EVS27
Barcelona, Spain, November 17-20, 2013

*eco*nnect Germany – performance and evaluation of an electrically propelled minibus for public transportation

Dipl.-Ing. Felix Töpler[1], Univ.-Prof. Dr.-Ing. Lutz Eckstein[2],
Dipl.-Ing. Gerrit Geulen[2], Dipl.-Ing. Jérôme Homann[1]

[1]*Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka), Steinbachstr. 7, 52074 Aachen (Germany),*
toepler@fka.de
[2]*Institut für Kraftfahrzeuge, RWTH Aachen University*

Abstract

Within the econnect project and its predecessor project SmartWheels, which are both funded by the German Ministry of Economics and Technology (BMWi), a battery electric passenger bus on the basis of a Mercedes Sprinter City 65 has been developed and tested on public roads. Driving without local emissions, high energy efficiency and reduced energy costs for driving are the main advantages of electric drivetrains compared to conventional ones. Otherwise the limited energy content of the battery reduces range and availability of electric propelled vehicles.

Passenger buses in public transportation systems are usually driving on specified inner-urban routes and have an average driving speed of ca. 20 km/h. Next to that the breaks at the end of service offer the possibility to recharge the battery so that the average daily driving distance can be easily covered by the developed electric bus. At the EVS 26 in 2012 ika has presented the design and concept of the electric bus [1]. This paper presents the results of test drives on urban and extra-urban bus routes. Some of the routes have also a significant elevation profile. A second bus with a conventional diesel engine was also used on the same routes so that a detailed comparison and evaluation of the electric and the diesel propelled bus has been made. All test drives have been carried out in or near the city of Aachen.

Keywords: battery-electric-vehicle (BEV); passenger bus; energy costs

1 Introduction

The public transport system allows a comprehensive and low cost mobility [2]. Most of the vehicles used in public transportation in Europe are driven by diesel engines. Alternatives are natural gas, fuel cells or hybrid drives as well as electric drive systems, which are supplied with energy from a battery or a special infrastructure (trolley busses). Compared to other alternatives, electric drive systems have no local emissions and a low noise level. However, the batteries have a relative low energy density, so that these vehicles have a significantly shorter range than combustion or fuel cell-powered vehicles. Among various commercial vehicles such as for long-distance transport, city buses have a low average speed and a shorter daily mileage. As city buses are used on fixed routes with only little changes over time, charging stations might be installed in a limited number to reduce the necessary investment costs. With the possibilities provided by a quick charging device the average daily mileage can be reached with a few charging stops. Fig. 1-1 shows the average moving velocity of a selected city bus line as well as an overland connection close to the city of Aachen [3]. The average moving velocity is defined as the average speed without standstill phases.

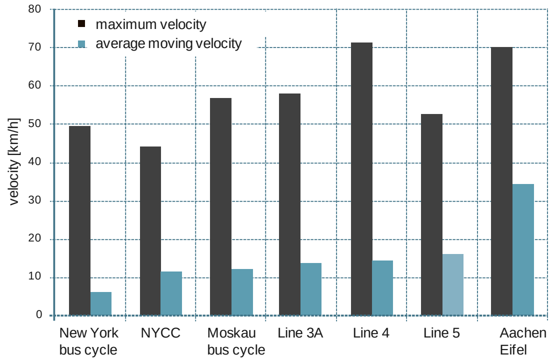


Fig. 1-1: Maximum and average moving velocity of selected bus cycles

The inner city cycles are driven in the city area of Aachen and the overland cycles with a significant elevation profile between Aachen and the Eifel mountains. The objective was to demonstrate the performance of the electric drive and to determine the actual range of the test vehicle in real driving conditions as well as the required charging time. Next to that a diesel driven passenger bus was used in the tests to compare the performance of the electric bus with the series vehicle.

2 Test vehicles

The test vehicle is an electrified minibus with a passenger capacity of around 25 people as shown in Fig. 2-1.

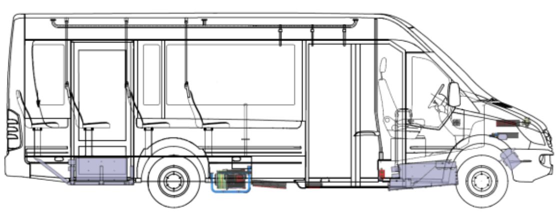


Fig. 2-1: Prototype of electric propelled bus

The diesel engine and the automatic gearbox of the series vehicle were replaced by a hybrid synchronous motor with a maximal power of 150 kW. A single stage planetary gear with a transmission ratio of 4.5 is flanged to the electric machine and connects the new propulsion system to the rear axis from the series car.

The characteristics of the test vehicles are shown in Fig. 2-2 and Fig. 2-3.

	Series vehicle	Unit
Seats	12 + 1 (Driver)	-
Stance	18	-
L x W x H	7700 x 1993 x 2845	mm
Max. Weight	5650	kg
Motor power	120	kW
Maximum Speed	80 (electronically limited)	km/h
Max. Torque (at rpm)	360 (1200 - 2400)	Nm (rpm)
Max. rpm	4000	rpm
Gearbox	6-speed automatic	-
Motortype	In-line 4-cylinder Diesel	-

Fig. 2-2: Vehicle data of conventional diesel bus

	Electric prototype	Unit
Seats	12 + 1 (Driver)	-
Stance	10 to 15	-
L x W x H	7700 x 1993 x 2845	mm
Max. Weight	5650	kg
Motor power	150 (peak)	kW
Maximum Speed	78	km/h
Max. Torque (at rpm)	300 (0 - 4500)	Nm (rpm)
Max. rpm	12 500	rpm
Gearbox	Single speed planetary gearbox	-
Battery capacity	45	kWh
Usable SOC window	15 – 95	%
Discharge current (max)	400	A
Charge current (max)	160	A
Charging time @230 V	12	h
Charging time @400 V	< 1	h
Motortype	Hybrid-synchronous-motor	-

Fig. 2-3: Vehicle data of electric prototype bus

In comparison to the series car the passenger capacity is reduced due to the higher curb weight and the changed weight distribution. The replacement of the propulsion system requires small modifications to the body of the minibus. The passenger cabin remains unchanged and does not differ from the diesel-powered model. The battery consists of two blocks of the same size, which are electrically connected in parallel and which are also cooled or heated from a common liquid circuit in parallel. A PTC element installed in the battery circuit functions to heat the battery at low temperatures. Via a heat exchanger the PTC can also be used for heating the interior. Since the heating requirements for a bus are much higher than those of a passenger car due to the large interior volume and the frequent stops, an additional diesel-powered heater is used as well as in the series vehicles. The fuel is supplied from an auxiliary tank with a capacity of about 30 l. This ensures that in winter time the range is not reduced by using the electric heater permanently. The high-voltage components of the drivetrain (E-motor, drive inverters, DCDC converter) are liquid-cooled in a further closed cycle. The waste heat is not used because both cooling circuits of the motor and the batteries are at a low temperature level. Moreover, due to the high efficiency the power losses are considerably lower than in an internal combustion engine.

To ensure the driveaway at a slope of more than 20 % with maximum load or even overload the powertrain is designed in a way that the maximum traction force is corresponding to the series vehicle in first gear. The maximum speed of 78 km/h is only slightly below the series car (80 km/h) and sufficient for a city bus. A change of the drive characteristics towards a higher final speed or a higher traction force at lower speeds can be achieved by using one of the other available differential gears from the series vehicles.

Fig. 2-1 shows in principle the positioning of the new drive components added in the engine compartment and underbody area. The drive unit, which consists of an electric machine and a planetary gear, is installed in the space of the optional retarder. Drive inverter and the high voltage distributor box are installed under the low-floor section between the longitudinal beams. The front battery block is located behind the front axle in the space of the 12 V battery, the automatic transmission and the offset gearbox of the diesel-powered model [4].

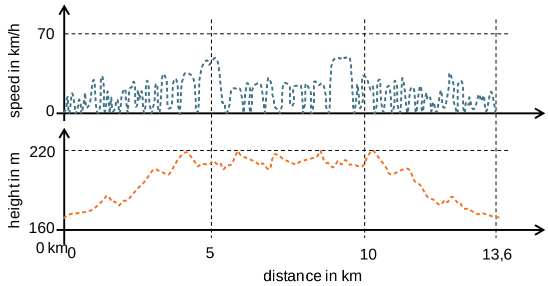
The high voltage battery can be charged via an onboard installed 230 V charger at any normal household socket. The RWTH Aachen University institute ISEA has developed a quick charging option within the SmartWheels project to increase the availability and daily mileage of the vehicle. Thus a bipolar socket is installed in the vehicle which has the mechanical structure of the CHAdeMO standard plug and allows a charging capacity of up to 64 kW at 400 V DC Voltage [5]. While charging the plug is connected directly to the high voltage intermediate circuit. By using the quick-charger the time required for recharging the batteries can be reduced to 45 minutes. However, it depends on additional parameters such as actual battery temperature and state of charge.

The motor power is transferred only to the rear axis similar to the series vehicle. This might restrict the recuperation, so that the slip of the drive wheels is limited while breaking. Recuperation can be activated manually by the driver in three stages by actuating the gear selector lever. The brake characteristics correspond to the retarder of the series car. The maximum braking power is 60 kW. There are no changes in the hydraulic braking system compared to the series car. Just an electric pump generates the vacuum required for the brake booster.

3 Test drive results

The testing of the vehicle on several city bus lines of Aachen started in September 2011 and is still going on. In addition, an overland bus line from Aachen to the Eifel is selected to investigate the influence of an inclination profile and higher average speeds in overland driving.

Each route is driven at least twice with different loading conditions to determine maximum and minimum energy consumption. The vehicle was loaded with water-filled ballast dummies and sandbags up to the allowed weight limit. During the tests all data, which are transferred via CAN bus, are recorded and subsequently evaluated. Among other things, this data shows the ratio of recuperation to propulsion. Bus lines in cities have a great potential to recuperate energy due to the traffic situation and short distances between stops which leads to many braking procedures. Based on the information provided by the investigated bus lines, the average travel distance between two stops is equal to 200 to 300 m and each stop has an average stopping time of 20 to 30 seconds. An example of the collected data is shown in Fig. 3-1.



	Unit	Min. payload (300 kg)	max. payload (1500 kg)
Energy demand	kWh/100km	41,4	60,2
Recuperation / Drive energy	-	0,20	0,19
Range with 35 kWh available energy	km	84,5	58
Charging time for 100 km with 26 kW charger	h	1,77	2,57

Fig. 3-1: Test results in real life traffic (Line 4)

Fig. 3-2 shows in detail the energy balance of line 4 driven without payload. The red arrows represent the power loss in the components emitted as waste heat into the surrounding environment. As recuperation allows only a limited deceleration and is reduced at low speeds because of drivability, a part of the kinetic energy of the vehicle must be converted into heat by the mechanical friction brake. The numbers shown in the figure represent the energy flow in Wh for a distance of 12.5 km. The upper numbers in the „E-Motor + ACDC" and „Generator + ACDC" block are for the DC side of the converter and the lower numbers shows the energy given to and taken from the electric machine.

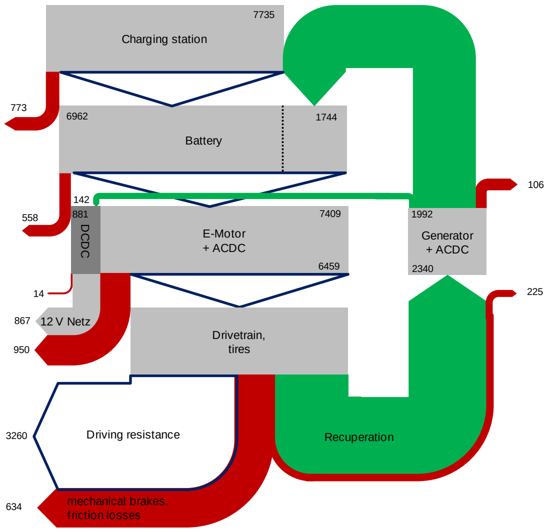


Fig. 3-2: Energy flow diagram of electric bus (Line 4)

The required energy in this example is 50 kWh per 100 km. The minimum and maximum consumption during the test was 38 kWh and 60 kWh per 100 km. The energy losses incurred in the battery and the charging station during charging are not included in these figures.

The losses shown in Fig. 3-2 are based on the assumption that the efficiencies are 95 % for the batteries and 90 % for the charging station. In order to reload the needed energy for balancing the SOC amount to 7735 Wh by using a quick charging station with a power of 60 kW at optimum conditions, a period of less than eight minutes is required. By normal operation the regular rest periods at the end of a line can be used to charge the battery. At the end of service the battery can be fully charged overnight and preconditioned for the next day.

4 Analysis of performance and energy costs

The test data from more than 50 test drives on several inner-urban and extra-urban bus lines under different environmental conditions and load conditions has been evaluated to extract the minimal and maximal energy (fuel) consumption of the electric and the diesel bus. The average values are shown in the following Fig. 4-1.

	Unit	With minimal payload Ø values	With maximal payload Ø values
Ø – energy consumption at battery	kWh/100km	41,6	54,6
Ø – energy consumption at grid	kWh/100km	45,8	60,1
Recuperation / drive energy	-	0,19	0,18
Ø – range	km	88,5	63,9
Ø – charging time* for 100 km	h	1,7	2,4
Ø – Diesel consumption	*l/100km*	*15,9*	*20,2*

Fig. 4-1: Average energy demand of diesel and electric bus

These measured values are used to calculate the energy costs and the overall CO_2 emissions. As electric vehicles are running without local emissions a well-to-wheel analysis of the CO_2 emissions is made for different sources of electric energy and fossil fuels. Next to that the energy costs are compared for different price scenarios for diesel fuel and electric energy. As the prices for electric energy strongly depend on the annual energy consumption and differ within the countries of the European Union, the following three price scenarios for one kWh have been assumed, which are based on [6] and [7]:

1. 3,8 cent/kWh: This is the average price for electric energy at the EEX energy stock exchange in the year 2012.

2. 11,8 cent/kWh: This is the average price for electricity for industrial consumers with an annual consumption between 500 and 2,000 MWh in the 17 countries of the Euro area.
3. 40 cent/kWh: In this case the energy costs would be very high. Today there is no country in the EU with such high energy costs, so this would be just a possible price for a future scenario with very high costs for electricity.

The price for fossil fuels has also a high volatility so that the following three different scenarios are assumed to calculate the annual fuel costs for Diesel:

1. 1 €/l: This would be the price for Diesel in the low cost scenario.
2. 1,50 €/l: This is the medium cost scenario with a diesel price close to the actual average price in the European Union.
3. 2 €/l: This would be the high price scenario for a future with higher prices for fossil fuels. Today there is no country in Europe with such high diesel prices.

The assumed prices have been used to create a bandwidth of annual costs for electric energy and diesel depending on the annual mileage as shown in Fig. 4-2. The maximum costs result from the maximum price scenario in combination with the maximum fuel / energy consumption.

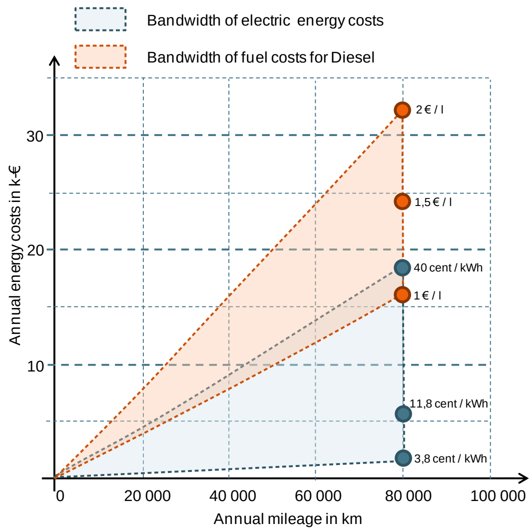


Fig. 4-2: Annual energy costs for different diesel and electricity prices

It is obvious that the annual energy costs for the electric bus are much lower compared to the diesel bus. As busses for public transport systems are used almost every day for the most time of the day they have a higher average annual mileage compared to passenger cars. Thus they also have a different ratio of energy costs compared to the vehicle purchasing costs. This results in a high saving potential for the energy costs of roundabout 10,000 € per year if the bus has an annual mileage of 40,000 km and if the scenario 2 prices are assumed (1,50 €/l and 11,8 cent/kWh).

The second part of the data analysis investigates the overall CO_2 emissions of the test vehicles. The CO_2 emissions from electricity production differ very much depending on the power plant type as Fig. 4-3 shows [8].

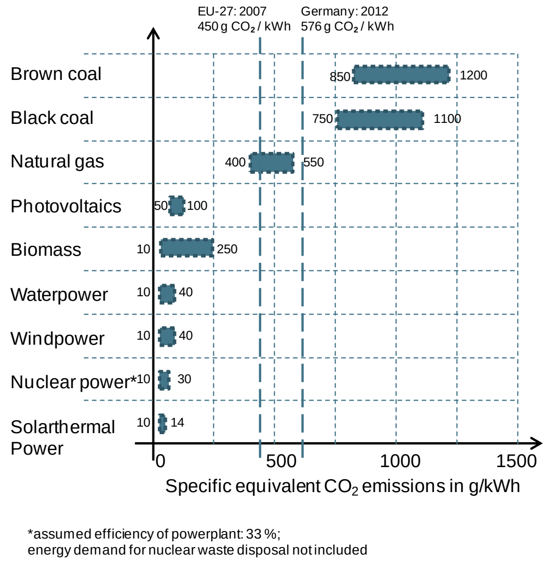


Fig. 4-3: CO_2 emissions from different electric energy sources

Fossil fuels can be conveyed from different sources, next to that bio-fuels are also a possibility to run internal combustion engines. Fig. 4-4 shows the CO_2 emissions for several fuel types [9].

With this data a comparison of the well-to-wheel CO_2 emissions is possible. Once again, the minimal value for each energy source is determined by combining the minimum fuel / energy consumption with the minimum well-to-tank CO_2 emissions for this kind of energy source. So the minimum CO_2 emissions for brown coal are calculated with the emission factor of a high efficiency power plant combined with the lowest energy consumption. The maximum CO_2 emissions are calculated with a low efficiency power plant, which produces more CO_2/kWh and the maximum energy consumption from the test drives.

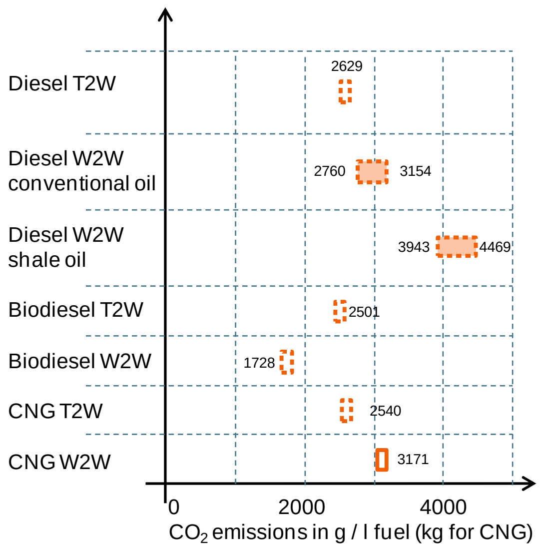


Fig. 4-4: CO_2 emissions from different fuel sources

Fig. 4-5 shows the overall CO_2 emissions from the electric and the diesel bus for different energy sources.

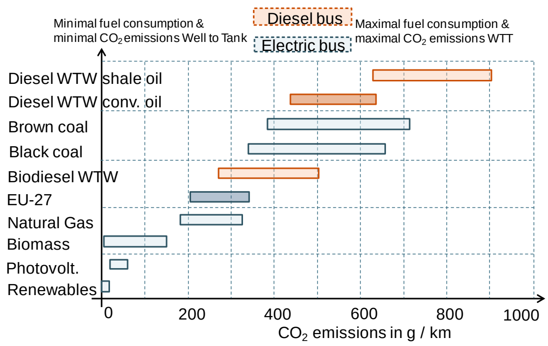


Fig. 4-5: CO_2 emissions in g/km from diesel and electric bus depending on energy source

With the average CO_2 emissions from electricity production in the EU the electric bus has CO_2 emissions between 200 and 350 g/km, while the diesel bus has CO_2 emissions between 440 and 640 g/km if the diesel fuel is made from conventional oil. For unconventional oils like shale oil higher emissions up to 900 g/km are expected as more energy is needed to produce the fuel. It is expected that the emissions from electricity production will decrease in the future as more and more renewable energy power capacity and more efficient power plants are installed and used for electricity production.

5 Summary

The test drives have shown that an electric bus can have the same or even better driving performance compared to a conventional diesel bus. The range that could be achieved with a 45 kWh battery in the test drives was between 60 and 90 km and thus significant lower than the range of the diesel bus. So a high power charge system, which can recharge the battery within 1 hour, is necessary to allow the bus to drive the average daily travel distance of a citybus.

The high efficiency of the electric drive train allows a significant reduction of the energy costs and the overall CO_2 emissions if today's costs for fuel and electricity and today's well-to-tank CO_2 emissions are assumed, although the losses while the high power charging procedure increase the energy consumption of the electric bus by 10 %.

Acknowledgments

The project-team would like to thank the German ministry of economics and technology for funding the project. We would also like to thank the econnect consortium for the given support.

econnect Germany

Gefördert durch:
Bundesministerium für Wirtschaft und Technologie
aufgrund eines Beschlusses des Deutschen Bundestages

References

[1] J.-W. Biermann et. al., *Electric City Bus "Smart Wheels" – a concept for electric mobility in public transportation"*, EVS 26, 2012

[2] U. Reim; B. Reichel; *öffentlicher Personenverkehr mit Bussen und Bahnen*, Statistisches Bundesamt, Fachserie 8, Reihe 3.1, 2008

[3] J. Homann; L. Eckstein et. al.; *Smart Wheels Electric Bus – a concept for electric mobility in public transportation*, 20th Aachen Colloquium, 2011

[4] S. Mathar; L. Eckstein et. al.; *Gesamtfahrzeugintegration von Traktions-batterien: Herausforderungen und Lösungs-ansätze*, Kraftwerk Batterie, Aachen, 2011

[5] CHAdeMO Association; *chademo.com*

[6] Schlussbericht BMU - FKZ 03MAP146, *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global*, DLR, ITT, IWES, IFNE, 2012

[7] K. Weyerstrass, *Künftige Entwicklung der Energiepreise*, IHS, Wien, 2008

[8] H.-J. Wagner, M. Koch; *CO_2 Emissionen der Stromerzeugung*, Lehrstuhl für Energiesysteme und Energiewirtschaft, Ruhr Universität Bochum, 2007

[9] A. Kranke, *CO_2 Ausstoß Güterverkehr*, Verkehrsrundschau 51-52, 2010

Authors

Dipl.-Ing. Felix Töpler is Senior Engineer in the drivetrain department of fka and works on the simulation and testing of alternative drivetrains.

Univ.-Prof. Dr.-Ing. Lutz Eckstein is director of ika.

Dipl.-Ing. Jérôme Homann is working at fka as Manager Design and Prototyping in the drivetrain department.

Dipl.-Ing. Gerrit Geulen is a scientific researcher in the electronics department at ika.