

Econnect Germany—Testing of an Electric Minibus Designed for Public Transportation

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Abstract: Within the econect project (funded by the German Ministry of Economics and Technology), a battery electric passenger bus on the basis of a Mercedes Sprinter City 65 has been tested on public roads. Driving without local emissions, high energy efficiency and reduced energy costs are the main advantages of electric drivetrains. 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 inner-urban routes and have an average driving speed of app. 20 km/h. Next to that 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 electric buses. This paper presents the results of test drives on urban and extra-urban bus routes for the electric bus and a second bus with a conventional diesel engine.

Key words: Battery-electric vehicle, public transportation, energy consumption, emissions.

1. Introduction

The public transport system allows a comprehensive and low cost mobility [1]. 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 an overhead catenary system (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 few charging stops. Fig. 1 shows the average moving velocity of a selected city bus line as well as an overland connection close to the city of Aachen [2]. The average moving velocity is defined as the average speed without standstill phases.

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.

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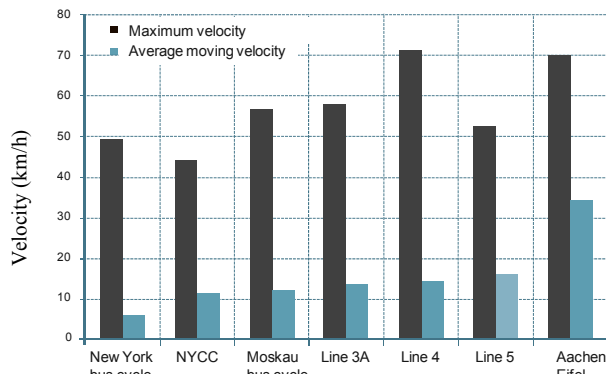


Fig. 1 Maximum and average moving velocity of selected bus cycles.

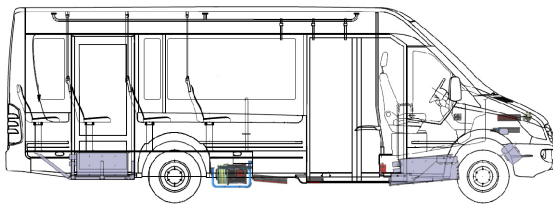


Fig. 2 Prototype of electric propelled bus.

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 axle from the series car.

The characteristics of the test vehicles are shown in Tables 1 and 2.

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 (positive temperature coefficient) element is installed in the battery circuit to heat the battery at low temperatures. Via a heat exchanger the PTC can also be used for heating the interior. Since heating requirements for a bus are much higher than those of a passenger car due to the

Table 1 Vehicle data of conventional diesel bus.

	Series vehicle	Unit
Seats	12 + 1 (Driver)	-
Stance	18	-
L × W × H	7,700 × 1,993 × 2,845	mm
Max. weight	5,650	kg
Motor power	120	kW
Maximum speed	80 (electronically limited)	Km/h
Max. torque (at rpm)	360 (1,200-2,400)	Nm (rpm)
Max. rpm	4,000	rpm
Gearbox	6-speed automatic	-
Motortype	In-line 4-cylinder diesel	-

Table 2 Vehicle data of electric prototype bus.

	Electric prototype	Unit
Seats	12 + 1 (Driver)	-
Stance	10-15	-
L × W × H	7,700 × 1,993 × 2,845	mm
Max. weigh	5,650	kg
Motor power	150 (peak)	kW
Maximum speed	78	Km/h
Max. torque (at rpm)	300 (0-4,500)	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
Motor type	Hybrid-synchronous-motor	-

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, and DC/DC (direct current) 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 drive away at a slope of more than 20% with maximum load or even overload the power train 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 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 [3].

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 Smart Wheels project to increase the usability 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 [4]. While charging the plug is connected directly to the high voltage DC link. By using the quick-charger the time required for recharging the batteries can be reduced to 45 minutes. However, the necessary charging time 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

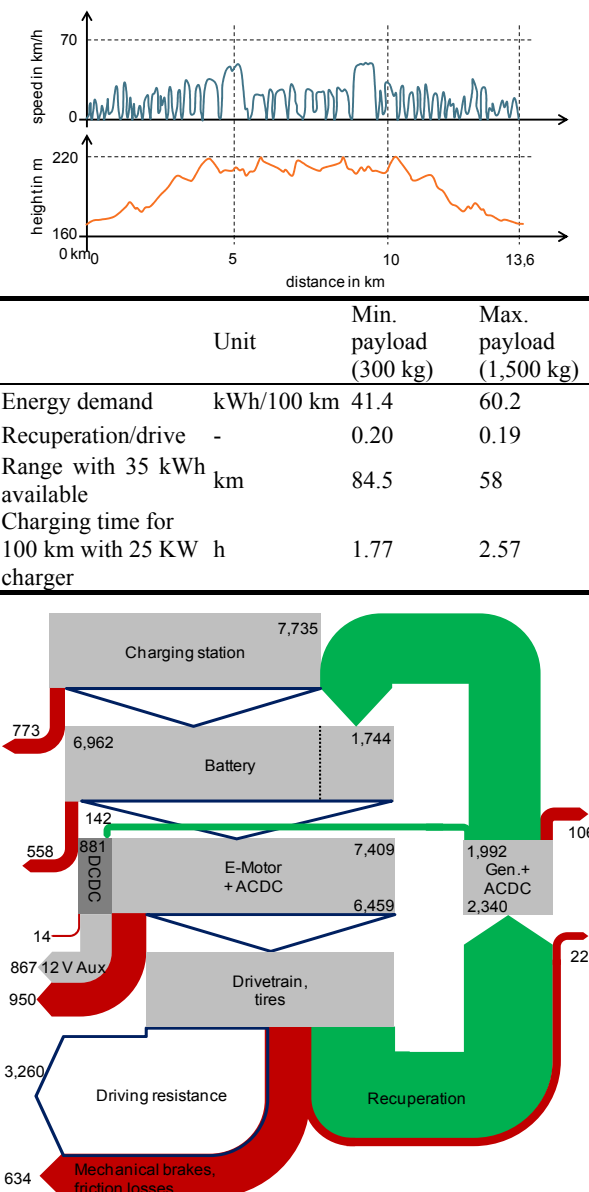
recuperation, so that the slip of the drive wheels is limited while braking. Recuperation can be activated manually by the driver in three stages by actuating the gear selector lever. The brake characteristics correspond to the retarder of the series car. The maximum braking power is 60 kW. There are 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 took place on several city bus lines of Aachen. In addition, an overland bus line from Aachen to the Eifel Mountains 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 (controller area network) 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 m to 300 m and each stop has an average stopping time of 20 seconds to 30 seconds. An example of the collected data is shown in Table 3.

Fig. 3 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

Table 3 Test results in real life traffic (Line 4).


	Unit	Min. payload (300 kg)	Max. payload (1,500 kg)
Energy demand	kWh/100 km	41.4	60.2
Recuperation/drive	-	0.20	0.19
Range with 35 kWh available	km	84.5	58
Charging time for 100 km with 25 KW charger	h	1.77	2.57

charging station while charging the vehicle are not included in these figures.

The losses shown in Fig. 3 are based on the assumption that the efficiencies are 95% for the batteries and 90% for the charging station. In order to recharge the needed energy for balancing the SOC (state of charge) amount to 7,735 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 have 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 Table 4.

These measured values are used to calculate the energy costs and the overall CO₂ emissions. As electric vehicles are running without local emissions a well-to-wheel analysis of the CO₂ 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

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

the Table 3 represent the energy flow in Wh for a distance of 12.5 km. The upper numbers in the “E-Motor + AC/DC” (alternating current) and “Generator + AC/DC” block are for the DC side of the converter and the lower numbers shows the energy given to and taken from the electric machine.

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

Table 4 Average energy demand of diesel and electric bus.

	Unit	With minimal payload ø values	With maximal payload ø values	ø
Ø-energy consumption battery	at kWh/100 km	41.6	54.6	
Ø-energy consumption at grid	kWh/100 km	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/100 km	15.9	20.2	

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 have been assumed, which are based on [5, 6]:

(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 MWh 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. The maximum costs result from the maximum price scenario in combination with the maximum fuel/energy consumption.

It is obvious that the annual energy costs for the electric bus are much lower compared to the diesel bus. As buses 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

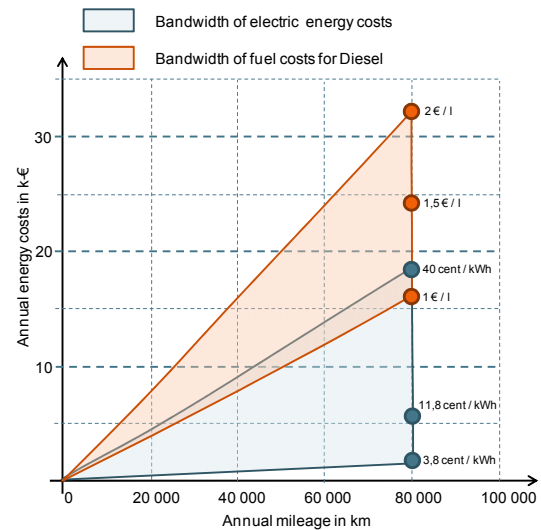


Fig. 4 Annual energy costs for different diesel and electricity prices.

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 CO₂ emissions of the test vehicles. The CO₂ emissions from electricity production differ very much depending on the power plant type as Fig. 5 shows [7].

Fossil fuels can be conveyed from different sources, next to that bio-fuels are also a possibility to run internal combustion engines. Fig. 6 shows the CO₂ emissions for several fuel types [8].

With this data a comparison of the well-to-wheel CO₂ 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 CO₂ emissions for this kind of energy source. So the minimum CO₂ emissions for brown coal are calculated with the emission factor of a high efficiency power plant combined with the lowest energy consumption. The maximum CO₂ emissions are calculated with a low efficiency power plant, which produces more CO₂/kWh and the maximum energy consumption from the test drives.

Fig. 7 shows the overall CO₂ emissions from the electric and the diesel bus for different energy sources.

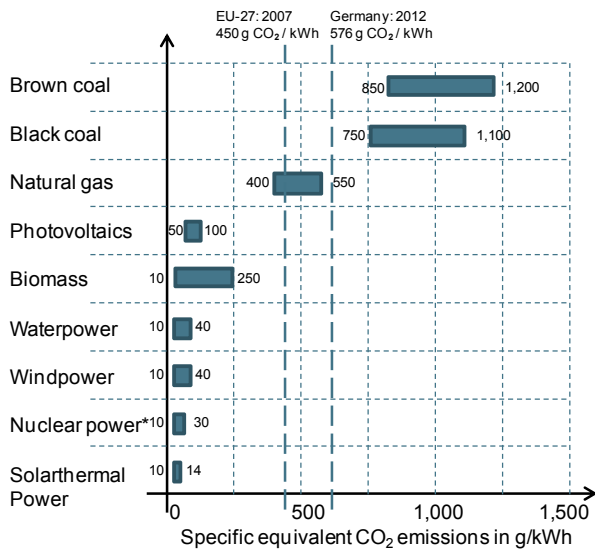


Fig. 5 CO₂ emissions from different electric energy sources.

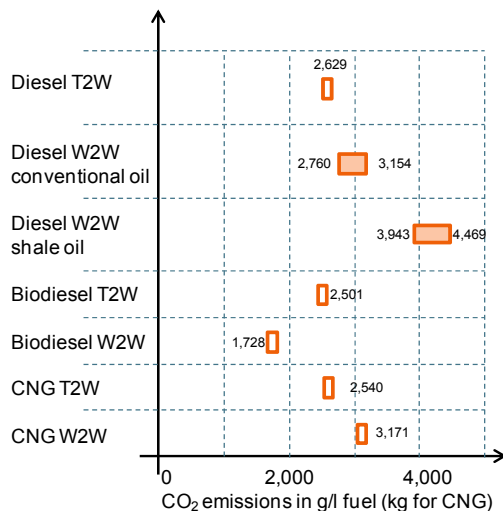


Fig. 6 CO₂ emissions from different fuel sources.

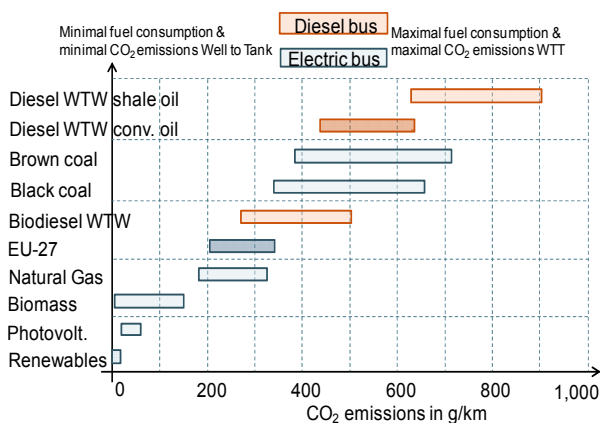


Fig. 7 CO₂ emissions in g/km from diesel and electric bus depending on energy source.

With the average CO₂ emissions from electricity production in the EU the electric bus has CO₂ emissions between 200 g/km and 350 g/km, while the diesel bus has CO₂ emissions between 440 g/km 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. Conclusions

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 km 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 city bus.

The high efficiency of the electric drive train allows a significant reduction of the energy costs and the overall CO₂ emissions if today's costs for fuel and electricity and today's well-to-tank CO₂ emissions are assumed, although the losses from high power charging procedure increase the energy consumption of the electric bus by 10%.

Further work will include a holistic thermal management system to save energy for driving in hot and cold environments and to improve interior comfort for the driver and passengers.

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References

- [1] Reim, U., and Reichel, B. 2008. *Public Transportation with Busses and Trams*, Federal Statistical Office (destatis).
- [2] Homann, J., and Eckstein, L. 2011. "Smart Wheels Electric Bus—A Concept for Electric Mobility in Public Transportation." Presented at 20th Aachen Colloquium, Aachen, Germany.
- [3] Mathar, S., and Eckstein, L. 2011. *Vehicle Integration of Traction Batteries, Challenges and Solutions*, Powerplant Battery, Aachen.
- [4] CHAdeMO Association. *chademo.com*. Accessed January 15, 2014.
- [5] BMU-FKZ 03MAP146, 2012. *Longterm Scenarios and Strategies for the Development of Renewable Energies in Germany under Consideration of the European and Global Development*. Final report.
- [6] Weyerstrass, K. 2008. *Future Development of Energy Prices*. IHS, Vienna.
- [7] Wagner, H. J., and Koch, M. 2007. *CO₂ Emissions from Power Generation*, Bochum University, Institute of Energy Systems and Economics.
- [8] Kranke, A. 2010. *CO₂ Emissions from Freight Haulage*. Traffic review (Verkehrsrundschau).