Real world emission measurement of different city bus concepts

J. Blassnegger, A. Kies, S. Hausberger

Research Area Emissions, Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology, 8010 Graz, Austria

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Presenting author email: hausberger@ivt.tugraz.at

Introduction

Beside life time operation costs the real world emission behaviour seems to get increasingly important in the decision process for new city bus acquisition. To provide realistic data, on board emission measurements of more than 30 different city bus concepts were performed in real world operation by TU Graz during the last two years in the cities of Vienna and Graz.

The examined vehicles in Vienna were EEV and EURO VI buses with compressed natural gas, diesel and diesel-electric hybrid operation. In the city of Graz a diesel-electric hybrid city bus was measured in more detail to analyse the drivers influence on the hybrid control strategy and to elaborate “Eco-Drive” recommendations to make best use of the hybrid bus technology. The city buses tested covered solo buses and articulated buses.

The measurements were carried out on typical city bus lines, each route per bus was measured twice. The gaseous emission components CO_2, CO, HC, NO_x (NO, NO_2), and soot were collected. The measurement equipment used includes a SENSORS Semtech DS for the gaseous emission components and an AVL Micro-Soot Sensor.
The determination of the exhaust gas mass flow was carried out with an Exhaust Flow Meter (EFM). The EFM accurately measures every forward and reverse flow pulsation from idle to maximum flow rate, and properly accounts for these pulsations in the exhaust flow determination.

Figure 1: The exhaust flow meter after the tailpipe, the gas analyser instruments and the ballast

The fuel consumption was calculated with the carbon balance method (1 kg_{CO2}/km ≈ 38.2 l_{Diesel}/100km). During the test drives, the distance, velocity profile and GPS coordinates were also recorded.

Onboard measurement of buses with different powertrain concepts in Vienna

As part of the new city bus acquisition in Vienna, standard and articulated buses with different powertrain concepts and emission standards were measured in real world operation. These measurements were founded by the city of Vienna.

The measurements were realised on three different bus lines which represent typical routes in the city of Vienna. Each vehicle was measured at every bus line two times under unloaded conditions and with a payload of 5000 kg. The results in Figure 2 show the average of all measurements with articulated buses for each kind of powertrain concept:

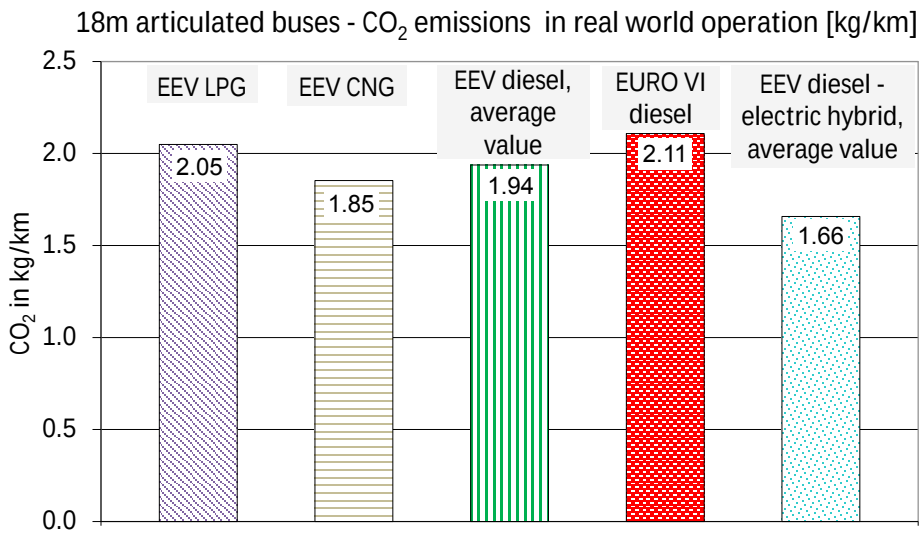

Figure 2: CO_2 emissions of 18m buses in real world operation

The CO_2 emissions from the EEV hybrid buses were 14 % lower than from the conventional diesel buses. This complies well with the test of six diesel-hybrid delivery trucks from 7.5 to 26 t in Germany [Willms 2012]. There the fuelsaving compared to standard trucks ranged around 10 %. The tested EEV CNG (Compressed Natural Gas) bus has emissions which were 4 % lower in relation to the EEV diesel vehicles, the emissions of the LPG (Liquefied Petroleum Gas) bus were 5 % higher. The highest CO_2 level was emitted by the EURO VI bus. When compared to EEV diesel buses, the emissions increased for 8 %.

The following Figure 3 shows the NO_x and soot emissions compared to the CO_2 emissions.

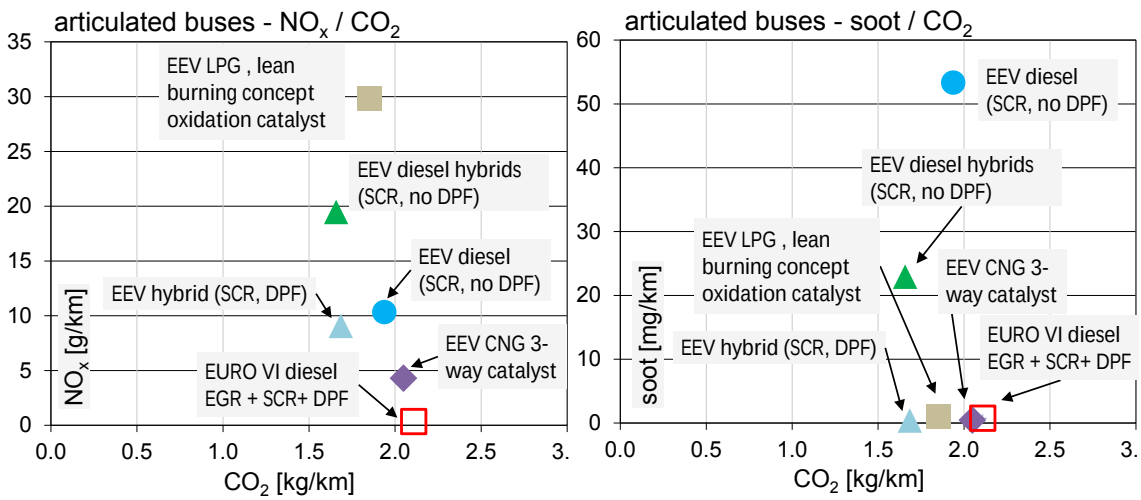

Figure 3: NO_x and soot emissions compared to CO_2 emissions of articulated buses in real world operation

The highest NO_x emissions were realised by the EEV CNG bus. The reason for this is the lean burning engine concept. The NO_x levels of the EEV diesel buses and the EEV LPG buses were significantly lower than from the EEV CNG bus. The lowest NO_x level has been achieved by the EURO VI diesel bus which works with a SCR system and exhaust gas recirculation.

Generally the soot emissions were at a low level in all measurements. The EEV diesel buses without wall flow filter (DPF) emit the highest soot emissions. The lowest emission values were reached by the gasoline concepts and the EURO VI bus.
To interpret the soot emissions for EEV diesel and EEV diesel-hybrid, the results distinguished according to exhaust gas aftertreatment and air conditioning on/off are listed:

EEV Diesel		EEV Dieselhybrid	
bus 1, no DPF, AC-off	28 mg/km	bus 3, with DPF, AC-on	0.4 mg/km
bus 1, no DPF, AC-on	50 mg/km	bus 4, no DPF, AC-on	13 mg/km
bus 2, with PM cat, AC-on	82 mg/km	bus 5, with PM cat, AC-off	32 mg/km

It can be seen, that the city bus with the DPF has the lowest soot emissions while an “open filter (PM cat)” in combination with high raw emissions does not necessarily lead to low tailpipe emissions due to the lower reduction rate compared to a DPF. In addition the operation of the air conditioning leads to increased engine power demand and thus influences the soot emissions.
The EURO VI diesel bus shows a clear advantage for the soot and NO_x emissions. This concept works with an exhaust gas recirculation, a SCR system and a DPF. So it compensates the disadvantages of diesel engines at soot and NO_x emissions. On the other hand, the CO_2 emissions and the fuel consumption were up to 8 % higher than from the conventional diesel buses

Onboard measurement of hybrid and standard buses

As part of the EHEV project ("Eco Drive for Hybrid Electric Vehicles") two 12 m buses, a Volvo 7700H parallel hybrid bus EURO V and a Mercedes Benz Citaro standard bus EURO III were measured in the city of Graz. This project is funded by the Austrian Klima- und Energiefonds and part of the program NEUE ENERGIEN 2020. Its objective is to elaborate an economic driving style, saving fuel consumption and battery wear of hybrid commercial vehicles. To analyse the influence of the driving style, onboard measurements with the PEMS system on the urban bus line 31 were conducted. This line represents a typical bus course with one half heavy urban traffic in the inner city and the other half normal urban traffic in the suburbs. The drivers were asked to actuate brake- and accelerator pedal passive or aggressive, with every bus each driving style was measured for two laps. To create similar conditions for the two buses, an equal payload of 3.8 t was used, what resulted in a GVW of the hybrid bus of 16 t and of the standard bus of 15.7 t. In addition, the air conditioning was switched off.
The results are shown in Figure 4.

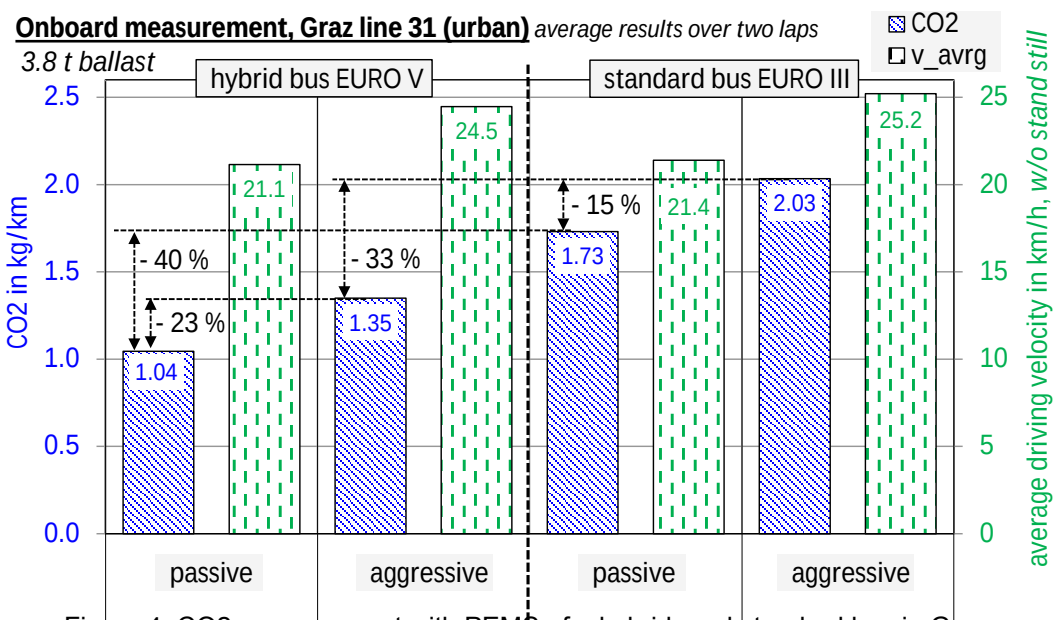

Figure 4: CO2 measurement with PEMS of a hybrid- and standard bus in Graz

Both buses were fuelled with fossil diesel, so the CO_2 emissions correspond directly with the fuel consumption. The hybrid bus shows a clear advantage for the fuel consumption, dependent on the driving style from - 33 to - 40 %. The minor consumption of the passive against the aggressive style, depending on the bus type, varies from - 15 to - 23 %. Also it is important, that the average driving velocity is very similar for both bus types. Especially the aggressive style with full acceleration and strong braking is the standard case for urban buses, because the drivers need to keep their short time slot of less than 10 min. If they drove passive and fuelsaving, their bus would become too late, the next bus from behind gains on and they would need to leave the bus route. So a realistic economic driving style will be a compromise between the necessary minimum velocity and the possible saving of fuel and, in case of hybrid vehicles, the battery wear.
In addition to the PEMS measurements the refuelling data of the public transportation services Holding Graz Linien were analysed. Every evening after the shift the buses are refuelled and this data and the mileage were recorded. These datasets for the hybrid and the standard buses needed to be checked for plausibility, and only data filtered by two standard deviations around the average and of the same work day were used.
The population of the remaining data for the hybrid bus on line 39 is shown in Figure 5:

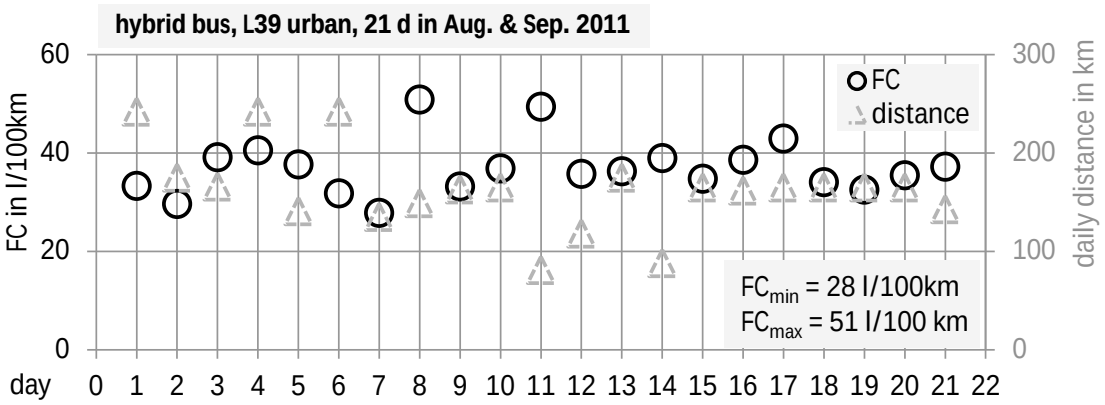

Figure 5: Population of the refuelling data for the hybrid bus on line 39

Here the daily fuel consumption values are usually lower than for the passive driving style during the PEMS measurements (≈ 40 l_{Diesel}/100km). The reason is, that the bus is normally not loaded with 3.8 t payload, what would be about 45 passengers, which means a full bus with 10 standing persons.
An uncertainty of the refuelling protocol remains, but the trend is the same as for the PEMS measurement, see Figure 6.

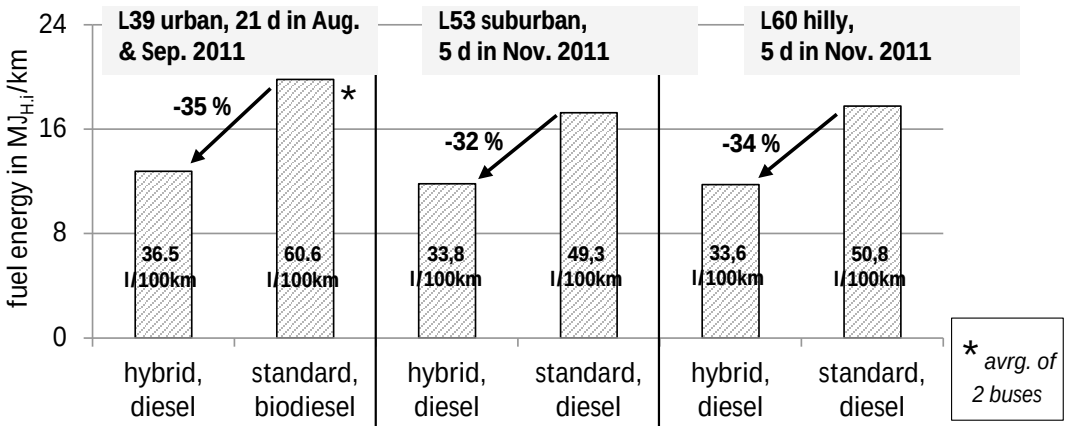

Figure 6: Evaluation of the refuelling protocol of hybrid and standard buses

Because for one line the standard buses were fuelled with biodiesel, what is the normal case at Holding Graz Linien, the y-axis value is the fuel heating value in $MJ_{H,i}$/km. But nevertheless the result of this comparison complies with the PEMS tests: The hybrid bus has got a fuel saving potential versus the standard buses of more than 30 %.

It must be considered that in this case the standard buses were all of EURO III technology, what is no more state of the art. A direct comparison in Vienna of the best 12 m EEV diesel-hybrid bus with the best 12 m EEV standard bus resulted in a saving potential for the hybrid of only - 9 %.

Summary

True real world emission measurement is very different from laboratory testing. The advantage of this kind of testing method is, that it can take place during the real world operation of the test vehicles. This is one of the approaches followed by the legislators, and becomes an important regulatory tool. In Europe, the application of PEMS to verify the conformity of heavy-duty engines with the applicable emissions standards is possible since directive COM(2007) 851.
On the other hand the real world emission behaviour seems to get increasingly important in the decision process for new fleet acquisition. To provide realistic data, on board emission measurements are a very useful application.
A result of the two presented measurements is, that EURO VI standard diesel buses reduce the pollutants NO_x and soot almost to zero, but emit the most CO_2. Hybrid buses offer the highest fuelsaving potential of about 20 % versus new EURO VI and about 10 % versus new EEV diesel buses, but even this could be not enough to reach an acceptable payback duration regarding the surcharge for the technology.
Another result is the difficulty of realising a fuelsaving driving style for hybrids. When driving passive instead of aggressive, the fuel consumption of a hybrid might decrease for more than 20 %, but also the driving velocity is about 14 % slower. In the case of adopting the timetable to slower buses, the maximum possible passenger transport performance (passenger-kilometres / hour) decreases. Then the need for additional buses to keep the required performance in the rush hour would outweight the reduced fuel costs. So a compromise between fuel efficiency, battery wear, driving velocity and transport performance needs to be elaborated.

References

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