ENVIRONMENTALLY FRIENDLY BUS TECHNOLOGIES

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As the largest public transport operator in Germany, the Berliner Verkehrsbetriebe (BVG) is obliged to set standards, even in the area of environmental protection. This article provides information on how BVG meets this challenge by:

1. Implementing, testing, and demonstrating fuel cell vehicles;
2. Implementing sulfur-free city diesel buses;
3. Using Continuously Regenerating Trap (CRT) exhaust filters in the entire fleet;
4. Carrying out tests using aquazole fuel for buses;
5. Testing hybrid series busses.

INTRODUCTION

As the largest public transport operator in Germany with approximately 1,400 buses, the BVG is obliged to set standards, even in the area of environmental protection. Until such time as the fuel cell series has been completed and zero emission buses have been introduced, the BVG is using sulfur-free city diesel buses as recommended for implementation by the European Union (EU) from 2005. Furthermore, it has already started installing CRT exhaust filters within its entire fleet. The use of the CRT filter system, consisting of an oxidizing catalytic converter and a smoke filter, ultimately reduces the particle amount to a detectable limit and contributes to the substantial reduction of other pollutants.

Moreover, the BVG is currently carrying out tests using aquazole fuel for buses. In addition to this, a hybrid series bus has been successfully tested over the past three years on a specific route in Berlin. From a technical viewpoint, this entails the use of a lead battery to absorb brake energy input. Under certain operational strategies, interim results have shown that it is possible to achieve a 15% reduction in fuel consumption. This state-of-the-art technology is anticipated for the future incorporation of fuel cell technology within the BVG’s fleet. So, in order to support the development of a pollutant free and particularly quiet bus, the BVG is currently participating in a fuel cell bus project under an EU program.

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This paper is structured as follows:
1. Introduction to the BVG’s activities and aims
2. CRT
3. Aquazole (diesel-water mix)
4. Project "Hybrid Bus"
   • Bus technology
   • Operational experience
   • Fuel consumption
   • Future development
5. Project "Fuel Cell Bus".

ENVIRONMENTAL PROTECTION MEASURES ON THE BUSES OF THE BERLINER VERKEHRSBETRIEBE

A problem that still has to be solved in Berlin, as in all large cities, is the reduction of emissions caused by transport. As Germany’s largest public transport company, the BVG is committed to setting standards for environmental protection while taking economic conditions into consideration.

If the development of average limit values is examined, it is clear to see that a major step has already been taken with the introduction of engines meeting the European-American Unity and Rights Organization (Euro) II norms. Emission values, however, will have to be halved again by the year 2005 (in line with Euro IV). In 2008 (probable introduction of Euro V) only NOx values will have to be lowered significantly. Targeted research and development is both desirable and necessary to achieve the emission limit values set by the European Commission. Please refer to Figure 1.

The implementation of clean vehicles in the urban areas of Berlin is also requested by local authorities to reduce the city’s air pollution hot spots. In the future, these streets could be closed to vehicles not meeting advanced emission standards. Figure 2 shows the streets of Berlin in which the permissible average limits for soot in the air are at present being exceeded.

Thus, the BVG is continuously seeking alternative vehicles and fuels for public transport that are environmentally friendly and at the same time economically viable. Furthermore, they need to be suitable for operation in a highly urbanized environment with dense traffic, small distances between stops, and a high-noise sensitivity, in particular, at night.
FIGURE 1  Development of emission limit values in the EU.
Exceeding yearly permissible soot average limits

FIGURE 2 Map showing where the yearly permissible average limits for soot have been exceeded.
THE BVG’S INVOLVEMENT IN ENVIRONMENTALLY-FRIENDLY MEASURES

Engine Development

Only vehicles meeting Euro I norms have been purchased since December 1992 and from January 1995 only those meeting Euro II standards have been bought. The BVG always buys vehicles with the most modern engines available. In the mid-nineties, the BVG’s bus fleet consisted of more than 1,800 vehicles.

Increased vehicle performance (travel distance) and reduced operating and workshop reserves have led to the BVG running approximately 1,400 buses at present, of which 135 are equipped with engines meeting Euro I norms and 356 with Euro II engines.

As a rule, the BVG purchases new buses according to the state of the art. For example, in 2002 the BVG purchased 25 diesel buses meeting Euro V/EEV norms, which were cofinanced by the German Ministry for the Environment.

Moreover, the BVG has owned a diesel electric hybrid bus since 1997. When in use, this vehicle makes a significant contribution to environmental protection.

Fuel

As a rule, the BVG has only bought sulfur-free fuel (with less than 10 ppm) since the middle of 1999. Starting in March 1999 the BVG also tested a diesel-water mixture (aquazole). The field test ran at a small bus depot with 15 vehicles over a period of three months. It was necessary to separate the tanking process with aquazole having its own tap.

![Figure 3](image-url)  
FIGURE 3 Characteristics of aquazole.
A clear reduction of black smoke was visible when running these buses. An average drop of 40% was calculated in an exhaust gas emission test. Despite water content of 13% in the diesel fuel, an improvement in acceleration was noted positively by the drivers. The increase in fuel consumption measured at this time only came to around 8%. It may not be necessary to use a NO\textsubscript{x} filter system with this type of fuel. The first results of measurements determining this appear to be optimistic.

**Filter Technology**

Starting with the Mann & Hummel particle filter in 1990 and then using the MAN Duplex particle filter in 1991, the BVG has consistently used state-of-the-art filter technology for over ten years.

The disadvantage of the Mann & Hummel system was that the incinerating temperature of 250\textdegree C in the exhaust was not always reached in urban bus operation. The MAN Duplex system proved to be very complicated technically and expensive to maintain. At present, 53 buses are still equipped with this system.

As a consequence, testing of the CRT technology, which came onto the market in 1998, began in the same year. This technology lowers the amount of all soot particles produced when an engine is in operation to the lowest level that can be detected, in addition to reducing carbon monoxide and hydrocarbons emitted. As a result of successful field tests, the BVG had equipped 126 buses with this system by the end of 1999 and 1,000 by the end of 2002.

**What Did the BVG Learn from the CNG Project?**

In 1994 the European Commission sponsored the purchase and operation of ten buses running on compressed natural gas (CNG) within the framework of the THERMIE Program. Four single-deckers of the type 0 405 N, two 0 405 GN-articulated buses manufactured by Mercedes and four MAN NG 232 buses were put into operation in Berlin.

The gas tanks were made of steel as approved at the time. Either five or seven pressurized tanks with either 825 or 1,055 liter-capacity were installed. Refueling was done in mobile filling stations using a tank with a capacity of 45 Nm\textsuperscript{3}/h, which was only approved by the BVG in this field test.

**Results in Brief**

Experience has shown that consumption data has to be looked at critically. Depending on whether a bus is running on a line with long distances between stops or whether it is often caught in traffic buildups, such as, for example Line
119 on one of Berlin’s main roads the Kurfurstendamm, extreme differences in consumption can be measured.

The operating costs totaled approximately 20% more than those of diesel buses. This was essentially caused by the higher purchase costs of the vehicles as well as the higher refueling costs. Maintenance costs were also expensive, as spark plugs had to be changed about every 15,000 km.

The tank range of the vehicles, which amounted to between 220 and 250 km, was much too low, meaning that an increased tank capacity had to be devised taking into consideration the weight problem of locating the tank on the roof. The time needed for refueling was too long as a result of the nature of the project. The BVG’s operating conditions demand fast refueling and thus considerable costs for the construction of the necessary filling stations would have ensued.

**Reasons for Using the CRT Technology**

Testing of CRT filters began in 1998 when it became clear that in the medium term CNG buses could not be operated in an environmentally friendly way in Berlin. Fifteen buses were equipped with these filters to investigate the suitability of the technology in a field test under the special operating conditions in Berlin.

The user friendliness of the technology in workshops was tested along with the amount of cleaning of exhaust fumes undertaken in Berlin’s slow-moving traffic. It was important to determine whether the required operating temperature of the filters was reached in order to guarantee the continuous regeneration process. For the operation of the filters the temperature of the exhaust gas must be higher than 200°C. Only under these conditions is NO₂ produced in a sufficient amount (NO₂ is needed for the continuous transformation of soot into CO₂). It is clear that the typical speed of a bus in Berlin is fast enough to meet the limit value. Excessive oil consumption can lead to the filters being blocked with oil ash due to the characteristics of this particular system. This also happens when the exhaust gas temperature is too low, if the soot particles that have not been burnt enough stick to the filter. If this happens, for example, in a faulty engine, blockages can occur relatively quickly within 14 days.

Testing the filters by measuring the pressure of the exhaust gases is obligatory every three months as stated in the legislation on vehicle testing. A filter that is slowly being blocked can thus be detected in good time. Test results: of the 15 buses equipped with the filters in June 1998, the filters from four vehicles had to be removed and then cleaned. The four buses affected were vehicles dating from 1992 with engines meeting Euro 0 norms. The filters had been in operation for approximately 60,000 km. An operational advantage of using this type of filter is
that the conventional silencer can simply be exchanged in all the BVG’s workshops. Removing and installing a filter takes an estimated three hours.

The BVG logically decided to equip all its buses with CRT filters, as previously mentioned. Although the cleaning of filters occurs very rarely, cleaning is occasionally necessary in a fleet the size of the BVG’s (particularly as some of the buses with Euro 0 specifications are over 17 years old). A filter-cleaning device was thus purchased, too.

**Hybrid Technology**

Hybrid vehicles create a new technical approach to bus operation.

Conventional drives, such as the so-called Otto engine principle or the diesel engine, are only efficient under certain operating conditions. In real vehicle operation, however, the whole range of combustion engine operation is used so that the engine is forced to run at poor efficiency when only low performance is required.

In hybrid-drive vehicles it is possible to influence the energy balance and emission level of the vehicles positively, through a suitable combination of different drive components. Other advantages of this technology are the reduction of vehicle noise and vibrations and the avoidance of mechanical coupling between the combustion engine and the drive gear, whereby more scope is available to design passenger space depending on the energy storage devices used. Certain urban areas can thus be served free of emissions. To test this type of drive, the BVG
has operated a hybrid bus since the start of 1998. The bus runs on a different line each day to put its suitability for practical bus services to the test.

Vehicle Technology
The 12-meter long hybrid bus manufactured by Mercedes Benz with intermediate frequency wheel hub-drive represented the realization of the concept of a serial hybrid drive system. Serial hybrid drives are characterized by complete mechanical decoupling between the combustion engine and the electric motor. The components of the combustion engine, generator and electric motor form a series connection whereby the engine and the generator, the electrical motor and the drive gear are each coupled mechanically. Driving the wheels is therefore achieved exclusively by electric motors that are positioned close to them. There is, in addition, a battery, which allows brake energy to be recovered (recuperation) and allows the vehicle to run "free of emissions" over short distances.

Technical Data:
- Vehicle type: O 405 N 2
- Engine: OM 447 hIA, Euro 2
- Synchronous generator: Continuous output 145 kW, max. 220 kW
- 2 hub drive motors: Continuous output 50 kW each, max. 75 kW
- Batteries: 51 MAXXIMA high-currency lead batteries 50 Ah
Voltage rating: 612 V
Passengers: 31 seats, 55 passengers standing

Vehicle Operation and Results of Measurements

The bus is running on Route 128 to Tegel Airport. The length of the line is around 8 km. The bus only runs on its battery thereby producing no emissions in the vicinity of the airport (approximately 1.2 km).

The Technischen Fachhochschule Berlin (TFH) (Technical College Berlin) and the Department of Internal Combustion Engines at the Technischen Universität Berlin (Technical University of Berlin) have supported the comprehensive measurements of the vehicle under operating conditions.

Values such as the weight of the bus, the speed cycle, the profile of the bus line, and road resistance were recorded indirectly via instrument readings in the electrical circuits. The results of the conditions measured formed the basis for the creation of a simulation model to calculate different modes of operation when driving the bus.

The most important components for the quality of operation of the hybrid drive are its management, i.e., the division and the regulation of the electric power between the combustion/generator unit, the battery and the hub drive motors in accordance with the desired driving capacity. There are two regulatory systems in our model, which can be considered independently of each other. The
The characteristic curve regulator is responsible for the adjustment of the load at the generator as well as for the coordination of the amount injected into the combustion engine. The goal of this regulator is to reproduce the optimal effectiveness of the trajectory with low scattering. This minimizes the consumption of fuel demanded at a particular capacity.

The so-called capacity/power split regulator manages the capacity distribution between the battery and the generator to make the drive capacity available. This device decides when and with what capacity the battery is charged or discharged.

In order to make the ways in which this drive works more transparent, the following three operating strategies were examined more closely:

1. **Conventional Operation**

In this case, the bus is run purely on diesel and electricity. There is no regulated, intermediate saving of energy from the generator in the battery. All of the braking energy produced has to be absorbed via the braking resistors. If the battery charge drops as a result of zero emission, battery-driven operation and the load voltage of the battery falls under the intermediate circuit voltage. The battery will then be charged in an unregulated manner because of the difference in voltage in the intermediate circuit after the combustion engine is switched on again. The operating range of the combustion engine is only limited by the maximum

**FIGURE 7** Driving cycle for Route 128.
capacity depending on the engine speed of the generator to which it is connected. The operation of the engine in inefficient ranges cannot be avoided by using a specific regulatory strategy.

2. Trajectory Operation

Trajectory operation is an operational strategy in which the combustion engine is always running except for in zero emission phases. Unlike in conventional operation, the combustion engine works according to the characteristic curve of the optimal energy consumption in a limited performance area. The maximum capacity of the generator has been limited to 100 kW, as the combustion engine runs most efficiently at this capacity. When accelerating and running in conditions in which the bus has to operate at the maximum possible drive capacity, the battery works as a booster. A consistent battery balance is achieved through recovering brake energy or additional, regulated battery charging via the generator in stationary operating phases. This leads to an increased efficiency of the combustion engine, in particular, in operating ranges that require low driving capacity.

3. ON/OFF Operation

An intermittent combustion process, whereby the engine is also run on its most optimally efficient characteristic curve, characterizes ON/OFF operation. The combustion engine is preferably switched off in operating phases in which no or little drive capacity is needed. An essential index of ON/OFF operation is the lowest limit of capacity required in which the change from pure battery operation to electrical operation and vice versa can take place. The selection of the lowest limit of capacity cannot be made arbitrarily. This value depends first and foremost on the driving cycle of the vehicle.

Apart from the energy recovered from braking, only ranges of capacity that lie above the lowest limit of capacity are available to charge the battery. This range is further limited, because in high capacity ranges, in which the combustion engine works efficiently anyway, additional charging of the battery is senseless.

In comparison, the operating strategies that incorporate energy management show a clear improvement in total efficiency than does conventional operation, which is partly caused by the improvement in the efficiency of the combustion engine (characteristic curve operation). It is, however, the recovered brake energy that creates the main improvement. When the lead battery is used, this accounts for around 10% of the total brake energy created in the cycle. A driving cycle with a very high amount of braking is understandably necessary for a high saving potential. This is always the case in buses operating in inner cities. The serial hybrid bus can be used to its advantage here, as only it allows a high electrical capacity to be delayed, because of its generator driven motor located near the wheels.
ON/OFF operation has the highest potential for fuel savings. However, the realization of this operating strategy is more costly than, for example, trajectory operation as regards driving, due to the fact that the combustion engine is always in use in trajectory operation.

To summarize, the results show that there is a large potential for the development of fuel savings reducing exhaust fumes and lowering operating costs for serial hybrid operation under certain conditions (urban bus lines).

Using means of energy storage that are more powerful than lead batteries (for example, metal hybrid batteries, supercondensators, or electric flywheel systems) can achieve even more efficient performance.

The use of a storage system for recovered energy will still be sensible for the future use of fuel cells, which will replace combustion engines and generators.

To actively support the further development of a zero emission, particularly quiet bus, the BVG is participating in a fuel cell bus project funded by the EU. The bus will be fueled by liquid hydrogen and will be equipped with a highly efficient energy storage device.

The experience gained from the hybrid bus project will therefore also be applied in future drive concepts for buses in order to save fuel.
Fuel Cell Bus Project

The bus is a MAN N L223 low-floor bus that is powered by a fuel cell system instead of a diesel engine. The hydrogen tank system consists of thermo-insulated bottles with a capacity of 600 liters LH₂. The hydrogen is stored at a temperature of −253°C. The tank, the shutoff and the safety devices are situated on the roof of the bus. The company Linde, a subcontractor of MAN, is responsible for the installation of the hydrogen refueling system from the filler neck to the engine.

The fuel cell to be implemented is produced by the Italian company, NUVERA. The French company, Air LIQUIDE DTA, will carry out the system integration.

The fuel cell, consisting of 3 stacks at 40 kW, is a drive module with an integrated net capacity of 120 kW_max. After completion, the drive module will be delivered to MAN and installed onboard the bus.

The drive module is supplied with hydrogen, according to the required flow, temperature, and pressure and supplies nonconverted electricity, the specification of which depends on the configuration of the fuel cell. The energy for the compressor and other auxiliary devices of the drive module will be provided under steady conditions controlled locally and electronically.

Where optimal storage capacity is concerned, as with other gases, it is necessary for hydrogen to be in a liquid form. When comparing the systems, liquid hydrogen storage systems are more efficient as far as volume and weight are concerned.

In order to obtain the storage capacity of liquid hydrogen vehicle tanks in the quantity specified here, more effort is required, as the essential demands on such tanks, namely an optimal use of space, minimal weight, and simultaneously highest insulation quality are, in principal, contradictory.

The possible heat convection mechanisms, circuit, convection, and radiation will be shut off most effectively in a cryotank by the so-called vacuum super insulation. The cold inner tank is surrounded by a vacuum blanket, in which numerous individually insulated radiation sheets can be found.

The bus can be refueled with hydrogen at a stationary filling station that has been constructed at an inner-city bus depot especially for this project. The refueling station will have a 12,000-liter cryotank and the accompanying tap and safety devices.

The LH₂ filling equipment will be installed in a container on a concrete base. The filling connection points are clearly marked as safety areas with a radius of 5 m to be maintained. Within these safety areas no inflammable sources, no additional installations, and no traffic or unauthorized personnel are permitted. The installations must be protected against unintentional knocks.
The project will demonstrate the constructed fuel cell bus in three inner-urban situations in Berlin, Copenhagen, and Lisbon. Initially, the bus will be tested in Berlin on the route between Berlin Tegel Airport and the train and underground station, Berlin Zoologischer Garten (Line 109).

Further test runs will be carried out in Copenhagen by HT and by CARRIS in Lisbon. Of particular interest will be how geographic (hilly/flat) and climatic factors can influence the operation of the fuel cell bus. Following this, the bus will be brought back to Berlin.

The use of a highly dynamic energy storage device will increase the efficiency of the fuel cell system. This will result in the braking energy, produced during the operation of city buses, being stored and used again during acceleration.

Depending on the particular characteristics of the driving profile, fuel savings of up to 15% are expected. It is planned to use supercondensators as energy storage devices.

Eight modules with a total capacity of around 10 farads will be tested in the fuel cell bus.

The use of liquid hydrogen at –253°C for a super conductor mechanism will be investigated as a further energy storage option.
In addition, to enable the greatest possible loss-free storage of energy, the use of a flywheel energy storage unit, through the nonfrictional storage of a rotating mass, could be investigated.

The loss-free, self-stabilizing storage of the rotating parts is possible through a high-temperature superconductor. The principal effect of this type of storage is
Figures 11 and 12 show components of environmentally friendly bus technologies. Figure 11 illustrates a supercap module with specifications:

- **Supercap syste**
  - 8 supercap modules
  - Voltage: 640 V
  - Max. current: 400 A
  - Energy content: 0.4 kWh
  - System weight: 400 kg

- **Supercap module**
  - 36 supercapacitors
  - Each capacitor: 2.3 V, 2700 F

Figure 12 depicts a storage device with high-temperature superconductor.
to fix a magnetic flow within the properties of the superconductor materials. If it comes into contact with a permanent magnet with a symmetrical rotational inhomogeneous field, then a stabilizing reserve power is registered in all directions.

This technology makes it possible to fuse the rotor and storage unit of a permanent magnetic drive with one another. This renders maintenance mechanics unnecessary. The storage unit runs on a contact-free and friction-free basis.

**Project Partners**

The project is financed using the resources of the organizations and companies participating in the project, as well as by funds from the THERMIE and Energy Programs of the European Commission, Directorate-General Energy and Transport. Additional costs, arising as a result of introducing the fuel cell technology, amount to around 10 million euros.

The coordinator of this European Community project is the Berliner Senatsverwaltung fur Wirtschaft und Betriebe.