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City buses with alternative power trains under realistic driving conditions

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Summary
City buses with hybrid and battery electric power trains as well as conventional reference vehicles have been examined using a standardized methodology, mainly focusing on exhaust and noise emissions, overall energy efficiency and operational availability. A combination of realistic test drives on bus lanes, test track runs, long term data acquisition and simulation has been utilized to conduct a complete assessment of the technology. First results indicate an improvement over conventional city buses in every technical area.

Keywords: emissions, noise; energy consumption, HEV, public transport

1 Introduction

City buses operate under several restraints: Apart from the primary task of moving passengers under adequate conditions to their desired destinations, economical and ecological demands are tasking both the operational environment as well as the vehicle technology. Hybridized power train concepts promise a reduction of exhaust and noise emissions along with a reduction of fuel consumption.
Hybrid city buses are in line operation in the German Rhine-Ruhr area since 2009. The Verkehrsverbund Rhein-Ruhr, the association of local carriers, funded the acquisition of hybrid city buses. Those vehicles have been incorporated in the daily schedule at local bus carriers. In order to quantify the benefit of hybrid propulsion under real world driving conditions, accompanying research projects have been funded by the Federal Ministry for Transport and Digital Infrastructure. This publication aims to highlight the methodology and results of the latest assessment project.

2 Project goals

For a technical evaluation of the city buses with hybrid power train concepts, energy consumption, exhaust and noise emissions have to be considered. The following main project goals have been defined:

- Dedicated measurement of fuel consumption, gaseous exhaust and noise emissions
- Analysis of main auxiliary systems
- Simulation of power train concepts under constant environmental conditions
- Observation of differences in vehicle behavior based on weather conditions
- Determination of operational availability in comparison to conventional vehicles
- Determination of fuel consumption as a function of route profiles and topography.
- Impact of start-stop operation on the efficiency of exhaust aftertreatment systems

3 Methodology

In order to assess the performance of those novel drive trains under realistic driving conditions, a combination of long term data acquisition, test runs on actual bus lines and track tests has been chosen. Additionally, simulation models are used to extrapolate measurement results and conduct further technological case studies.

Test runs on 8 different bus lanes in 4 different cities in the Rhein-Ruhr area have been conducted to measure exhaust emissions, fuel consumption and energy distribution. The test vehicles have been equipped with portable emission measurement systems, fuel flow meters and electrical power measurement. In addition to those values, torque and rotational speed measurement have been used to determine mechanical power. Vehicle GPS positions and auxiliary information have also been recorded, so that an analysis of the complete vehicle behavior is possible. Average speed and topographic profiles of the bus lanes have specifically been chosen to be diverse.
Noise emission measurements have been taken on the IKA test track. In order to evaluate the noise behavior in the passenger compartment specific acoustic measurement equipment was used. In addition, tri-axial structure-borne noise sensors were used at comfort relevant positions in order to detect the vibration behavior. Main focus of the exterior noise investigations are departure maneuvers from bus stops. Corresponding to the interior noise measurements a standardized setup and different reproducible driving maneuvers have been defined.
During the entire project duration, the bus operators tracked fuel consumption and mileage on a daily basis for both hybrid and conventional reference vehicles. Incidents and breakdowns regarding whole vehicles or single components are recorded. This database allows a first assessment of component and vehicle reliability as well as fuel efficiency over a longer period of time.
Detailed simulation models of the vehicles have been created and validated using the measurement data. Based on the detailed dedicated fuel and power measurement of both power train and auxiliaries, the longitudinal models can be verified. Time based values of actual gear, transient torque for electric machines and engines as well as fuel flow and power readings have been utilized for the validation. All considered vehicle concepts can be compared with regards to energy consumption. In comparison to test runs, this simulation based analysis is free from undeterminable influences like weather, driver behavior and surrounding traffic.

3.1 Vehicles

The tested vehicles cover a wide range of available models. Both 12 and 18 meter buses are considered. Conventional and hybrid models with EU6 certification have been added to the test fleet.

Table 1: Test vehicles

	Vehicle type	**12m**	**18m**	**Euro V/EEV**	**Euro VI**
Hybrid	Volvo 7700 Hybrid	✓		✓	
	MAN Lion's City Hybrid A37	✓		✓	
	Mercedes Benz Citaro G O530 Bluetec Hybrid		✓	✓	
	Hess SwissHybrid BGH-N2C		✓	✓	
	Volvo 7900 Hybrid	✓			✓
Alternative	Solaris Urbino 12 electric	✓			
	VDL Citea LLE - 120	✓		✓	
Conv.	Mercedes Benz Citaro Euro VI 12m		✓		✓
	Mercedes Benz Citaro Euro VI 18m	✓			✓
	Solaris Urbino 12	✓		✓	
	MAN Lion's City A37	✓		✓	
	Mercedes Benz Citaro G O530		✓	✓	

In addition to the hybrid vehicles, conventional reference buses have been tested to provide data sets for comparison.

3.2 Measurement: Exhaust emissions and energy consumption

Exhaust emissions of diesel powered vehicles contain gases that are both harmful to human health and negatively impact the composition of the atmosphere, furthering the green house effect. Therefore, strict regulation is being enforced on multiple levels: Vehicle homologation for city buses follows the EU5 EEV and EU6 rule set, municipalities and cities set up local environmental zones and additionally implement air

pollution control plans. Failure to comply with European air pollution limits – especially regarding particle and NOx emissions – can result in fines for the municipalities. Due to the major role of public transport in urban areas, new power train technologies come under special scrutiny, spawning assessment projects like EFBEL. An additional aspect is the reduction of fuel consumption through modern drive trains, which directly reduces emissions, cost of operation and reliance on fossil fuels. It is imperative to define a set of rules and measurement conditions in order to create comparable results in a large measurement campaign with a high amount of vehicles. A preliminary study has been conducted in which vehicle speed and GPS profiles of several bus lanes in selected cities have been recorded. Those recordings have been used to classify the main characteristics, average speed and hilliness of the area. In order to reduce the extent of the measurement campaign to accommodate budget constraints, a subset of cities has been chosen.
The bus lanes in the highlighted cities represent almost the entire range of possible operational characteristics. Test runs included multiple runs on one day on those lanes with stops at every bus stop.
All vehicles have been loaded with additional steel weights up to 1/3 of their maximum permissible weight. This represents an average capacity utilization of the buses that is backed up by operational experience. During testing, no passengers were on board due to the amount of measurement equipment necessary for the gaseous emission analysis. The tested vehicles have only partly been equipped with air conditioning systems so the decision was made to switch all AC units and heating systems off to ensure equal measurement conditions. All test runs have been conducted in a time frame from late spring to early autumn to avoid extreme external temperatures. Whenever possible, the same professional drivers have operated the vehicles. To eliminate effects of the power consumption of the measurement equipment on the fuel consumption, a separate power supply is used.

Table 2 Testing areas

Topography/ speed range	**SORT 1**	**SORT 2**	**SORT 3**
Topo 1	**Krefeld** (2 lines)	**Düsseldorf** / Essen	**Düsseldorf**
Topo 2		Essen	
Topo 3	**Hagen**	**Dortmund** / Bochum / Wuppertal	
Topo 4		Ennepetal / **Hagen**	**Dortmund**

For the measurement of exhaust emissions (CO_2, CO, HC, NO_x, NO_2, NO) Portable Emission Measurement System (PEMS) equipment according to European regulations is used (see Figure 1). Beside the emission data additional GPS data, speed and torque of the drive shaft (if possible, depending on the power train concept) as well as different engine parameters are recorded.

Figure 1: Analyzer systems inside and measurement pipes outside the vehicle

In addition to the harmful gaseous emission, both fuel flow and electric power levels have been determined. A temperature compensated fuel flow meter has been used to measure the diesel flow with high accuracy. Electric power values have been taken at different points in the electric system of the buses, depending on the power train layout. Separate data has been recorded for electric motors, generators, energy storage systems (i.e. batteries and supercapacitors) and electric auxiliaries. Combining all data makes it possible to create complete energy balances for the tested vehicles under varying load. Also, the main contributing factors to energy consumption and emission behavior can be determined.

3.3 Measurement: Noise emissions

Noise pollution represents one of the major environmental impairment in the residential area and is perceived as more disturbing than air, water or waste pollution according to several studies [1]. In this context, the road traffic has to be considered as the most significant noise source. In order to improve the urban soundscape, noise limit values regarding the type approval test (pass-by noise test) are continuously reduced for road vehicles. However, a significant improvement on the urban noise pollution cannot be determined. Different reasons lead to this effect, e.g. increasing traffic volume and driving speeds in the past decades [2]. With increasing variety of powertrain concepts used for public transportation, a detailed analysis of the noise emissions is required to evaluate the impact on the urban soundscape of each technology. Thus, acoustic measurements are carried out in a wide operating range in order to evaluate the noise emissions in representative driving maneuvers. In parallel to the evaluation of the exterior noise, the interior noise and the vibrations are measured and analyzed, as well. By distributing microphones and accelerometers in the passenger compartment it can be verified if innovative bus concepts can satisfy the increasing expectations regarding driving comfort.

During the legally required type approval test, the noise emissions of buses are typically measured and evaluated for vehicle speeds above 30 km/h [3]. Compared to this, the average speed of urban buses in most city cycles is in-between 5 and 15 km/h [4]. For the evaluation of the NVH (Noise, Vibration, Harshness) behavior of the different bus concepts in statistically more representative test conditions, test series have been conducted with typical driving maneuvers and operating states. Therefore, following maneuvers are considered for the acoustic measurements:

- acceleration with full load and partial load
- deceleration
- constant speed
- idling during standstill

One of the most typical driving maneuvers is the arrival and departure at bus stops with passengers getting off and on the bus. For that reason, variations of this maneuver are considered with different incoming speeds for deceleration and load conditions for acceleration. After the bus finished accelerating to the desired travelling speed, the next important driving condition is characterized by constant vehicle speed and low load. Three representative speeds in the urban area (15 km/h, 30 km/h and 50 km/h) are thus chosen for the test series. Depending on the operating strategy of the tested hybrid buses each maneuver is carried out with purely electric powertrain in zero emission (ZE) mode and in addition with running diesel engine in hybrid electric (HE) mode.

The noise emitted by buses, which are powered by a diesel engine or an electric powertrain is generated by several components. In addition, the body structure of a bus consisting of tubular steel profiles together with panels, the floor structure and additional parts (e.g. glass panes) represents a highly complex, vibro-acoustic system which needs to be taken into account, as well. The following partial sound sources contribute in general to the overall noise of buses:

- Components of the conventional powertrain, including exhaust and intake system
- Components of the electric powertrain, e.g. the electric machines and inverters
- Auxiliary units, e.g. the climate control, battery cooling and pneumatic system
- Tire-/road noise
- Aerodynamic (wind) noise

In order to increase the comparability of the tested vehicles' noise emissions, all measurements are carried out on the ika test track with conditions according to ISO 10844. For the evaluation of the exterior noise, microphones are placed in a distance of 7.50 m to the centre line of the driving lane and 1.20 m height according to the measuring positions of ISO 362-1 [5]. In addition to the microphones, a binaural measuring system (artificial head) is placed at a representative position for a pedestrian standing on a bus station to analyze the bus stop maneuvers in more detail. Figure 2 shows the sensor positions for the exterior noise measurements with a diesel-electric hybrid bus standing in the simulated bus stop.

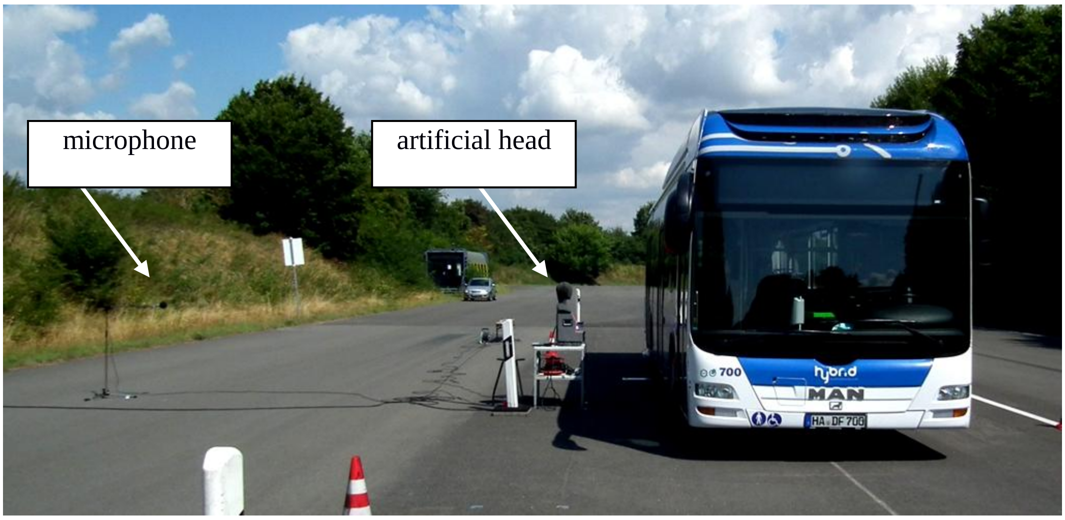

Figure 2: Measuring positions exterior noise

For the measurement of the interior noise and vibrations, accelerometers and microphones are placed on each axis and at relevant positions regarding the driving comfort (grab handles, floor and seats). All microphones are set to a height of 1.50 m and an additional artificial head is placed in the last seating row. With a microphone placed at the driver's position, it is also possible to evaluate the influence of the different bus concepts on the driver's working environment. The sensor positions for the interior NVH measurements are displayed in Figure 3 for an exemplary, articulated bus.

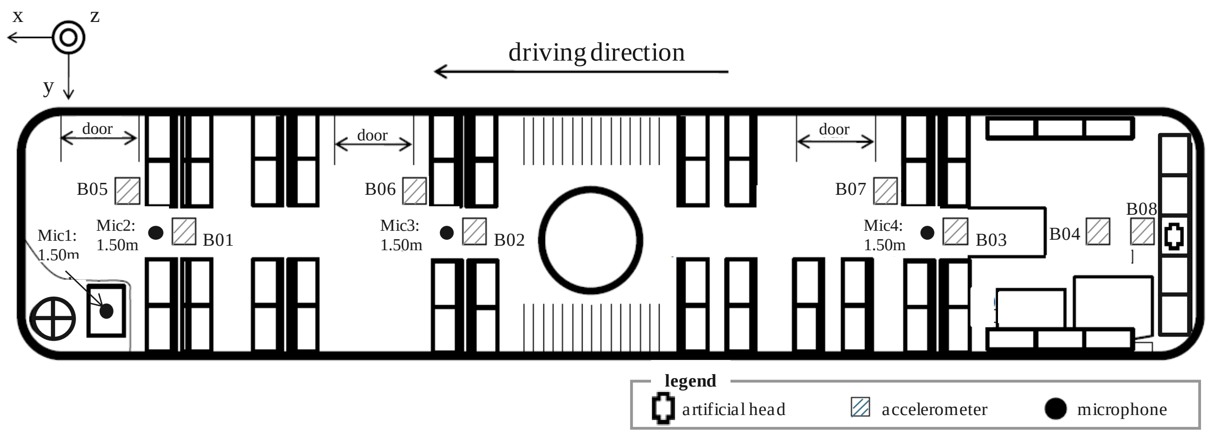

Figure 3: Measuring positions interior noise and vibrations

By installing additional light barrier, telemetry and GPS systems, triggered and time-synchronous measurements for the exterior and interior noise are obtained. In this way, occurring noise phenomena can be correlated between the different measurements.

3.4 Long term data acquisition

While test runs under controlled conditions are important tools to determine the system behavior of vehicles with regards to energy consumption and harmful emissions, long time effects cannot be observed. Especially the overall availability of the vehicles with alternative power trains in comparison to conventional diesel-powered buses can only be determined over a longer observation period. Additionally, fuel consumption and the impact of varying external temperatures requires at least one year of data acquisition. A specified process was set up at different carriers to accumulate fuel consumption per shift, operation hours, breakdown and maintenance hours, breakdown reasons and a variety of additional items.

For a scientifically sound comparison, the test vehicles and their conventionally propelled reference buses have been deployed on the same bus lane.
It is important to note that not all of the vehicles listed in Table 1 are included in the long term data working package. For budgetary reasons, it was only possible to deploy a part of the vehicles in real world service. Also, vehicles have been tested that were not commercially available at the start of the data acquisition.

4 Results

Due to the broad scope of the assessment project and the large amount of vehicles, not all results can be shown in this paper. A subset was chosen to accentuate the benefits of hybrid power train concepts and stricter regulation. Overall, the hybrid city buses show great potential to reduce energy consumption and harmful gaseous emissions as well as noise levels. Between the tested models, major differences have been detected.
The measurements show a spread of -2% to -28% average fuel consumption reduction, depending on model, power train concept, bus lane characteristics, external temperature and bus driver. Nitrogen oxide emissions have been reduced by up to 99% in comparison to the reference vehicles with EU5 EEV certification. Under ideal conditions, noise levels of a hybrid bus in electric mode departing from a bus stop are up to 61% lower than those of a diesel-powered conventional bus. Availability of the hybrid vehicles has been steadily rising over the project duration, showing average value of 78% operation hours in relation to planned operation hours.
More detailed results including a brief discussion of the main points can be found in the next chapters.

4.1 Exhaust emissions and energy consumption

Due to the diversity in power train technology present in the fleet of tested vehicles, a variety of aspects can be focus of the analysis. In this paper, a comparison of 12m buses was chosen to highlight the effects of hybridization and stricter regulation on harmful exhaust gas emissions. In Figure 4, three hybrid and one conventional vehicle are compared to a reference value. This reference is the average value of two buses, both certified with EU5 EEV, but with different exhaust gas aftertreatment systems. Their total share of the existing bus fleet in Germany qualifies this value as a valid basis for comparison. All test areas have been lumped together to showcase the emission behaviour under all possible operational conditions.

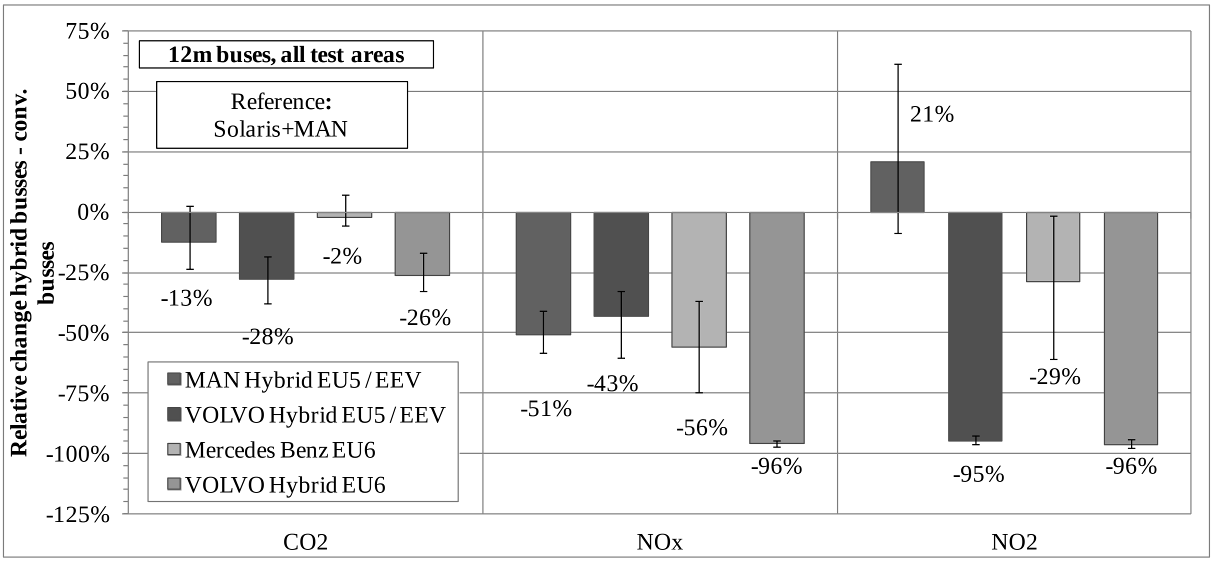

Figure 4: Emission measurement results for 12m buses, all test areas

Three different components of the exhaust gas are shown: CO2, NOx and NO2. Error bars indicate the maximum and minimum data points that occurred during any single test run. Carbon dioxide (CO2) emissions directly convert into fuel consumption and have been identified as a major contributor to global warming via the green house effect. All test vehicles emit less CO2 compared to the reference, ranging from -2% up to -28% reduction. Specific test runs also show an increase in CO2-emission for the serial hybrid vehicle and conventional EU6 bus. Regarding the serial hybrid, this can be attributed to the influence of the speed and height profile on the operational behaviour of the hybrid system. For the conventional vehicle, the additional exhaust gas aftertreatment necessary to comply with the stricter limits of EU6 results in an increase of fuel consumption and thus CO2-emission.The same effect can be observed when comparing the two parallel hybrid vehicles. Both show an impressive reduction of over 25% in a majority of the test areas, but the EU6 vehicle is lagging behind by 2%. This can mainly be attributed to the extended aftertreatment system.

Nitrogen oxides are not immediately toxic to humans, but irritate and damage the respiratory organs. Also, the exhaust emissions are the main cause of sour rain and summer smog and, as a consequence, are heavily regulated. High displacement diesel engines are a main contributor to NOx emissions in urban areas. All vehicles show a dramatic reduction of NOx emissions in comparison to the reference vehicles. While this is to be expected from vehicles with a EU6 certification, with a much tighter threshold, the EU5 EEV hybrid vehicles also demonstrate a significant potential in reduction.

NO2 emissions fluctuate for the displayed subset of vehicles. One outlier, the MAN EU5 hybrid, uses an aftertreatment system with exhaust gas recirculation (EGR) that effectively cuts down overall NOx levels, but produces slightly more NO2 in comparison to the other systems. Total values for NO2 readings are close to the detection limit of the measurement hardware, so small absolute changes induce large relative values. Further analysing the origin of the NOx emissions, a relation between vehicle speed and emission levels is shown in Figure 5. Only one reference vehicle is included.

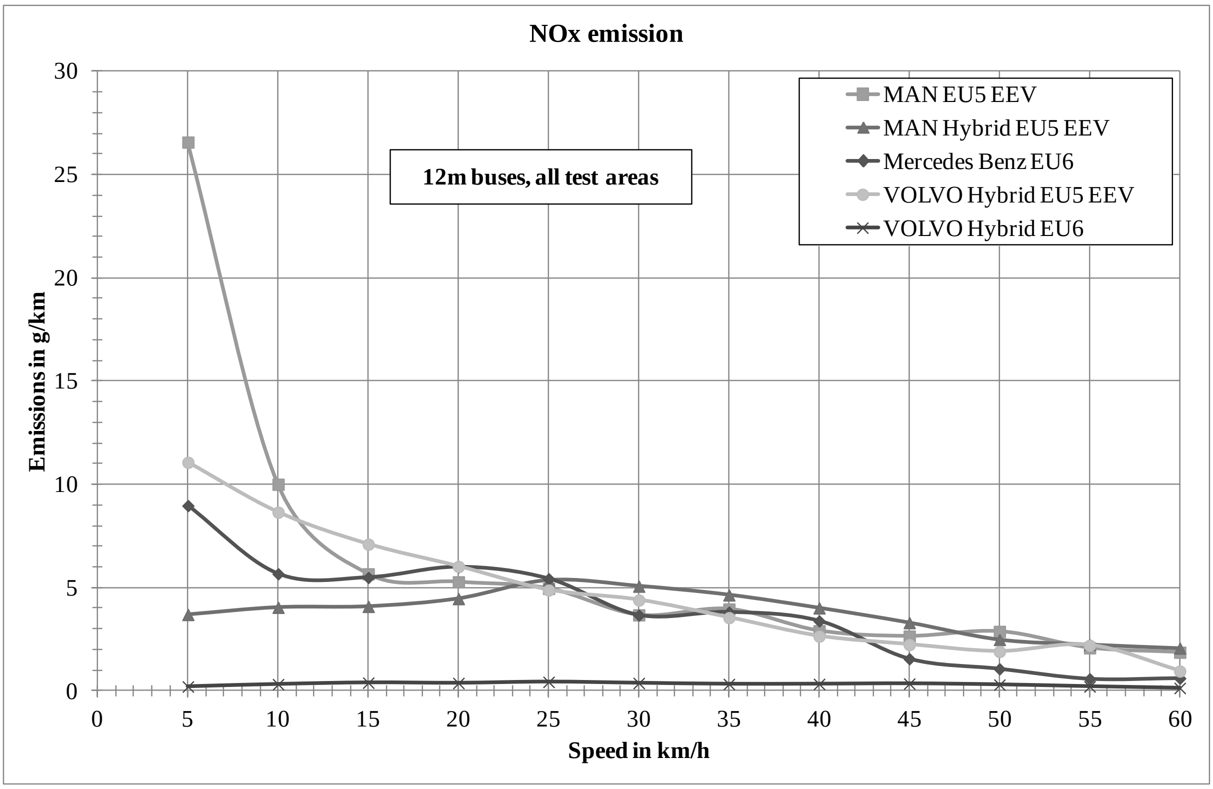

Figure 5: NOx Emissions as a function of vehicle speed, 12m buses, all test areas

For the conventional vehicles, a very clear operational characteristic can be identified in the lower speed regions. There, the relative emissions per distance increase exponentially, since the engines are operating under part load conditions, at low efficiency, and the vehicles are moving very slowly. Hybrid vehicles, on the other hand, can use their start-stop automatic to shut down the engine under those circumstances, negating the majority of emissions at low speeds. Since city buses operate at very low average vehicle speed ranges under urban traffic conditions, this effect is amplified. The results are the pronounced reduction of NOx emissions for hybrid vehicles. The buses with EU6 certification emit very little NOx due to their effective aftertreatment systems.

Overall, the effectiveness of two trends has been proven. The introduction of the EU6 limits for city buses result in a reduction in harmful exhaust gasses such as NOx, albeit at the expense of fuel efficiency. Hybrid buses utilize their start-stop and load changing possibilities to also decrease fuel consumption and NOx emission.

4.2 Noise emissions

In order to analyze the impact of the different bus concepts on urban noise pollution, a detailed analysis of the exterior noise has to be conducted. Therefore, this publication focuses on the results of the exterior noise measurements. A detailed study on the interior NVH measurements and a comparison to subjective results obtained in a passenger survey will be published in the final project report. For the purpose of the exterior noise analysis, the A-weighted sound pressure level curves are calculated for each maneuver and are compared to each other in a first step. By plotting the resulting level curves against the buses' driven distance instead of the measuring time, the quality of the analysis can be further improved. The position of the artificial head (bus stop) is defined as the reference point (0 m) so that the emitted noise can be evaluated in dependency of the relative distance to the bus stop. In Figure 6 the sound pressure level of the pass-by tests with constant speeds is shown for the tested full-electric bus, a diesel-electric hybrid bus and a conventional diesel bus as reference. For the evaluation of these maneuvers, the microphone in a distance of 7.50 m instead of the closer artificial head is used in order to reduce the influence of air turbulences of the passing bus on the measuring result.

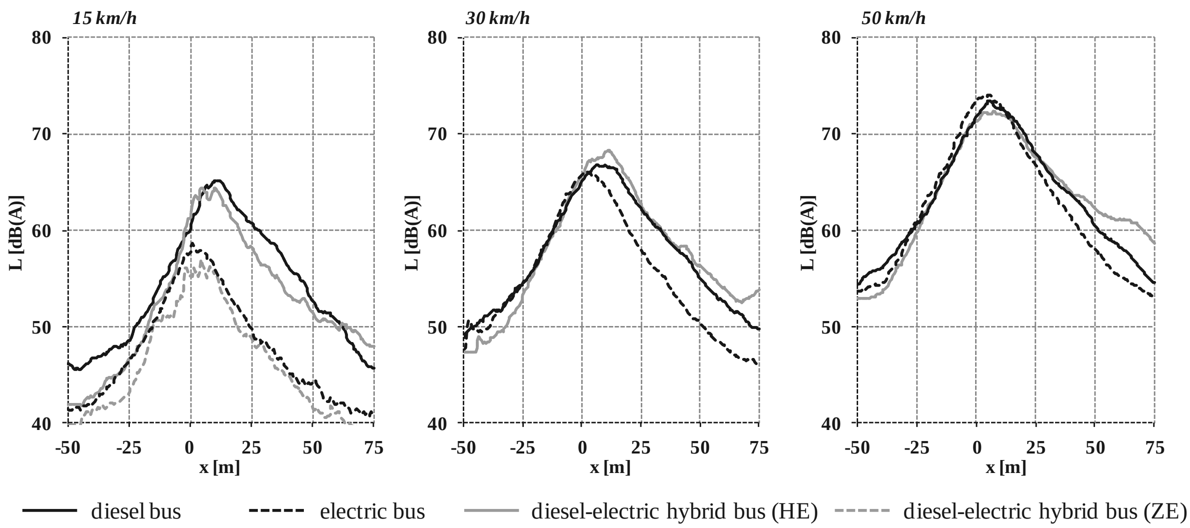

Figure 6: Measured exterior noise for pass-by tests with constant speeds

It can be noticed, that the biggest differences between the tested bus concepts occur at a speed of 15 km/h and are continuously narrowed in the tests with 30 and 50 km/h. This effect is caused by the increasing dominance of tire-/road and wind noise at higher vehicle speeds. For approaching vehicles (negative distance values), the level curves are almost identical and no significant difference between the buses' noise emissions can be noticed. But when the buses drive past the microphone position, the location of the maximum value is shifted in case of the diesel bus and an almost constant offset occurs for the departing buses (positive distance values). This effect is based on the missing diesel engine of the electric bus, which is typically located in the back of urban buses. Thus, electrically operated buses offer highest advantages in reducing the noise emissions when they are operated at low vehicle speeds. This is a very important aspect, considering the average speed of most city cycles is underneath 15 km/h [4]. Comparing the bus departure maneuvers starting from standstill, the differences between the noise emissions measured with the artificial head system are even more distinctive (Figure 7).

In case of the diesel bus and lightweight diesel bus, a significant peak value of more than 80 dB(A) occurs in the moment the diesel engine and exhaust pipes pass the microphone position. Highest values are measured in case of the lightweight bus during full load acceleration. This effect could be caused by two reasons. Either more noise is emitted by the power train or the reduced mass of the lightweight structure leads to less structural damping and therefore increased vibration and noise amplitudes. Operating the diesel-electric hybrid bus with partial load, it is possible to accelerate the hybrid bus without running diesel engine up until a distance of approx. 30 m. In this way, the noise emissions can be reduced in a similar way to the electric bus. Once the diesel engine is running, the emitted noise level is in a similar range compared to the conventional buses without electrical power train. Accelerating the hybrid bus with full load leads to an early activation of the diesel engine but nevertheless, the maximum noise emissions are still underneath the values of the tested diesel buses. The reason for the early activation of the diesel engine lies in the concept of the hybrid bus itself. By storing the recuperated electrical energy in supercapacitors instead of

Li-Ion batteries, electrical charges can be exchanged faster and therefore potentially absorb more energy during fast retardation of the bus. The disadvantage is the limited capacity and thus the diesel engine is switched on early because the stored energy is consumed very fast during full load acceleration. Considering the noise emissions of the electric bus, the full potential of this bus concept can be observed in the bus departure maneuvers. With regard to the maximum sound pressure level a reduction of more than 20 dB can be achieved compared to the lightweight bus. But even in the further progress an average reduction of more than 10 dB can be determined over the entire measuring distance.

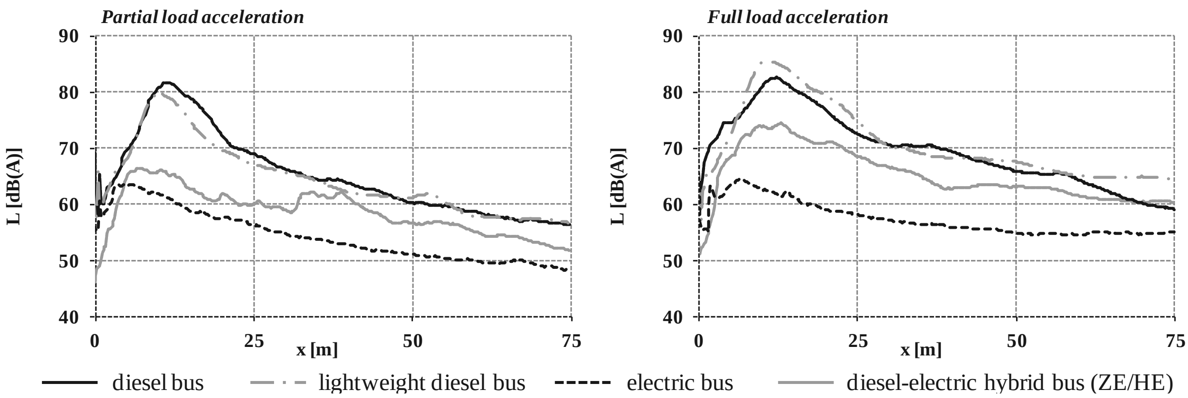

Figure 7: Measured exterior noise for bus departures with partial and full load acceleration

Besides the analysis of the sound pressure level, the calculation of the loudness is used as a psycho-acoustic analysis technique. On one hand, the frequency weighting of this calculation method resembles the characteristics of the human hearing in a better way than the A-weighting function. On the other hand, the calculated values can be interpreted in a linear way and a better comparison to the subjective loudness sensation can be achieved. Doubling the loudness value therefore means that the noise is also perceived twice as loud. In addition to this, the percentile loudness N_5 (the loudness value reached or exceeded in 5 % of the measuring time) is used to calculate a single value for the loudness of each maneuver in order to improve the clarity of the entire test series. Several studies have shown that this is a valid method that correlates highly with the perceived total loudness in case of unsteady noise and can be used to determine the perceived annoyance of such noise phenomena [6], [7]. Table 3 shows the results of all tested buses during bus departure maneuvers. The test results have been ranked by the average value of partial load and full load accelerations and additionally a linear color scale has been introduced to highlight the results from lowest (green) to highest (red) values.

Table 3: Loudness percentile evaluation of the exterior noise measurements

bus type	**bus length**		**energy storage**	**partial load acceleration**		**full load acceleration**
	12 m	18 m		percentile loudness N_5 [sone]		
electric bus	x		Li-Ion batteries	18,6		19,8
diesel-electric hybrid bus	x		fuel tank + supercapacitors	22,8		35,1
diesel-electric hybrid bus		x	fuel tank +Li-Ion batteries	20,9		38,9
diesel-electric hybrid bus	x		fuel tank +Li-Ion batteries	28,7		29,9
diesel-electric hybrid bus	x		fuel tank +Li-Ion batteries	30,8 (HE)	20,1 (ZE)	35,9
diesel-electric hybrid bus		x	fuel tank +Li-Ion batteries	24,6		45,8
diesel bus	x		fuel tank	52,3		51,9
diesel bus	x		fuel tank	52,5		58,7
diesel bus	x		fuel tank	50,9		63,8
lightweight diesel bus	x		fuel tank	49,7		74,1

This overview shows very clearly the advantages of hybrid and electric buses on the noise emissions in the area of bus stops. Subjectively speaking, the electric bus will be perceived around three times quieter than the conventional buses and thus offers the highest potential for reducing urban noise pollution. The prerequisite for this is an increased percentage of electrified buses in the fleet of Municipal Transport Services.

4.3 Long term data

Three different project goals can be addressed with the evaluation of long term data. In addition to the measurement of fuel consumption during the test runs, a real operation value for diesel consumption can be determined. Since the test runs took place on only one day with very specific weather, traffic and road conditions, driver personnel and fixed vehicle weight, only a snapshot of the vehicle characteristics has been recorded. Varying operational parameters result in a fuel consumption behaviour that differs from those singular measurements. Figure 8 shows the accumulated relative fuel consumption values for all vehicles in the long term data programme.

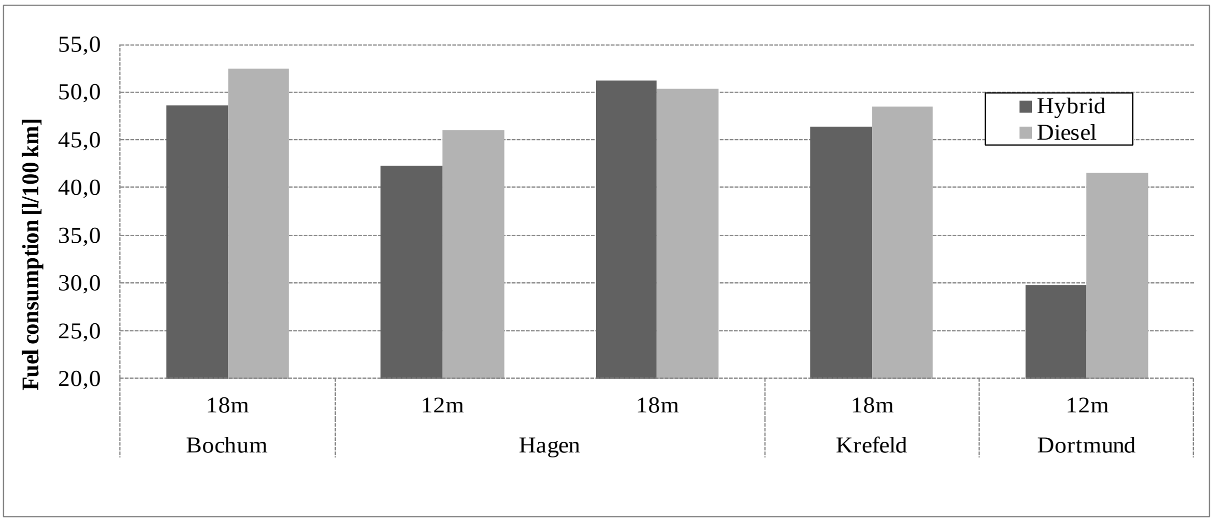

Figure 8: Fuel consumption, long term data

Apart from the 18m bus category that ran in Hagen, all vehicles show a decrease of fuel consumption in comparison to their conventionally propelled diesel counterparts. The 12m bus – a Volvo 7700 Hybrid - in Dortmund shows the most significant reduction. This result is mirrored in the data of the measurement campaign. It is noteworthy that different manufacturers designed vehicles with variations on hybrid power trains, and nearly all show a reduction of fuel consumption. Taking into account that the operational context with average speeds and topography fluctuates wildly, this is a remarkable result.
Hybrid propulsion for city buses is a relatively new technology. Experts rate most of the vehicles at a technology readiness level of 7-8. For carriers, one predominant concern is in the availability of the vehicles. Over the project duration, operation hours, planned hours and maintenance and failure incidents have been logged. Additionally, the cause for maintenance has been noted, so that it is possible to identify hybrid specific failure and breakdowns that are also possible in a conventional vehicle. An overall availability rating based on operation hours per planned operation has been derived, which is displayed in Figure 9.

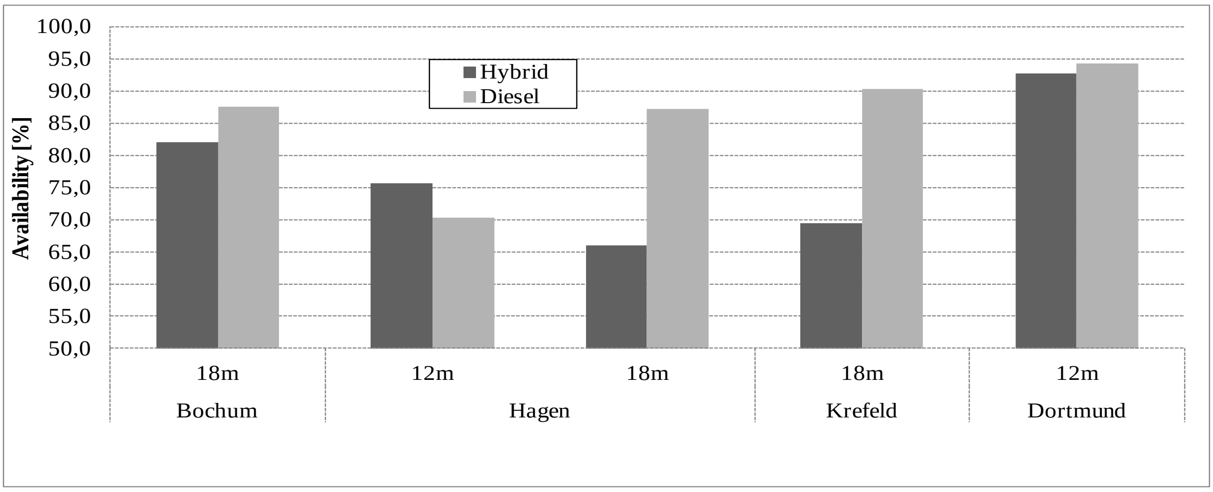

Figure 9: Availability, long term data

For a standard diesel vehicle, availability figures above 90% are industry standard. In this investigation, only a low amount of vehicles have been tracked. One vehicle with technical problems has a greater statistical impact in this case and can skew the results. For the 12m category in Hagen, this is the case, so that the availability of the diesel reference vehicle is abnormally low. As depicted above, the other diesel vehicles feature values above 85%.
Looking at the hybrid vehicles, lower availability figures can be observed across all areas. The vehicles in Bochum and in Dortmund are nearly as usable and reliable as their diesel reference. Availability in Hagen and Krefeld is significantly lower.
Further investigating the failure factors reveals that the hybrid propulsion systems are not the main reason for the reliability of the buses. Figure 10 shows the distribution of operating hours and failure events for all hybrid buses in all test areas.

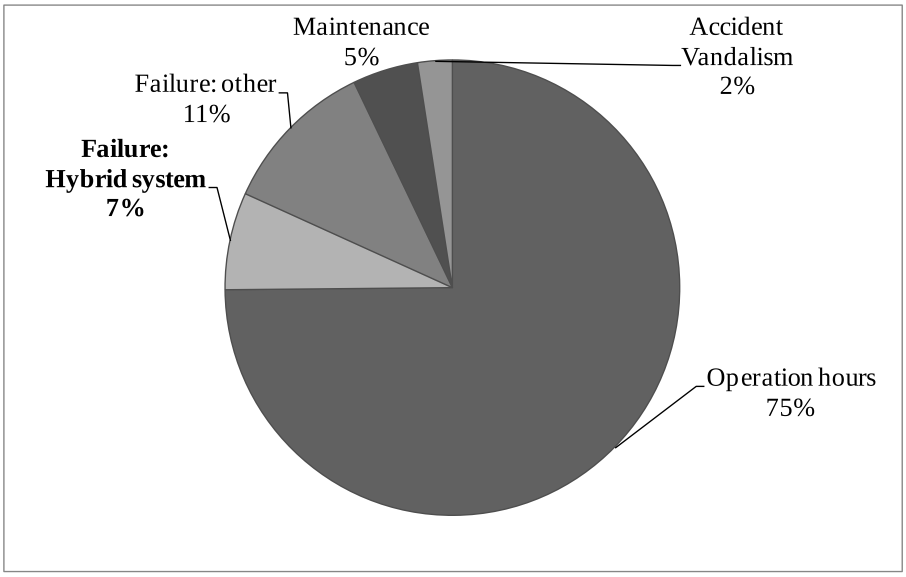

Figure 10: Operating hours, distribution, all hybrid vehicles

An overall availability factor of 75% is not convincing, but nonetheless adequate for the technology readiness level of the vehicles. The hybrid propulsion systems (f.ex. motors, converters, generators and storage systems) only account for 7% of downtime. Other systems (f.ex. brakes, doors, electric auxiliaries etc.) in the buses caused downtime of nearly 11%. Those systems are also found in conventional vehicles.
More detailed analysis of the long term data is ongoing to address the remaining project goals.

5 Summary

In this project, city buses with hybrid and alternative drive train concepts have been compared. A methodology was derived to assess a multitude of vehicle characteristics, including exhaust and noise emissions, energy consumption of power train components and auxiliaries and long term effects. Results of the test campaign are promising and further fortify the position of hybrid propulsion as a valuable technology to reduce energy consumption and pollution. The methodology can be used to test more vehicles with updated and new power train technology and generate comparable data.
Further studies will include the use of the validated simulation models to project the impact of (semi)-automated driving, subjective evaluation of the noise emissions measurements at bus stops in a study and additional long term data acquisition.

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