Design of an efficient, low weight battery electric vehicle based on a VW Lupo 3L

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Abstract—A battery electric vehicle is being developed at the Eindhoven University of Technology, which will be used in future research projects regarding electric mobility. Energy storage in batteries is still at least 25 times heavier and has 10 times the volume in comparison to fossil fuel. This leads to an increase of the vehicle weight, especially when trying to maximise the range. A set of specifications is derived, taking into consideration the mobility requirements of people living in the Netherlands and the capabilities of electric vehicles. The VW Lupo 3L 1.2 TDI has been selected as the vehicle to be converted into a battery electric vehicle, since it has many favourable characteristics such as a very low mass and good aerodynamics. The design choices considering the power train and component selection are discussed in detail. Finally the battery electric Lupo is compared to the original Lupo 3L considering energy usage, costs per km and CO₂ emissions. With respect to these aspects the advantages of electric propulsion are relatively small, as the donor vehicle is already very fuel efficient. Copyright Form of EVS25.

Keywords—battery electric vehicle, power train, vehicle performance

1. Introduction

Battery electric passenger cars have a very long history, but they have failed to gain any significant market share, a short period at the beginning of the 20th century aside. At the beginning of the 1970’s with the oil crisis and increasing worries about air pollution the electric car gained interest again. At the Eindhoven University of Technology a project was executed in which a VW Golf was converted to a battery electric vehicle, figure 1 gives an impression. Though interesting research was done with this vehicle, in particular regarding the possible efficiency increase using various gearbox configurations, it was also clear that the converted vehicle was no match for the internal combustion engine (ICE) cars of those days [1].

![Figure 1: The TU/e battery electric VW Golf 1 as developed in the years 1980 to 1983.](image)

Actually it turns out that throughout the 20th century that the electric car always has kept the promise of being the “car of tomorrow” but failed to deliver for various (not only technical) reasons, as described by Mom [2]. With the advent of mobile phones, laptop computers and cordless power tools in the 1990’s battery technology developed rapidly. These new technologies also found their way into road vehicles, with the Tesla Roadster probably being the most exciting example.

In 2005 the Eindhoven University got involved in the “car of the future” project, as initiated by the Netherlands Society for Nature and Environment. The aim of this project is to develop and demonstrate environmentally friendly alternatives for personal transport. On the Dutch national car exhibition (AutoRAI) in 2007 the vehicle, known as the c,mm,n 1.0, was presented [3]. Mock-ups of the exterior, interior and hydrogen powered power train were on display, as created by the students of the three technical universities of the Netherlands. Inspired by the work of for example Ulf Bossel [4], a critical review of the well-to-wheel efficiency of a hydrogen powered vehicle was made and it is concluded that a battery electric vehicle is the most efficient way to get energy from renewable sources to the wheels.

At the AutoRAI 2009 the electric c,mm,n 2.0 was presented and an action plan was offered to the Dutch government to speed up the introduction of the electric vehicles in the Netherlands [5]. The next step in the development of the c,mm,n is to create a running prototype. As building an entirely new vehicle from scratch will prove to be quite difficult and costly, the choice was made start with converting an existing vehicle.

This paper is organised as follows. In section 2 a comparison is made between carrying the propulsion energy in batteries and fossil fuel. Existing battery electric vehicles are analysed and some rules of thumb are developed. In section 3 the design objectives are discussed. The aim is to develop a car with four seats, which could be attractive to a large audience and to minimise the impact of the inherent limitations of a battery electric vehicle.

Section 4 discusses the selection of the donor vehicle and the various power train components. The various design choices are substantiated. Emphasis is put on achieving a low curb weight, energy efficiency, practical usability and good performance characteristics. In section 5 calculations are made to compare some characteristics of the battery electric vehicle with those of the donor ICE vehicle. In particular energy usage, CO₂ emissions and costs per km are analysed. Some concluding remarks are given in section 6.
2. BEV characteristics

In a battery electric vehicle (BEV) all energy to propel the vehicle is carried in batteries, which has major consequences for the vehicle design and performance. Table 1 gives an impression of the different possibilities for energy storage and it is clear that the energy density of fossil fuels is orders of magnitude greater than that of the battery technologies available today. For the batteries a utilization factor has to be taken into account, as it is good practice to limit the depth of discharge to 80% of the nominal battery capacity in order to achieve an acceptable life. The efficiency of the all electric drive train is much better than that of a petrol or diesel internal combustion engine (ICE), about a factor of four. Nevertheless the overall picture is that carrying energy in the form of batteries is 25 to over 100 times heavier than petrol, with respect to the volume factors ranging from 10 to 40 apply.

An overview of different battery electric vehicles has been created using data from a multitude of sources on the internet. When comparing the BEV to the ICE equivalent, carrying the energy in batteries results in a heavier vehicle as is clearly shown in figure 2. For the battery electric vehicles at least 15% up to over 35% of the vehicle mass consists of batteries. Certainly for the higher percentages the sheer volume and vehicle load carrying capacity may become somewhat problematic. Typically between 15% to 25% battery to vehicle mass it appears to be feasible to construct a family car with four seats and sufficient luggage space. Figure 2 also makes clear that vehicle weight without the batteries is very similar to that of the ICE equivalent. An electric motor can be much lighter than the equivalent ICE with a similar power rating, as will be discussed. But apparently this weight advantage is lost in other systems of the electric power train and/or chassis reinforcements to carry the batteries.

Despite the significant mass and volume of the batteries, the amount of energy which is carried in the vehicle is still small compared to an ICE vehicle resulting in a limited range. The results presented in table 1 can be used to develop some rule of thumb: in order to get the same energy at the wheels the required energy from the battery in kWh is about twice the required amount of petrol expressed in litres. This can be used in an empirical formula to calculate the equivalent petrol tank volume for a given battery capacity:

\[ V_{eq, \text{petrol}} [L] = \frac{0.8 \cdot C_{\text{batt}} [kWh]}{2} \]  

(1)

So if a nominal battery capacity \(C_{\text{batt}}\) of 16 kWh is specified, the equivalent petrol tank volume is 6.4 litres. In case of 24 kWh the equivalent volume is 9.6 litres. This rule of thumb can be useful when making a first estimate on the achievable range of a battery electric vehicle.

Equation (1) can also be used to get an impression of the charging speed. In the Netherlands a maximum current of 16A at 230 V can be drawn from a regular power socket, provided it is the only load in the group. This translates into an energy flow of 3.68 kWh per hour. The charging process is not 100% efficient; an estimated 20% of the energy is lost in the form of heat or can’t be extracted from the battery again at a later stage. The factor 0.8 now accounting for efficiency losses, (1) now gives an equivalent flow of 1.5 litres of petrol per hour. At a regular fuel station the petrol flow is around 40 litres per minute. So for a petrol car the energy transfer is 1600 times faster compared to charging a BEV on a regular European power socket. Even when considering state-of-the-art level 3 DC fast charging (50 kW), it is still a factor 120 slower.

<table>
<thead>
<tr>
<th>energy carrier and powertrain characteristics</th>
<th>kWh/kg</th>
<th>kWh/L</th>
<th>efficiency</th>
<th>utilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>petrol</td>
<td>12.10</td>
<td>9.12</td>
<td>18%</td>
<td>100%</td>
</tr>
<tr>
<td>diesel</td>
<td>11.80</td>
<td>9.97</td>
<td>22%</td>
<td>100%</td>
</tr>
<tr>
<td>battery (lead-acid)</td>
<td>0.030</td>
<td>0.06</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>battery (NiMH)</td>
<td>0.060</td>
<td>0.15</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>battery (LiFePO4)</td>
<td>0.100</td>
<td>0.15</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>battery (LiPo/LiCo)</td>
<td>0.135</td>
<td>0.25</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>

Table 1: Comparison of different energy carriers.

<table>
<thead>
<tr>
<th>10 kWh at the wheels</th>
<th>energy</th>
<th>mass</th>
<th>volume</th>
<th>relative to petrol</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWh</td>
<td>kg</td>
<td>L</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>petrol</td>
<td>55.6</td>
<td>4.6</td>
<td>6.1</td>
<td>1.00</td>
</tr>
<tr>
<td>diesel</td>
<td>45.5</td>
<td>3.9</td>
<td>4.6</td>
<td>0.84</td>
</tr>
<tr>
<td>battery (lead-acid)</td>
<td>12.5</td>
<td>252.0</td>
<td>260.4</td>
<td>113</td>
</tr>
<tr>
<td>battery (NiMH)</td>
<td>12.5</td>
<td>260.4</td>
<td>104.2</td>
<td>57</td>
</tr>
<tr>
<td>battery (LiFePO4)</td>
<td>12.5</td>
<td>156.3</td>
<td>104.2</td>
<td>34</td>
</tr>
<tr>
<td>battery (LiPo/LiCo)</td>
<td>12.5</td>
<td>115.7</td>
<td>62.5</td>
<td>25</td>
</tr>
</tbody>
</table>

Figure 2: Weight comparison of a number of BEV and equivalent ICE cars.
It can be noted that the factor 0.8 occurs a number of times in the calculations: battery charging is 80% efficient, 80% of the nominal battery capacity is utilised and the electric power train has an efficiency of 80%, as is illustrated by Figure 3. Overall these numbers would indicate that the socket-to-wheel efficiency is 64%. For the Mitsubishi i-Miev 82.8% efficiency is claimed for the charging and battery efficiency and 80.2% for the power train; overall an efficiency of 66.5% socket-to-wheel is achieved [6]. Though the 80% rule of thumb may involve some conservatism, it prevents us from making overly optimistic assumptions with respect to range and energy usage.

![Figure 3: The 80% rule of thumb for the BEV power train efficiency and battery utilisation.](image)

As the numbers for battery utilisation and charging efficiency are about the same, it may appear to the casual user that the charging process is actually very efficient: 16 kWh AC electricity would be needed to charge a battery with a nominal capacity of 16 kWh, but actually only 12.8 kWh is added to the battery and 10.2 kWh will be available at the wheels. Another point of attention is that the energy consumption of a BEV is expressed in Wh/km or kWh/100 km. During driving typically the DC energy extracted from the battery is measured. But this figure does not reflect the true energy usage of the vehicle: due to charging losses the actual AC energy usage is 25% (1/0.8) higher. Finally when the battery capacity is specified generally the nominal value is meant, but it could also be the usable capacity. The specifications of the Mini E are very clear in this respect: nominal battery capacity equals 35 kWh of which 28 kWh can be used.

Summarising, the battery electric vehicle today:

- is about three times as efficient when considering the energy usage from the power socket/fuel station to the wheels. (BEV efficiency 64% versus 18% for ICE petrol or 22% for ICE diesel).
- will be heavier than a comparable ICE vehicle, the weight increase may be several hundred kilograms.
- will have a comparatively small range, in real-life typically 100 to 200 km can be achieved with li-ion batteries.
- can only be recharged slowly in comparison to refueling an ICE car.

Though the last three items may appear disappointing at first, it should be noted that over the last 20 years major progress has been made in the field of battery technology:

- the energy density has increased by a factor 3 to 4.
- the number of charge cycles has increased from 300-500 for lead acid to 2000-3000 cycles for some li-ion chemistries.
- the efficiency of a charge-discharge cycle has been increased from 70 to 75% for lead acid to over 90% for li-ion batteries [1],[6].
- some li-ion chemistries allow fast charging to 80% of the usable capacity less than 30 minutes.

These factors make that a battery electric vehicle today is a much more viable option compared to earlier attempts in the late 20th century.

### 3. Design objectives

Given the limitations of a battery electric vehicle as outlined in section 2, it is not reasonable to expect that it can replace the ICE vehicle for all applications today. On the other hand, the niche market battery electric vehicle may get mainstream appeal given the recent improvements in battery technology.

The Netherlands seems to be well suited for all-electric vehicle usage:

- it is a compact country (dimensions 195 km x 310 km), densely populated with 16.5 million inhabitants, 490 people/km². The biggest cities have less than 1 million inhabitants; they are located relatively close together and are connected by highways.
- it is a very flat country, mostly at sea level. The highest "mountain" is 322 m; the second one makes it to 110 meters.
- it has a moderate maritime climate, the average temperature during the winter is 0 °C and during the summer 20 °C.
- it has no culture of fast driving: the maximum legal speed on the highways is 120 km/h and there are many roads with speed restrictions of 80 or 100 km/h.
- the average annual mileage driven by petrol cars is slightly over 11000 km and this figure has been almost constant over the past decade. This translates into an average of just over 30 km per day. Diesel cars drive on average 25000 km annually, almost 70 km per day [7].
- air pollution and noise is a problem in some areas
- the electric infrastructure is reliable

Inhabitants of the Netherlands travel 33 km per day on average and about 75% of this distance is covered by car. When considering the trips made by car a distribution can be made, see figure 4. About 92% of all trips are below 50 km and quite a number of trips have a length not exceeding 5 km. Though these numbers are helpful in showing that the distances travelled are generally small, they cannot provide a definite answer with respect to the required range. Experiences with the Mini-E seem to indicate that the lack of boot space was more of a problem than a lack of range, which is approximately 150 km for
this particular vehicle [8]. Having the possibility of fast charging also relaxes the requirements on the available range of the electric vehicle (and thus the battery size/weight). Reference [9] shows that fast charging is quite effective in preventing “range anxiety” and results in a better usage of the available battery capacity.

Fast charging during the daytime the driver should be bothered as little as possible. Fast charging during the day is considered as a form of range extending for the limited electricity available. So a depleted battery should be fully charged again within approximately 8 hours. During daytime the driver should be bothered as little as possible by the charging process. Fast charging during the day is considered as a form of range extending for the limited number of cases when very long trips have to be made. Fast charging requires significant amounts of electric power, if introduced on a large scale it would result in a major additional load to the electricity network and require huge investments. The effect on the life of the batteries and efficiency of the fast charging process are other concerns, though clear numbers to quantify these effects are missing.

Vehicle size is another consideration. It is expected that in the future the price of electricity (and energy in general) will only go up, increasing the market for more fuel efficient, smaller cars. This can already be noticed in sales figures of ICE cars. In the Netherlands the most sold new car is the Toyota Aygo (and equivalent Citroen C1, Peugeot 107 cars), which has a length of 3.5 meters and weight of 765 kg. With decreasing the vehicle size a smaller and thus cheaper battery pack can be employed to achieve the same range compared to a larger vehicle. In the Netherlands the average vehicle occupation is approximately 1.3 persons, nevertheless the vehicle should have four seats, being able to transport for example parents with their children.

With respect to the vehicle performance the minimum requirement is that the vehicle can be used in a safe way on all roads in the Netherlands, so a top speed of at least 120 km/h and acceptable acceleration properties are required. Smaller cars typically manage to get to 100 km/h in less than 15 seconds.

The required range is a very difficult question to answer. As outlined at the beginning of this section the average numbers indicate that a vehicle actually does not travel that many kilometres during a day on average. On the other hand the driver will request flexibility and does not want to be limited by the vehicle in the choice of the destination. The choice is made to just go for the maximum range which can reasonably be achieved today, which is about 200 km. This will result in a relatively large battery pack considering the vehicle mass and dimensions, but this reduces the peak load on the pack and temperature increase. Also the depth of discharge will generally be smaller thus extending battery life. Furthermore it may offer some reserve capacity to compensate for battery degradation over the years.

Finally an aggressive weight target of 1000 kg was set. As shown in figure 2, the Mitsubishi i-Miev has a weight of 1080 kg and for the Peugeot 106 Electrique it equals 1060 kg. The range of these two vehicles is however not close to the specified 200 km and the Peugeot is severely limited in performance with a top speed of 93 km/h. The Think City A306 weighs 1038 kg, but it is not a true four seater and the performance is somewhat limited.

Within this project we aim at a broad range of potential customers, thus trying to avoid the extremes as described above.

As discussed in section 2, charging a battery electric vehicle is a rather slow process which can best be done overnight while the driver is sleeping and a surplus of electricity is available. So a depleted battery should be fully charged again within approximately 8 hours. During daytime the driver should be bothered as little as possible by the charging process. Fast charging during the day is considered as a form of range extending for the limited number of cases when very long trips have to be made. Fast charging requires significant amounts of electric power, if introduced on a large scale it would result in a major additional load to the electricity network and require huge investments. The effect on the life of the batteries and efficiency of the fast charging process are other concerns, though clear numbers to quantify these effects are missing.

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Summarising the objectives:
- small family car with four seats
- top speed above 120 km/h, acceleration time 0-100 km/h below 15 sec.
- range of 200 km
- charging time of 8 hours or less on a normal power socket (230 V/16 A)
- curb weight below 1000 kg

Figure 4: distribution of car trip length in the Netherlands [7].
4. Component selection

As mentioned in the introduction, the choice was made to convert an existing vehicle to all-electric to get more familiar with battery electric vehicles. This approach (“learning by doing”) appears to be very effective and stimulating for the students and employees working on the project. The available hardware budget is approximately 30,000 euro.

Vehicle selection

Considering the design objectives, it is clear that a small four seat passenger car will be the starting point. After considering various alternatives, the VW Lupo 1.2 TDI 3L was selected as the vehicle to be converted. The Lupo 3L is a remarkable vehicle: according to the manufacturer it can achieve an average fuel consumption of 3.0 litres of diesel per 100 km and it has a CO₂ emission of 81 g/km in the NEDC drive cycle. Although it was produced between 1999 and 2005, it can still be considered to be a very good benchmark for the fuel efficient ICE cars of the future.

To achieve this very low fuel consumption the Lupo 3L differs in many ways from the standard Lupo. Apart from improving the power train efficiency, various other modifications were made [10],[11].

- optimised aerodynamics, the drag coefficient is reduced from 0.32 to 0.29
- equipped with specially developed tyres with a very low rolling resistance
- many parts are made out of aluminium (e.g. side doors, rear door, bonnet, front sills, frame of chairs, disk/drum brakes) or magnesium (e.g. steering wheel, rims, parts of the rear door)
- thinner glass is used for all windows
- various weight optimisations (e.g. amount of rust protection wax, PVC undercover, door rubbers, seat rails, etc.)

The curb weight equals 829 kg and the vehicle is more than 120 kg lighter compared to the Lupo 1.7 SDI and 1.4 TDI. Figure 5 gives an overview of the main dimensions of the vehicle, the overall length is just over 3.5 m.

A VW Lupo 3L, built November 2003, was bought second hand. In some ways the vehicle can be described as “spartan”, as features like power steering, air conditioning, electric windows and central locking are missing. On the other hand important safety features like dual airbags and ABS brakes are available. The VW Lupo achieved a four star safety rating in the Euro NCAP crash safety test programme.

Motor/gearbox/inverter

The power train obviously has to undergo major changes. Some time was spent on investigating the benefits of having a gearbox with multiple ratios, which potentially can increase efficiency and performance [12]. As the Lupo 3L has a complex hydraulically operated 5 speed automated manual transmission, maintaining the existing gearbox was not considered feasible. Test drives with various battery electric vehicles revealed that gear shifts would probably ruin the very smooth and seamless acceleration. In-wheel motors were also considered: measurements and simulations have been done to investigate the impact of an increased unsprung mass on the ride comfort [13].

Water cooling of the motor and inverter is strongly preferred over air cooling. This leads to more compact components, keeps dirt or moisture away from the electronics and allows a better control of the temperature. In order to maximise vehicle efficiency, the cooling water will be used to assist in warming up the interior, though the expectations on its contribution are not too high.

Combining these considerations with the required performance and available budget actually does not leave too many options open. The choice was made to use the following components:

- MESDEA 200-200W water cooled AC induction motor (24 kW nominal/50 kW peak)
- MESDEA TIM 600W water cooled inverter (80 to 400 V, 236 A nominal/400 A peak)
- Carraro fixed ratio reduction (8.654:1)

A comparison of the diesel and electric power train is shown in figure 6. The maximum traction force at the wheels is nearly always larger for the electric motor compared to the diesel engine. The maximum speed of the electric power train at 130 km/h is limited electronically in order not to exceed the maximum angular velocity of the electric motor. At low speeds the maximum torque of the electric motor has to be limited in order not to provoke wheel spin and to reduce the loads on the drive shafts and final reduction. The Lupo 3L can accelerate form 0 to 100 km/h in 14.5 sec. The battery electric vehicle will be heavier but a time of about 12 sec. has been calculated by means of computer simulations.

Figure 5: Main dimensions of the VW Lupo 3L in mm.

Figure 6: ICE and BEV power train performance comparison.
A final note can be made with respect to the required battery voltage. Tests results provided by MESDEA indicate that the motor/inverter combination is more efficient at higher supply voltages. At nominal power and 188 V/165 A power supply an efficiency of approximately 87% is achieved for angular velocities above 3000 rpm. When the test is done at 288 V/100 A the efficiency increases to 92%. It is also noticed that in recent electric vehicles typically the battery voltage is typically between 300 and 400 V.

**Batteries/Charger/BMS**

The required capacity of the batteries is determined by two demands: charging time and range. A crude first calculation of the maximum battery capacity would be: 8 hours of charging at 3.68 kW with an efficiency of 80% results in 23.5 kWh. As we intend to use 80% of the nominal capacity, the battery pack capacity should thus become 29.4 kWh.

The performance of a number of battery electric vehicles has been analysed based on available tests in literature, see Table 2. It can be noted that major differences exist between the range obtained with a mild driving cycle or real life conditions with for example low outside temperatures and electric cabin heater usage. As the Lupo curb weight will be slightly lower than the Mitsubishi i-Miev, a battery capacity of about 40 kWh would appear to be necessary to always meet the range requirement of 200 km.

### Table 2: Battery capacity and vehicle range.

<table>
<thead>
<tr>
<th>battery</th>
<th>weight</th>
<th>cycle</th>
<th>min.</th>
<th>max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitsubishi i-Miev</td>
<td>16</td>
<td>1080</td>
<td>160</td>
<td>75</td>
</tr>
<tr>
<td>Tesla Roadster</td>
<td>53</td>
<td>1235</td>
<td>390</td>
<td>200</td>
</tr>
<tr>
<td>BMW Mini-E</td>
<td>35</td>
<td>1465</td>
<td>240</td>
<td>100</td>
</tr>
</tbody>
</table>

Some other requirements on the batteries are:

- **power:** the battery pack should be able to deliver about 55 to 60 kW peak power during acceleration and 10 to 20 kW continuously while driving at constant speed on a level road.
- **voltage:** the battery pack voltage should preferably be 300V or higher.
- **mass:** in order to stay below 1000 kg curb weight for the vehicle, 171 kg may be added. Furthermore the diesel engine and gearbox are replaced by a much lighter motor and fixed reduction, resulting in an estimated weight gain of 70 kg. So the maximum weight of the complete battery pack should around 240 kg.
- **volume:** the Lupo 3L is a small car and the batteries can be placed at three locations: underneath the rear seats (replacing the fuel tank), at the location of the spare tyre in the trunk and under the bonnet. The form factor of the batteries should allow placing them conveniently at these three locations. Ground clearance is insufficient to mount the batteries under the floor of the vehicle.

After consulting several battery suppliers, the choice was made to use large prismatic Thundersky TS-LFP90AHA cells. The chemistry is lithium iron phosphate (LiFePO₄), which is considered to be a safe solution for automotive applications. Disadvantage of this chemistry is that the energy density is somewhat low at 100 Wh/kg. For the battery pack 91 cells will be put in series resulting in a pack voltage of 300 V, a capacity of 27 kWh and a weight of 273 kg. The continuous power is 81 kW (3C) which is more than sufficient, as under normal driving conditions the load will be in the range between 0.4C to 0.8C with short 2C peaks during acceleration. From these numbers it is clear that the battery pack is loaded lightly. After sharing experiences with other EV builders, it was concluded that air cooling will be sufficient as the pack is divided in three separate blocks with air moving over the bottom of the two rear packs.

Thundersky claims that the TS-LFP90AHA batteries will have 80% of the original capacity after 3000 cycles when the depth of discharge is limited to 80% of the nominal capacity. At 70% depth of discharge this even increases to 5000 cycles. Assuming that single cycle would represent 100 to 150 km of driving, the life expectancy would be in the range of 300000 to 450000 km, which is more than sufficient and not easily reached if the average 11000 km is driven annually. Over time the calendar life of the battery may prove to be the limiting factor instead of cycle life.

The Thundersky batteries can be charged with a current up to 3C, indicating that fast charging would be a possibility. Though occasional fast charging is considered crucial for the success of battery electric vehicles in general, getting an operational vehicle is given priority and fast charging is not pursued at this stage of the project. For normal charging a Brusa NLG 513 has been selected, which has a charging power of 3.3 kW and efficiency of over 90%. This device is carried on board and is water cooled. The charging plug is according to the IEC 62196-2 standard (“Mennekes plug”). An Elithion battery management system (BMS) is used to monitor the voltage, current, temperature and state of charge of individual cells. It can also perform some pack balancing by dissipating energy from the cells with the highest charge.

### CAN bus

The various components of the electric powertrain (inverter, charger, BMS) communicate with each other via a CAN bus. The Lupo 3L also employs a CAN bus on which for example dashboard indicators, gear lever, airbags and ABS signals are exchanged. Before removing the ICE power train, quite some time was spent on analysing and reverse engineering of the VW CAN bus, as the aim is to have a fully functional vehicle including e.g. all dashboard indicators. Furthermore safety systems like ABS brakes and airbags still have to operate correctly in the new configuration. Tests on a rolling road confirmed that nothing was overlooked and thereafter the physical conversion process could start.

In the final configuration three separate CAN busses are utilized in the vehicle to minimize interference and maximize redundancy of the system. A central
programmable logic controller (PLC) is connected to the three CAN bus systems in the vehicle, one CAN bus for the original Lupo components, one for the electric drive train components and one for the built in touch screen, visualizing the available data. The PLC is used as the main controller for all components, enabling a very flexible and customizable operation of the vehicle. Figure 7 gives an overview of the electrical systems layout in the vehicle.

![Figure 7: System lay-out of the electric VW Lupo.](image)

Safety

Safety is a very important in electric vehicles and has significantly different aspects compared to conventional ICE vehicles. Especially the high voltage system requires attention. To prevent electric shock the high voltage circuit is completely isolated from the chassis. A Bender Isolation monitoring device measures the isolation value between the high voltage circuit, 12V circuit and chassis continuously. If the isolation is below the safe limit, all systems are shut down and the battery packs are disconnected. All three battery packs are equipped with a separate fast acting 400A fuse and a contactor to protect the batteries and cabling against a short circuit failure, in case of an accident or component failure.

The PLC controls the inverter throttle request, based on the throttle pedal. The throttle pedal potentiometer is safeguarded by a zero position switch, overruling the potentiometer value. Whenever there is any unwanted acceleration, the brake pedal signal is connected to the PLC and inverter, overruling any traction power request on both components. All components are equipped with temperature sensors, to prevent overheating. The battery temperature is supervised by the BMS and PLC for extra protection. During charging traction power is disabled.

Improving vehicle efficiency

To reduce the energy consumption Philips EcoVision energy saving halogen light is introduced for the main lighting. On a number of non-critical places LEDs are used. Also for the main lighting some LED aftermarket solutions exist, but their performance is generally substandard and they are likely to be forbidden in Europe in the near future.

The original VW Lupo is equipped with specially developed low rolling resistance tyres, but these tyres are not produced anymore. With the limited availability of state-of-the-art low rolling resistance tyres in the original tyre size (155/65R14), it was decided to go for the slightly wider Michelin Energy Saver tyre (165/65R14).

Interior heating of electric vehicles may require a significant amount of power and can therefore reduce the vehicle range considerably. As already mentioned, the heat produced by the motor and inverter is directed towards the interior via the water cooling system to reduce the required electric power. The Lupo 3L is already equipped with electric heating elements to support interior heating for some extreme conditions, as the diesel engine is very efficient. This system is maintained and tests will have to reveal if the overall interior heating system performs adequately.

Vehicle mass

Figure 8 gives an impression of the various power train components and their masses are listed in table 3. We managed to squeeze all the components in the Lupo chassis without sacrificing any interior space.

![Figure 8: Lupo 3L with the diesel and electric power train.](image)

<table>
<thead>
<tr>
<th>Table 3: Mass of the vehicle and power train.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE</td>
</tr>
<tr>
<td>vehicle chassis (without power train)</td>
</tr>
<tr>
<td>engine + gearbox + drive shafts</td>
</tr>
<tr>
<td>cooling (radiator, hoses, coolant, etc.)</td>
</tr>
<tr>
<td>exhaust</td>
</tr>
<tr>
<td>power electronics (inverter, charger, DC-DC conv.)</td>
</tr>
<tr>
<td>fuel tank + cooler + filter</td>
</tr>
<tr>
<td>diesel (7 L)</td>
</tr>
<tr>
<td>battery pack front (8.3 kWh)</td>
</tr>
<tr>
<td>center (7.7 kWh)</td>
</tr>
<tr>
<td>rear (11.0 kWh)</td>
</tr>
<tr>
<td>battery (12V)</td>
</tr>
<tr>
<td>miscellaneous (wiring, brackets, etc.)</td>
</tr>
<tr>
<td>complete powertrain</td>
</tr>
<tr>
<td>curb weight</td>
</tr>
</tbody>
</table>
5. Vehicle performance

At this moment we are in the final stages of the conversion process. In this section the calculations regarding energy usage, costs and range are presented. They will be validated at a later when the vehicle is fully operational.

Constant speed energy consumption

The energy usage is considered for a vehicle driving at constant speeds, which is a simpler type of analysis than evaluating a driving cycle. But it provides some useful insights, which may be lost when analysing driving cycles only. The constant speed diesel fuel consumption of the Lupo 3L is shown in figure 9. The lowest fuel consumption can be achieved while driving slightly over 50 km/h in 5th gear.

\[ F_x = \frac{1}{2} \rho AC_d v^2 + mgf_{rr} \]  

(2)

with \( \rho \) air density, \( A \) the frontal area, \( C_d \) aerodynamic drag coefficient, \( m \) mass of the vehicle including passengers and cargo, \( g \) gravitational constant and \( f_{rr} \) the tyre rolling resistance coefficient. The efficiency of the inverter, motor, reduction and drive shafts have to be taken into account to calculate the required DC power usage. A constant overall efficiency \( \eta_d \) is assumed. Furthermore there may be auxiliary systems in the vehicle with a constant power usage \( P_{aux} \), independent from the forward velocity. The required power which has to be delivered by the battery then becomes:

\[ P_{DC} = \frac{1}{\eta_d} \left( \frac{1}{2} \rho AC_d v^2 + mgf_{rr} \right) v + P_{aux} \]  

(3)

The DC energy usage of an electric vehicle is often expressed in the units Wh/km, so a certain amount of energy per kilometer driven. As 1 Wh/km is equal to 3.6 Ws/m or 3.6 N, it actually represents a force. The following expression can be derived for the energy usage per distance travelled:

\[ F_{DC} = \frac{1}{\eta_d} \left( \frac{1}{2} \rho AC_d v^2 + mgf_{rr} \right) + \frac{P_{aux}}{v} \]  

(4)

The following values are applicable for the electric Lupo: \( \rho=1.225 \text{ kg/m}^3, A=1.97 \text{ m}^2, C_d=0.29, m=1190 \text{ kg}, g=9.81 \text{ m/s}^2, f_{rr}=0.0085, \eta_d=0.81, P_{aux}=200 \text{ W} \). In order to compare the ICE and BEV the data provided in figure 10 is converted into Wh/km by considering that 1 L diesel contains 9970 Wh of energy. Assuming that the most efficient gear is selected for the diesel car, figure 10 can be obtained. Furthermore the battery or tank to wheel efficiency can be calculated by dividing \( F_x \) by \( F_{dc} \).

Figure 10: Comparison of diesel and electricity energy usage per km and efficiency.

As can be seen from figure 10 the Lupo 3L diesel achieves an excellent efficiency of over 30% for constant vehicle velocities above 70 km/h. This is much higher than the 22% mentioned in table 1 for a diesel engine, but it is also clear that below 50 km/h the 22% efficiency is not achieved. Figure 10 represents ideal conditions and excludes cold starts, acceleration, running idle, etc. For the electric vehicle the auxiliary power consumption leads to a reduction of the efficiency at low speeds. Nevertheless the forward velocity with minimal energy consumption is about 22 km/h, which is much lower than the diesel car. This will be advantageous in low speed city traffic.

Energy costs and carbon dioxide emissions

Knowing the fuel and electricity usage, as shown in figures 9 and 10 and accounting for charging losses, the costs per 100 km can be calculated. For diesel a price of 1.20 euro/litre is selected, whereas electricity costs 0.23 euro/kWh. The result is shown in the left graph of figure 11. It is remarkable to see that at the higher speeds the costs are almost identical, with a slight advantage for the diesel. At low speeds the energy costs for the electric car are lower. It can be noted that the price of petrol and diesel has been rather volatile over the years, whereas the 0.23 euro/kWh can be fixed for a period of five years. In the Netherlands the fuel for cars is taxed severely, for diesel the percentage is almost 60% and for petrol it close to
70%. Over the past decade also an energy tax has been introduced on electricity, resulting in an overall taxation level of approximately 65%. So it is expected that the revenues for the government (originating from the sales of energy) will not change very much, as the energy costs of diesel and electric appear to be similar.

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Vehicle range

Knowing the energy usage per distance travelled (4) and the available battery capacity, the constant speed range \( r \) can be calculated:

\[
    r = \frac{1}{\eta_{\text{batt}}} \frac{C_{\text{batt}}}{\eta_{\text{d}} \left( \frac{1}{2} \rho A C_d v^2 + mgf_{\text{d}} + \frac{p_{\text{aux}}}{v} \right)}
\]

where \( C_{\text{batt}} \) equals the battery capacity and \( \eta_{\text{batt}} \) the battery utilisation factor. For the Lupo: \( C_{\text{batt}} = 97.2 \ \text{MJ} (=27 \ \text{kWh}) \) and \( \eta_{\text{batt}} = 0.8 \). With these numbers the constant velocity line in figure 12 can be obtained. It is clear that the achievable range is very much dependent on the forward velocity \( v \). The target of 200 km is only achieved if the velocity is below 88 km/h and it is clear that the range is much reduced with respect to original 900+ km which the Lupo 3L can achieve.

Normal driving is not constant but includes braking, acceleration and stops. A simulation program has been written to determine the vehicle range for various driving cycles. The resulting ranges are plotted in figure 12 and listed in table 2. It appears that the range of 200 km can be achieved for most driving cycles, with the exception of the US06 and Artemis motorway driving cycles.

Increasing the auxiliary power from 200 to 1000 W will reduce the range, in particular when the average driving speed is low, see table 4. The range may also become smaller when the battery capacity is reduced, e.g. due to low outside temperatures, the cycle history and/or calendar life. In this case the energy available may be reduced by 5 to 25% and the range will be reduced by the same amount. For these worst case conditions the vehicle range is still 100 km or above.

Figure 11: Constant speed costs per km and CO2 emissions.

Figures 9 and 10 can also be used as a basis to compare the CO2 emissions of the diesel and electric vehicle. In a tank to wheel analysis the following numbers can be used. Burning a litre diesel emits 2.65 kg CO2, for a litre petrol 2.37 kg CO2 is released. With these numbers the specifications of the manufacturer can be reproduced with fair accuracy: the Lupo 3L uses 3 litre diesel every 100 km, resulting in 7.95 kg CO2/100 km, or 79.7 g CO2/km (VW specifies 81 g CO2/100 km). This approach excludes the well to pump emissions, which obviously is outside the scope of the vehicle manufacturer. The additional well to pump emissions are 410 g CO2/L for petrol and 510 g CO2/L in the case of diesel [14]. Thus the overall well to wheel emissions become: 3.16 kg CO2/L (diesel) and 2.78 kg CO2/L (petrol), an increase of approximately 18%.

A similar analysis has to be executed for the electricity, basically from well to socket. Electricity can be generated in many different ways, with widely varying CO2 emissions. A coal fired power plant may emit 800 to over 1000 g CO2/kWh, with natural gas this number ranges from 400 to 500 g CO2/kWh and for nuclear energy and renewable sources (PV, wind, hydro) the emission is generally below 100 g CO2/kWh. Furthermore the transport losses over the net have to be taken into account; an efficiency of 92% is suggested. In the Netherlands the electricity companies are obliged to report their carbon dioxide emissions, their numbers range between 0 and 500 g CO2/kWh. Taking into account some transportation losses 550 g CO2/kWh seems to be an upper limit. The various options are shown in figure 11, right graph. It seems that with a conservative estimate for the existing electricity mix that the electric Lupo has slightly lower emissions. To realize significant reductions electricity from renewable or nuclear sources should be used. Coal fired plants should be avoided in any case, unless methods to capture the CO2 emissions appear to be successful. Please note that these conclusions are based on a constant speed analysis only, driving cycles in different types of traffic will be necessary to provide a more definite answer. Furthermore it should be noted that the VW Lupo 3L is a very fuel efficient vehicle and does not represent the average car.
Table 4: Electric Lupo range for various driving cycles and two auxiliary power levels.

<table>
<thead>
<tr>
<th>driving cycle</th>
<th>P_{aux}=200 W</th>
<th>P_{aux}=1000 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEDC</td>
<td>214</td>
<td>172</td>
</tr>
<tr>
<td>Artemis urban</td>
<td>221</td>
<td>151</td>
</tr>
<tr>
<td>Artemis rural road</td>
<td>210</td>
<td>185</td>
</tr>
<tr>
<td>Artemis motorway</td>
<td>138</td>
<td>131</td>
</tr>
<tr>
<td>JAP 10.15</td>
<td>246</td>
<td>175</td>
</tr>
<tr>
<td>NYCC</td>
<td>230</td>
<td>131</td>
</tr>
<tr>
<td>UDDS/LA4</td>
<td>252</td>
<td>194</td>
</tr>
<tr>
<td>FTP75</td>
<td>243</td>
<td>192</td>
</tr>
<tr>
<td>LA92</td>
<td>193</td>
<td>163</td>
</tr>
<tr>
<td>HWFET</td>
<td>227</td>
<td>205</td>
</tr>
<tr>
<td>US06</td>
<td>153</td>
<td>142</td>
</tr>
</tbody>
</table>

8. Conclusions

Although much progress has been over the past decades, battery electric vehicles are still somewhat hampered by a heavy energy storage device with limited capacity and relatively slow recharging capabilities. Given these limitations an attempt has been made to design and realise a battery electric vehicle which could appeal to a broad audience. Emphasis is put on practicality (i.e. full charge overnight on a standard power socket, 4 seats), a low mass, energy efficiency and sufficient performance to be compatible with the vehicles on the road today in the Netherlands. Despite the limited budget, the vehicle specifications are in line with, or even exceed those of battery electric vehicles on the market today.

The donor vehicle is a VW Lupo 3L, which is a very fuel efficient car. It is also clear that improving on this, by converting it to a battery electric vehicle, has proven to be somewhat of a challenge. Initial calculations show at speeds above approximately 60 km/h that the costs per km and CO₂ emissions (using the regular electricity grid) are quite similar.

The next steps are to complete the conversion process of the vehicle, to optimise the controllers (e.g. regenerative braking) and to evaluate the performance. The aim is to obtain type approval, so that the vehicle is allowed to drive on the public road.

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8. References