is a one-off prototype vehicle, it is very difficult to make statements in this respect. The hardware costs of the Lupo conversion are about 35000 euro, which is unlikely to be regained as a result of lower energy costs per kilometre. Furthermore government incentives exist to promote electric driving, which will also affect the outcome.

4.5 CO₂ emissions

Considering the contribution of road transport to global warming, a major reduction of CO₂ emission is aimed for. First the CO₂ emissions associated with driving will be analysed, thereafter production will be considered too.

Using various sources from the internet and documentation of events like the “Challenge Bibendum” and “Future Car challenge”, it appears that the well-to-wheel emissions for diesel are 3.1 kg CO₂/L and 2.7 kg CO₂/L for petrol. The emissions of electricity generation in the Netherlands are 460 g CO₂/kWh, which has been agreed upon by a number of major agencies in the Netherlands [11]. In case of photovoltaic (PV) panels the emissions are 46 g CO₂/kWh and wind energy 12 g CO₂/kWh [12]. In the calculations a value of 50 g CO₂/kWh will be used. Applying these factors to the measurements Figure 18 can be obtained. This figure shows that CO₂ emissions, associated with driving the vehicle, can be reduced by approximately 30 to 50% with the existing grid in the Netherlands. The direct emissions can be reduced below 10 g CO₂/km for all driving conditions considered using solar and/or wind energy.

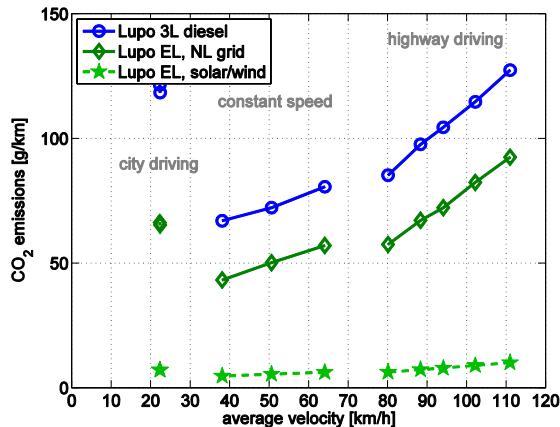


Figure 18: Direct CO₂ emissions.

So the direct emissions can be reduced greatly, but for a more complete picture a life cycle analysis (LCA) should be performed. A detailed study was performed by Renault to analyse the CO₂ of the Fluence petrol, diesel and Z.E. [13]. Smart also has provided similar numbers [14]. Table 7 gives an overview of the numbers.

Table 7: CO₂ emissions vehicle production and disposal.

emissions [kg CO ₂]	prod.	disp.	sum	increase
Fluence 1.5 dci (diesel)	5034	389	5423	
Fluence 1.6 (petrol)	5338	431	5769	
Fluence Z.E. (BEV)	8031	568	8599	±3000
Smart MHD (petrol)	3500	375	3875	
Smart ED (BEV)	7400	375	7775	±3900

Analysing the Renault study more in detail, it becomes clear that the production of the battery is the main contributor to the increased CO₂ emissions for the electric vehicle. Several studies can be found on the CO₂ emissions of battery production, with highly different figures. The report issued by the Environmental Protection Agency (EPA) in 2013 will be used here [15]. For a lithium iron phosphate (LiFePO₄) battery the production and disposal emissions are calculated to be 151 kg CO₂/kWh. So for the electric Lupo battery (27 kWh) 4077 kg CO₂ will be released.

To get an impression on the emissions, based on the previous information an educated guess is made that producing a Lupo 3L emits 4500 kg CO₂. If we assume a life of 150000 km, then the emissions for production and disposal will already be 30 g CO₂/km for the Lupo 3L and 58 g CO₂/km for the Lupo EL. Combined with the direct CO₂ emissions, Figure 19 is obtained. This figure clearly illustrates that no significant advantage is obtained when using the electricity from the dutch grid.

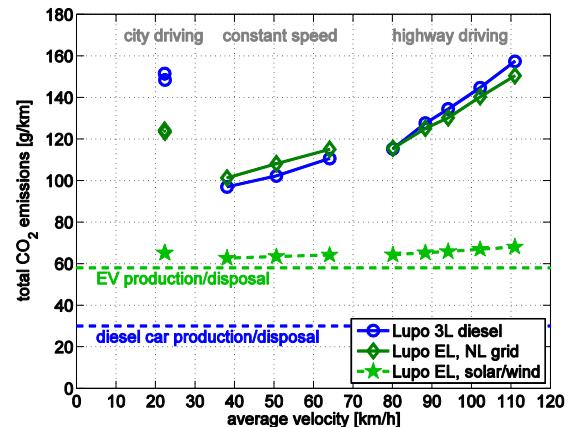


Figure 19: Total CO₂ emissions.

We may be able to more than halve the CO₂ emissions of the Lupo 3L diesel when using electricity generated by solar and/or wind power exclusively. For these conditions the incentive to drive slowly for environmental reasons will also disappear, though increased energy costs and safety considerations may still limit this. To further reduce emissions, the emphasis has to shift to the vehicle production phase and to extending the life of the vehicle.

It is well known that in wintertime the range of an electric vehicle decreases and that the energy consumption increases. In [16] it is shown for a specific electric vehicle that the energy consumption is 40% higher at an ambient temperature of -5°C compared to 15°C. Due to its low efficiency, an internal combustion car has sufficient excess heat to keep the interior at a comfortable temperature. On the other hand it should be noted that most trips made are relatively short and that the engine of a modern diesel car may require at least 15 km to get up to temperature. Research done in Belgium with different versions of the Toyota Auris indicates that for irregular city driving with a cold engine the fuel consumption and CO₂ emissions of the petrol car may rise by 50%, for the diesel car by 93% and for the hybrid even by 146%, compared to a warm engine [17]. So, depending on the driving conditions, an internal combustion car may also have increased energy consumption and CO₂ emissions in cold weather conditions.

5 Conclusions

With limited resources an interesting battery electric vehicle has been built using a VW Lupo 3L as donor platform. Despite the fact that the initial calculations were somewhat too optimistic, the actual vehicle range and energy consumption are quite competitive in comparison to many battery electric vehicles on the market today. Both electricity generation and vehicle/battery production need to be addressed to achieve a major impact on reducing the CO₂ emissions.

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