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Evaluation of 20000 km driven with a battery electric vehicle

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Abstract

The energy consumption and range of a battery electric VW Golf Variant are analysed in detail, using both dedicated tests and daily usage logs. The vehicle has been converted by the Dutch company ECE (Electric Cars Europe) into a battery electric vehicle. It is equipped with an AC Propulsion power train and Kokam lithium polymer batteries. Dedicated measurements are executed to analyse the energy usage as a function of the forward velocity and the contribution of auxiliary loads. During almost one year nearly all trips were logged, covering over 20000 km driven electrically. Trip length, outside temperature, battery state of charge and DC energy usage were recorded. Special attention is paid to recurring, fixed length commuting trips between home and work. They allow investigating seasonal variations, in particular the effect of the ambient temperature (-5 to 25 °C) on the vehicle range and energy usage in real life conditions. The results clearly show a decrease in battery capacity and increased energy usage at low temperatures, resulting in a major reduction of the vehicle range. Relatively simple computer models are already suitable to capture the energy usage for various driving conditions. The vehicle uses on average 25 kWh/100 km electricity from the grid.

Keywords: BEV, energy consumption, passenger car, vehicle performance

1 Introduction

In recent years electric vehicles are receiving a lot of attention and are seen as a suitable path to reduce the dependency on oil, decrease CO_2 emissions and allow driving with zero local emissions in city centres.
Due to the limited density of energy storage in a battery when compared to fossil fuel, it is difficult to achieve a driving range which is acceptable for the "normal user". The driver of an electric vehicle may also experience "range anxiety", a sense of fear not being sure if the destination can be reached. Manufacturers of electric vehicles tend to be optimistic on the achievable range and the vehicle may show very good range figures in a specific test.
In this paper real world data is analysed, to check the available range and energy consumption under daily conditions. The paper starts in section 2 with a description of the electric vehicle under study. Energy consumption and range are analysed for constant speed (section 3), daily driving (section 4) and fixed route commuting (section 5). Simple models are used to capture the measurement results and make predictions. In section 6 the experiences of the driver and improvements to the vehicle are discussed.

2 Vehicle characteristics

2.1 General description

The vehicle under study is a converted, battery electric VW Golf Variant, see Figure 1. The conversion was done by the company ECE, (Electric Cars Europe) located in Lochem, the Netherlands [1].

Figure 1: ECE VW Golf Variant BEV.

In the conversion process the engine is replaced by a motor and power electronics of the company AC Propulsion. The original gearbox is maintained, but it is restricted to the use of the 2nd gear forward and reverse gear. The energy storage is provided by Kokam lithium polymer batteries, which are placed in the trunk and at the former location of the fuel tank. The batteries, motor and power electronics are all air cooled. Interior heating is done using a MES-DEA 3 kW water heater. The vehicle is also equipped with air conditioning. More technical specifications can be found in Table 1 and [2].

Table 1: Specifications ECE VW Golf Variant.

description	value
dimensions (l/w/h)	4556/1781/1467 mm
curb weight	1602.5 kg
max. weight	1940 kg
weight distr. (front/rear)	48.1/51.9 %
tyre pressure (front/rear)	2.5/3.0 bar
charger	6 kW (32A, 230V)
battery capacity (nom.)	37 kWh
battery capacity (usable)	30 kWh
battery voltage	330 V
battery max. current	460 A
motor power (peak)	150 kW
motor torque	220 Nm
motor type	AC induction

The range was initially specified by the manufacturer as being 350 km (brochure 2008), later this number was revised to 200 km. The price of the vehicle is about 100.000 euro. Over 50 of these vehicles have been built.

2.2 Performance

Performance tests have been executed with two people on board, weighing 160 kg [2]. The top speed was found to be 140 km/h, which is reasonably close to the manufacturer specification of 145 km/h. Various acceleration tests have been executed and the results are listed in Table 2.

Table 2: Acceleration times.

acceleration	time
0 - 50 km/h	7.1 s
0 - 100 km/h	13.8 s
50 - 80 km/h	4.0 s
80 - 120 km/h	6.5 s

The 0 - 100 km/h acceleration time is significantly higher than the 9 seconds specified by the manufacturer. It was noted that at higher speeds the acceleration performance was quite good, but the vehicle responds relatively slow at low speeds, most likely due to software limitations on the applied torque.

2.3 Energy usage of auxiliaries

Apart from the energy needed to propel the vehicle, various systems in the vehicle require energy, e.g. lighting, heating, audio equipment, windscreen wipers, air conditioning, etc. During standstill the power requirements of various systems were measured, the results are listed in Table 3.

Table 3: Auxiliary DC power usage.

system	power
vehicle systems only	0.3 kW
vehicle systems, lights	0.5 kW
vehicle systems, lights, heating	3.5 kW
vehicle systems, lights, air conditioning	4.1 kW

Please note that these numbers refer to the DC energy usage, measured at the battery supply side. These tests were executed for a relatively short period. It is very well conceivable that the power requirements of the air conditioning and interior heating drop, once the desired temperature is reached. This has not been investigated any further.

2.4 Regenerative braking

One of the advantages of a battery electric vehicle is that energy can be recuperated while braking, instead of being converted into lost heat. In the vehicle regenerative braking is activated by releasing the throttle. At different forward speeds the regenerative braking power was measured, see Table 4. Considering the peak motor power of 150 kW the regenerative braking power is very modest. Applying the brake pedal does not change the amount of regenerative braking power.

Table 4: Regenerative power.

speed	power
50 km/h	7.3 kW
80 km/h	11.6 kW
100 km/h	15.0 kW
120 km/h	19.2 kW

3 Constant velocity energy usage

3.1 Measurements

Constant speed measurements have been executed on a level road surface and are repeated three times to determine the required power and energy usage. The auxiliary power is reduced to a minimum level: no air conditioning, heater or lights. The ambient temperature during the tests was on average 19 °C. The results are listed in Table 5. Obviously the required power increases with forward velocity due to aerodynamic drag and rolling resistance. The energy usage also increases, but is more constant at lower speeds.

Table 5: Constant speed power and energy usage.

speed	power	DC energy usage
10 km/h	0.97 kW	97 Wh/km
20 km/h	2.23 kW	112 Wh/km
30 km/h	3.13 kW	104 Wh/km
40 km/h	4.07 kW	102 Wh/km
50 km/h	5.60 kW	112 Wh/km
60 km/h	7.93 kW	132 Wh/km
70 km/h	10.53 kW	150 Wh/km
80 km/h	11.70 kW	146 Wh/km
90 km/h	14.73 kW	164 Wh/km
100 km/h	20.63 kW	206 Wh/km
110 km/h	24.40 kW	222 Wh/km
120 km/h	30.60 kW	255 Wh/km
130 km/h	37.80 kW	291 Wh/km
140 km/h	43.50 kW	311 Wh/km

3.2 Modelling

A simple model already appears to be capable to capture the measurement results as presented in Table 5. The power required from the battery P_{batt} consists of two parts:

$$P_{batt} = P_{aux} + \frac{1}{\eta} P_{mech} \tag{1}$$

The auxiliary power P_{aux} depends on the systems in use; some numbers for the vehicle are listed in Table 3. The mechanical power P_{mech} is needed to overcome rolling resistance and aerodynamic drag, assuming that the vehicle is running on a level road.

$$P_{mech} = \left(mgf_{rr} + \frac{1}{2} \rho C_d A\, v^2 \right) v \tag{2}$$

With m being the vehicle mass, g the gravitational constant, f_{rr} the rolling resistance coefficient, ρ the air density, C_d the aerodynamic drag coefficient, A the frontal area of the vehicle and v the forward velocity of the vehicle. Losses in the power train are taken into account by a single overall efficiency η.

To describe the constant speed characteristics of the ECE VW Golf Variant, the following values are used: m=1762.5 kg, g=9.81 m/s^2, f_{rr}=0.012, ρ=1.225 kg/m^3, C_d=0.32, A=2.19 m^2 and η=0.76. In the measurements the auxiliary power P_{aux} equals 300 W. For comparison also heating and lighting are included (P_{aux} =3.5 kW). The results are shown in Figure 2. Obviously the power is increasing with increasing velocity and matches closely with the measurements. Increasing the auxiliary power is particularly noticeable at low velocities, at approximately 33 km/h the battery power is doubled and the range will be halved. The specific energy usage displays a minimum at about 23 km/h for the low and 52 km/h for the high auxiliary power case respectively.

Knowing the energy usage and usable battery capacity of 30 kWh, the constant velocity range can be determined, see the bottom graph in Figure 2. Driving more slowly is normally always beneficial to reduce the energy consumption and increase the vehicle range. Only when the auxiliary power usage is high, the range is reduced again when driving more slowly than the aforementioned 52 km/h. The available range r can easily be calculated directly with the next formula [3]:

$$r = \frac{C_{batt}}{\frac{1}{\eta}\left(mgf_{rr} + \frac{1}{2} \rho C_d A\, v^2 \right) + \frac{P_{aux}}{v}} \tag{3}$$

where C_{batt} equals the usable battery capacity.

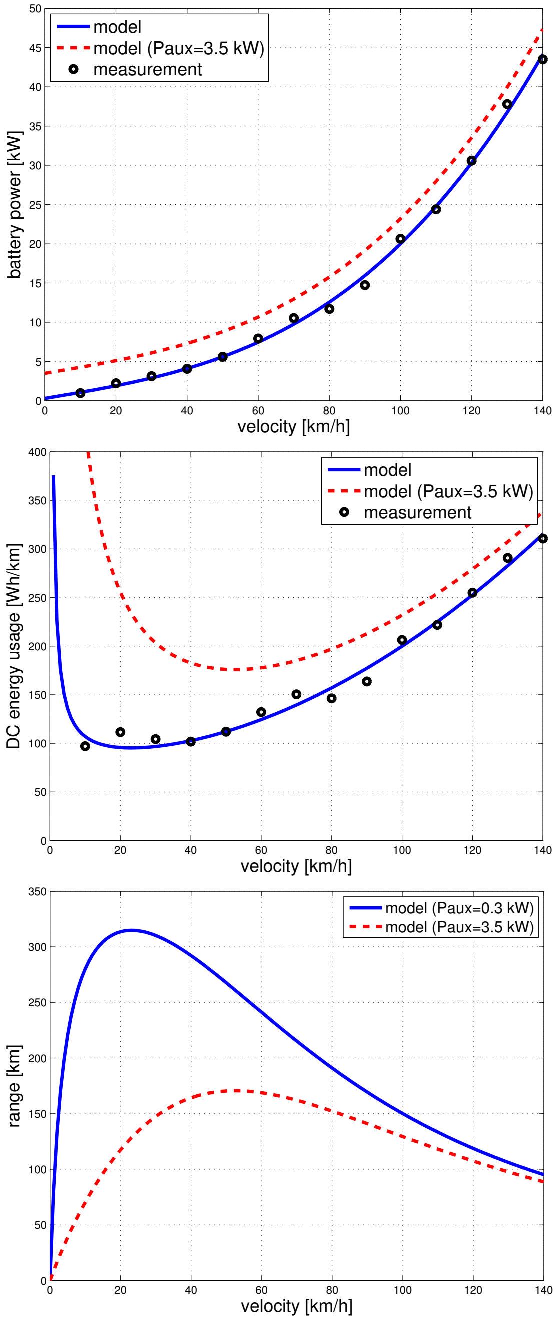

Figure 2: Battery power, DC energy usage and range as a function of forward velocity.

4 Daily driving

4.1 Logbook

The owner of the vehicle has kept a logbook and systematically recorded the trips made. The notes considered in this paper start December 28th 2009 and end November 16th 2010, so almost an entire year was covered. In this period a distance of approximately 25000 km was logged.

In this logbook the following entries are made:

- date
- outside temperature (°C)
- odometer reading at end of the trip (km)
- battery SOC at the begin of the trip (%)
- battery SOC at the end of the trip (%)
- the number of kilometres driven (km)
- electricity used during trip (kWh)
- the specific electricity usage (kWh/km)

These readings originate mostly from the BMS information display mounted in the vehicle, see Figure 3.

Figure 3: BMS display (during charging).

4.2 Data selection

As the entries were recorded manually, obviously some errors may have been made. Sometimes entries are forgotten or some results are implausible, e.g. when the battery state of charge is higher at the end of and trip than at the beginning. All data available has been carefully reviewed. The following checks have been done:

- Odometer reading versus trip length. The trip length should be the difference between two subsequent odometer readings. If this is not the case something must be forgotten or an error was made.
- Electricity usage check. Obviously the electricity used during the trip divided by the trip length should correspond to the specific energy usage. This is not always the case, particularly for short trips. If the difference is very large the entry is rejected.
- Entries where the battery state of charge is higher at the end of a trip than at the beginning are rejected.
- The outside temperature readings have been compared with data from a national weather station. No entries have been rejected based on this criterion.

Applying these criteria has reduced the number of entries from 349 to 274, so approximately 20% was rejected.

4.3 Data analysis

Using the trips considered to be valid, first some statistics are calculated, see Table 6.

Table 6: Statistical data valid entries.

description	value
number of trips	274
total distance	21467 km
total amount of electricity (DC)	4426 kWh
average energy usage (DC)	206.2 Wh/km
shortest trip	9.7 km
longest trip	171.5 km
average trip	78.3 km
lowest ambient temperature	-4 °C
highest ambient temperature	26 °C
average ambient temperature	10.7 °C

Considering the fact that this data was gathered in less than a year, already shows that the vehicle is used fairly intensively. The shortest trip length is relatively large at almost 10 km, this is due to the fact that the data of short trips appeared to be unreliable and some short trips may simply not have been recorded. Also the average trip length is high, this is caused by many commuting trips, since the owner travels about 77 km from home to work and vice versa. These commuting trips will be analysed more in detail in section 5.

The (specific) energy usage as a function of travelled distance is shown in Figure 4 and 5. Obviously the longer the trip, the more energy is required. But it can also be seen that for a fixed trip length the energy usage may vary considerably. On shorter trips the specific energy usage is higher compared to long trips. A possible explanation may be that the driver does not experience any 'range anxiety' and exploits the possibilities of the car. Furthermore the short trips may be in city traffic instead of highways. Finally heating up the vehicle could cost relatively more energy on a short trip.

The relation between the battery state of charge (SOC) and energy stored in the battery is given in Figure 6. Different than one perhaps would expect, this is not a 1:1 relation. Under ideal condition 100% SOC corresponds to 30 kWh. A peculiarity of the ECE car is that it is possible to charge to 108% SOC. Though this is impossible from a theoretical point of view, Figure 5 makes clear that 108% SOC corresponds to about 32.4 kWh, which is still possible considering the nominal battery capacity of 37 kWh. The manufacturer will also have defined some bounds not to completely discharge the lithium polymer battery as it will be permanently damaged then. So 0% SOC does not indicate a completely discharged battery pack. Apparently the philosophy is that the driver is informed with a range of 0 to 100% (or 108%) of the usable battery capacity being available.

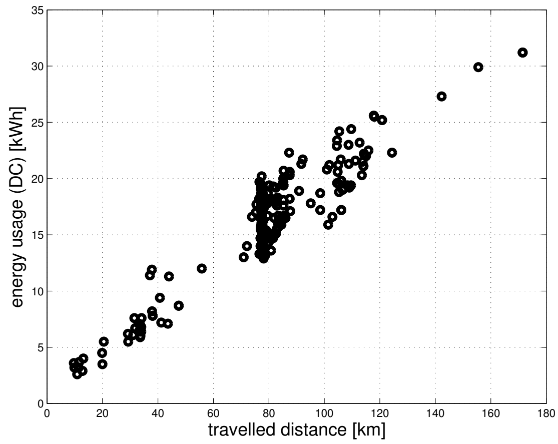

Figure 4: Energy usage as a function of trip length.

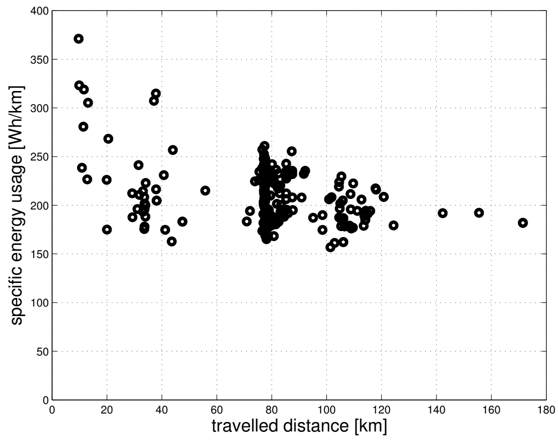

Figure 5: Specific energy usage as a function of trip length.

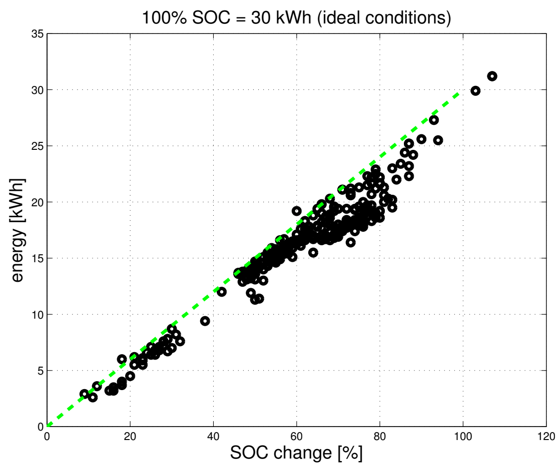

Figure 6: Relation between SOC change and energy stored in the battery.

Over the entire period considered, the vehicle never got stranded along the road with an empty battery. Based on the available data, the SOC at the start (and end) of the trip can be plotted as a function of the distance travelled, see Figure 7.

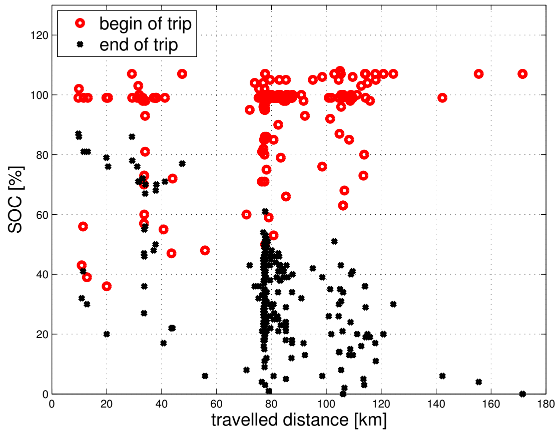

Figure 7: SOC at start and end of a trip.

From Figure 7 it can be observed that most trips are started with an (almost) fully charged battery (SOC ≥ 95%). This is the case for 85% of the trips. On the other hand Figure 7 also shows that trips were made of 106 km starting with 62% SOC and 81 km with 53% SOC. Furthermore many of the short trips are made with a less than fully charged battery, the lowest starting level is 36% SOC. As can be seen from Figure 4, 5 and 7, many trips are made with a length of around 77 km. They will be analysed in detail in the next section.

5 Commuting

5.1 Data analysis

The commuting trips have a length of about 77 km. All records with a trip length between 76 and 78 km are selected and are assumed to represent travelling from home to work and vice versa using a fixed route. There are 116 of these trips and the total mileage equals 8986 km.

The recordings are made throughout the year, with ambient temperatures varying between -5 ºC and 25 ºC. As the distance is fixed, it is now possible to investigate the effect of the ambient temperature. A first result is shown in Figure 8. At 15 ºC ambient temperature the lowest specific energy consumption (170 Wh/km) can be achieved. When the outside temperature drops to -5 ºC and the interior heating is used the specific energy usage increases to at least 240 Wh/km, an increase of over 40%.

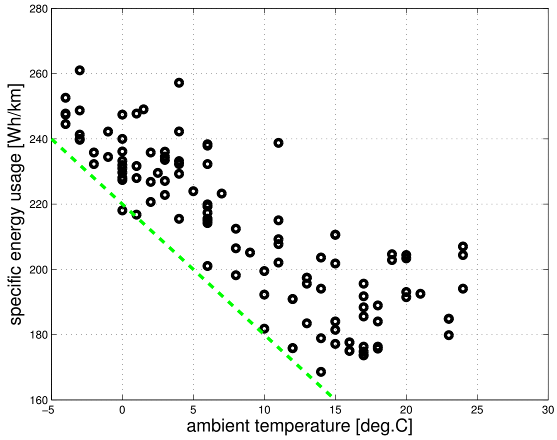

Figure 8: Temperature dependency of specific energy usage for commuting trips.

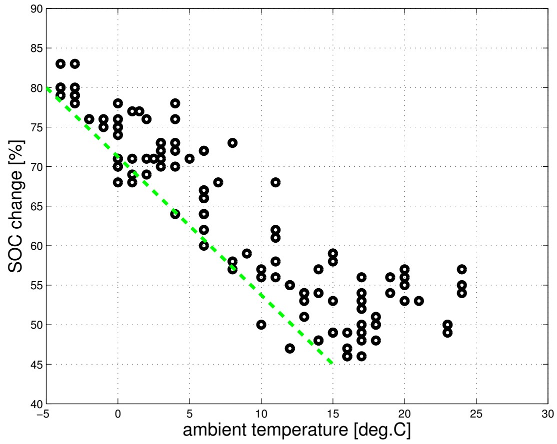

Figure 9: SOC change for different ambient temperatures while executing 77 km commuting trips.

Unfortunately this is not the only problem encountered at low temperatures. As can be observed in Figure 9, at 15 ºC the change in SOC to travel 77 km is at least 45%, but at -5 ºC is at least 80%: an increase of over 75%.

Combining the energy consumption with the change in the SOC, the battery capacity at 100% SOC can be calculated, as shown in Figure 10. Under ideal conditions at 15 ºC the usable battery capacity is about 30 kWh, but at -5 ºC this may have been reduced to 24 kWh or less.

A commuting trip equals 77 km, so the range for a 100% SOC change can be calculated, as shown in Figure 11. The combination of increasing energy usage and decreasing battery capacity at low temperatures, leads to a strong dependency of the range on the ambient temperature: at 15 ºC the range may be 170 km, whereas at -5 ºC it is only 100 km. The gradient appears to be approximately 30 km reduction of the range with an ambient temperature drop of 10 ºC.

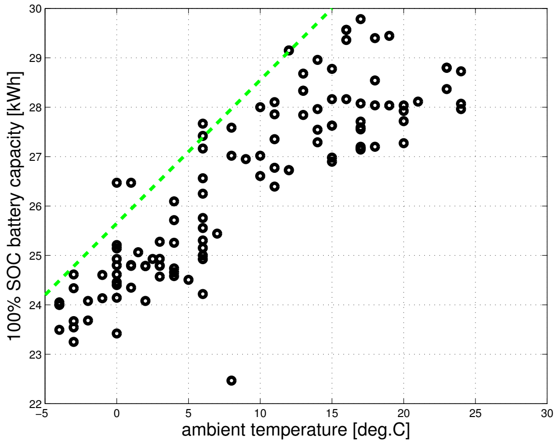

Figure 10: Calculated battery capacity using energy usage and SOC change for commuting trips.

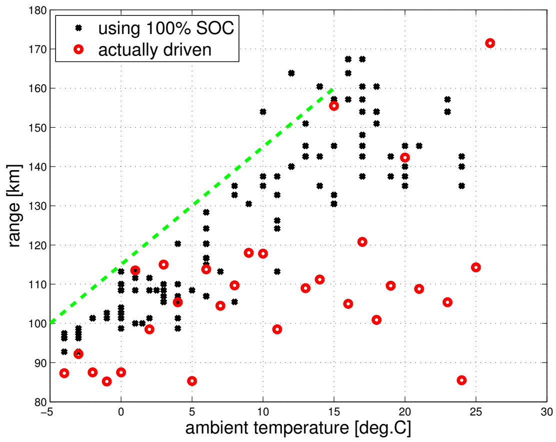

Figure 11: Calculated vehicle range using 100% SOC and actually driven distances.

Based on Figure 11 it appears that the driver normally uses the car up to a range of 120 km, with a few exceptions when longer trips are made. When the ambient temperature drops below 0 ºC, this expectation cannot be met by the car anymore. It seems that the driver is aware of this and limits the maximum distance driven to about 90 km.

5.2 Speed profile of commuting trips

To further investigate the commuting trips, speed profiles were recorded using a GPS device. Every second the actual position and vehicle speed are recorded. The owner of the car was asked to drive as he normally does from Voorburg (home) to Geertruidenberg (work), see Figure 12. Three valid recordings were made, the velocity profile is shown in Figure 13. On many parts of the road a speed restriction of 100 km/h is applicable, near Rotterdam it is 80 km/h. Also the sections driving to and leaving the highway can be distinguished clearly.

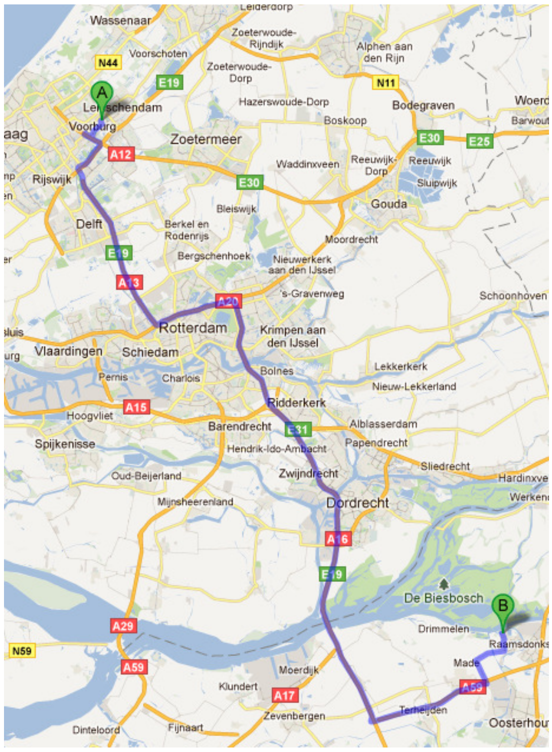

Figure 12: Commuting trip between Voorburg and Geertruidenberg (Google maps).

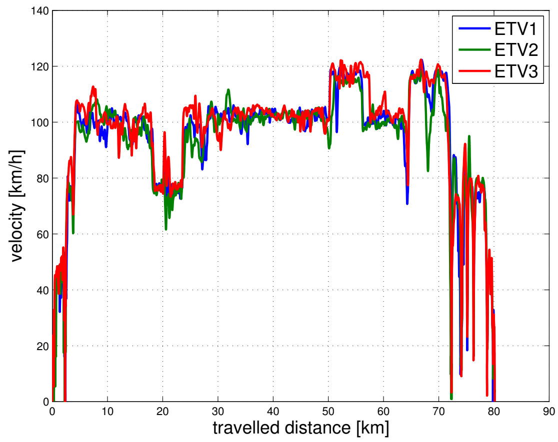

Figure 13: Commuting trip velocity profile.

There appears to be some discrepancy on the distance actually driven. According to Google maps the distance is 81.0 km. If we integrate the measured vehicle velocity using GPS a distance of 80.0 ± 0.2 km is obtained. Based on the logbook of the driver, using the vehicle odometer, the typical commuting distance would be 77 km. The exact source of these differences is not known and has not been investigated in detail. It can be conceived that the odometer in the converted vehicle is not 100% accurate and gives slightly lower readings compared to the actually driven mileage. The travelling time varies between 55:41 and 57:45 for the three recordings (min:sec).

5.3 Model calculations

To analyse the energy usage and range of battery electric vehicles a MATLAB model has been developed to make first estimates, using a minimal number of parameters [3]. It uses a velocity profile as function of time (a driving cycle) as input. Furthermore data on the vehicle is needed; most of the required parameters are already given in section 3.2. Two additional parameters are needed: the regenerative braking efficiency is set to 30%, considering the low regenerative power, as listed in Table 2.4. Secondly, when increasing velocity the rotational inertia of the wheels and drive train has to be accelerated. This is taken into account by a 6% increase in vehicle mass for these conditions. The calculated specific energy usage for the commuting trip, with a single 80 kg person in the vehicle, is listed in Table 7.

Table 7: Specific energy usage (P_{aux}=300 W)

cycle	specific energy usage
ETV1	200 Wh/km
ETV2	196 Wh/km
ETV3	205 Wh/km
measurements 15 °C	180 to 210 Wh/km

For lower ambient temperature it is difficult to access the exact amount of energy for heating the vehicle interior, as this figure has not been recorded. The assumption is made that the full power of the heater is used (3 kW), as some drivers of the ECE VW Golf Variant have complained that it was difficult to achieve a sufficiently high interior temperature in cold weather conditions. During wintertime it can be assumed that lighting is needed during the morning and evening commute. So for these conditions the auxiliary power is set to 3.5 kW, as listed in Table 3. Another effect is that at low ambient temperatures the density of the air is higher (at -5 °C: ρ=1.3163 kg/m^3). The results are listed in Table 8.

Table 8: Specific energy usage (P_{aux}=3500 W)

cycle	specific energy usage
ETV1	246 Wh/km
ETV2	243 Wh/km
ETV3	250 Wh/km
measurements -5 °C	240 to 260 Wh/km

When comparing the model results with measurements, it seems that for the higher temperatures we seem to be somewhat on the pessimistic side, whereas for the lower temperature to model is slightly optimistic. Additional factors playing a role could for example be the tyre pressure. At low temperatures the tyre pressure may be reduced and the rolling resistance will increase. This is not investigated further as no data is available. Given its simplicity, the model appears to give fairly accurate predictions on the energy consumption.

The commuting trip as discussed in this section is just one example of a driving cycle. There are many more standardised driving cycles, the NEDC or New European Driving Cycle to name one. As range is still a critical parameter of battery electric vehicles, it has been calculated for the ECE VW Golf Variant for two scenarios. The optimistic scenario assumes 108% SOC of the battery (32.4 kWh), an auxiliary power usage of 300 W and 15 ºC ambient temperature. The pessimistic scenario assumes -5 ºC ambient temperature and a usable battery capacity of 23 kWh and auxiliary power usage of 3500 W. The results are listed in Table 9 and shown in Figures 14 and 15.

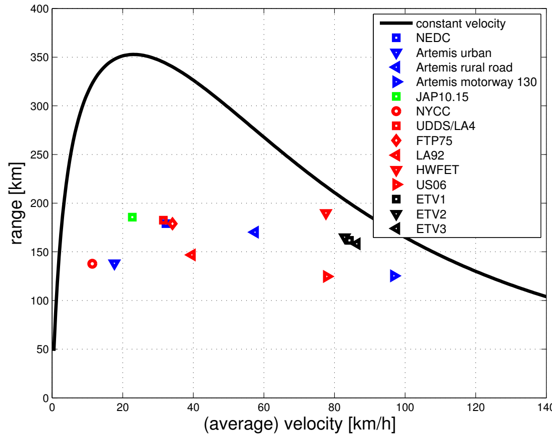

Figure 14: Vehicle range for various driving cycles (optimistic scenario, 15 ºC).

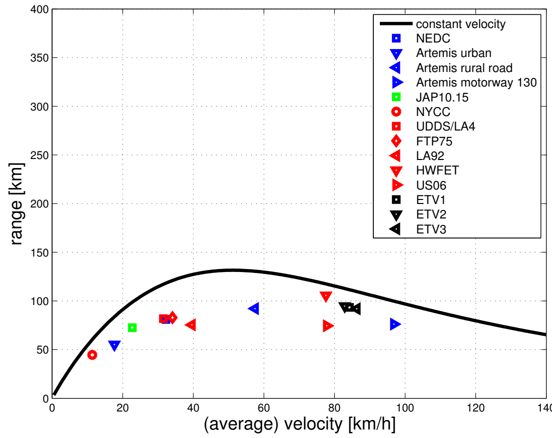

Figure 15: Vehicle range for various driving cycles (pessimistic scenario, -5 ºC).

Table 9: Vehicle range for different driving cycles.

cycle	optimistic 15 ºC	pessimistic -5 ºC
NEDC	179 km	81 km
Artemis urban	138 km	55 km
Artemis rural road	170 km	92 km
Artemis mway 130	125 km	76 km
Jap. 10-15	186 km	73 km
NYCC	138 km	45 km
UDDS/LA4/FTP72	182 km	82 km
FTP75	179 km	83 km
LA92	147 km	75 km
HWFET	190 km	106 km
US06	125 km	74 km
ETV1	162 km	93 km
ETV2	165 km	95 km
ETV3	158 km	92 km

It can be observed that the range suffers in particular for low speed city driving (NYCC: New York City Cycle, Artemis Urban and the Japanese 10-15 cycle), where the range may be reduced by over 60%. For cycles with a higher average speed, the reduction is in the order of 40%. Considering the fairly good agreement of the model with the measurements (see Table 7 and 8), it is no surprise that the calculated range in Table 9 for the ETV cycles agrees quite well with the measurement results shown in Figure 11.

A final remark is that the main application of the vehicle is commuting over a distance of approximately 80 km. For this task the vehicle is suited, as for this specific driving cycle the range is sufficiently large even under pessimistic assumptions.

6 Vehicle operation

6.1 Driver interview

The driver of the vehicle has been interviewed in March 2011, when a limited number of analysis results were available. At the time of the interview he has travelled over 40000 km with this vehicle. The vehicle requires very little maintenance; the only unscheduled activity was a repair of the rear suspension.

Since he stopped logging trips, the vehicle has been updated. First of all regenerative braking has been made more effective. It is now possible to drive the vehicle mostly by using the throttle pedal only, which is highly appreciated by the driver. The effect on the vehicle range is estimated to be about 4%, although in city traffic he estimates the benefits could be 20 to 30%.

The charging procedure has been changed and the vehicle is now always charged to 108% SOC, thus increasing the range. Furthermore a battery heating system has been installed. This should help in reducing the temperature dependency of the available battery capacity (as highlighted in this paper). Unfortunately no measurement data is available to weigh the increased energy usage due of the battery heating system against an increased battery capacity. The odometer reading in the BMS system has been modified and is more accurate now.

The driver has been economical with both heating and air conditioning. He states that heating uses clearly more energy than the air conditioning, something not observed in Table 3. During the summer he can drive from home to work and back without recharging, whereas during the winter this is certainly not possible. He is aware of the effect of temperature on the vehicle performance and notices that the vehicle operates best at temperatures of around 15 ºC. Figure 8 of this report completely agrees with his experience.

The household of the driver does have a second non-electric vehicle, but he hardly ever uses it.

6.2 Grid electricity usage

As listed in Table 6, the vehicle uses 206.2 kWh/km DC electricity on average. This is not the electricity needed from the grid, as charging losses also have to be accounted for. No data is available for the ECE VW Golf, but measurements have been executed for the BMW Mini-E, which uses the same power train and charger. For the Mini-E the charging efficiency is 82.5%. So the AC grid electricity usage of the ECE VW Golf Variant will be approximately 250 Wh/km, 25 kWh/100 km or 4 km/kWh.

7 Conclusions and outlook

The energy usage and range of a battery electric ECE VW Golf variant has been analysed, using over 20000 km of real life data. This study clearly shows the impact of ambient temperature: in cold weather conditions additional energy is needed to heat the interior resulting in a higher specific energy usage. The second effect is that the battery capacity is decreasing at lower temperatures. The combined effect is that for the vehicle under study the range may decrease by 30 km with a 10 ºC drop in ambient temperature. After the period analysed, the vehicle has been equipped with a

battery heating system, which may improve the cold weather performance.
The energy consumption and range of the vehicle can be predicted fairly accurately with simple models, using only a very limited set of parameters.
The data logged by the driver has proven to be very useful to analyse the vehicle behaviour, and it is concluded that with this limited number or sensors, already quite useful insights could be obtained.
Analysis of the energy consumption of electric vehicles will be continued with the research vehicle developed at the TU/e (Lupo EL), which has a more elaborate instrumentation.

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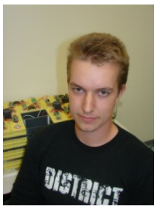

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