Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

HEAVY DUTY DIESEL EMISSION ROAD TESTS

Jerzy Merkisz, Jacek Pielecha

Poznań University of Technology
ul. Piotrowo 3, 60-965 Poznań
tel.: +48 61 6652207, fax:+48 61 6652204
e-mail. jerzy.merkisz@put.poznan.pl, jacek.pielecha@put.poznan.pl

Wojciech Gis

Motor Transport Institute
ul. Jagiellońska 80, 03-301 Warszawa
tel.: +48 22 8113231/125
e-mail: wojciech.gis@its.waw.pl

Abstract

The paper present the results of emission tests of city buses (Euro 5 hybrid and Euro 4 conventional diesel), under real traffic conditions with the use of a portable emission testing system. The tests have been carried out in city traffic conditions on road portions of several kilometers each; The test results contain information on the vehicle emission level in operation and pertain to real road conditions.

Keywords: *emissions, road tests, diesel engines, hybrid drivetrains*

1. Introduction

Contemporary vehicle manufacturers focus not only on the comfort and safety of their products but also on the issues related to the fuel economy [3, 18] and the emission level [1]. Owing to a high commitment of the vehicle manufacturers recent years saw a reduction of vehicle emission level from Euro 1 to Euro 4, which reduces the pollution by more than 90% [1].

European emission regulations for heavy duty vehicles set forth in Directive 1999/96/WE are commonly known as Euro 1...5 standards. Since October 2005 all newly homologated vehicles and since October 2006 all newly registered commercial vehicles (*Heavy Duty Diesel*, including buses) have had to comply with the Euro 4 standard. More stringent standard - Euro 5 will come into force in October 2008 (homologation) and October 2009 (registration) respectively. Additionally, the Directive 2005/55/WE adopted in 2005 introduced the EEV standard (*Enhanced Environmentally Friendly Vehicle*) for vehicles of particularly low emission level. The purpose of this directive is to replace the previous directives 88/77/EWG, 96/1/WE, 1999/96/WE and 2001/27/WE through a unification and consolidation of the regulations in a single act. Directive 2001/27/WE came into force on 9.11.2006. As the Euro 4 standard was introduced, the manufacturers of all powertrains of heavy duty vehicles including city buses had to fit them with OBD (*On-Board Diagnostic*) emission monitoring system [2, 4, 10, 14]. The implementation of the Euro 4 and Euro 5 standards forced the manufacturers to come up with new solutions such as EGR (exhaust gas recirculation) or SCR (selective catalytic reduction), the latter requiring an on-board supply of a solution of carbamide (AdBlue).

Currently, more attention is drawn to the measurement of the emissions under variable operating conditions, particularly regarding heavy duty vehicles. Emission testing in road conditions is in higher demand than stationary driving cycles. On-road emission testing became possible owing to a rapid advancement of the measuring techniques that came in recent years [5, 6, 8, 13, 17]. The said advancement also aimed at the measurement of extremely small pollutant concentration in the exhaust gas [7, 9, 15]. The Institute of Combustion Engines and Transport with a portable emission testing system carried out a series of on-road emission tests of two city buses with two different powertrains: hybrid and conventional diesel.

2. Emission testing methodology

The on-road emission tests were carried out in city traffic in Poznań (Fig. 1). The tests were performed on the city main streets in the afternoon, when the traffic was moderate. Such conditions were selected in order to ensure the highest possible use of the engine work field (regular bus operation was simulated including 10 second stops at the bus stops). The object of the tests were two buses manufactured by Solaris: one unit was fitted with a hybrid engine (Hybrid H18) and the other one – with a conventional diesel engine (U18 Aarhus) – characteristics – Tab. 1. The buses were selected based on the similarity of service routes (number of passengers) and at the same time in such a way that there was a possibility of comparing their functionality and ecology under real conditions.

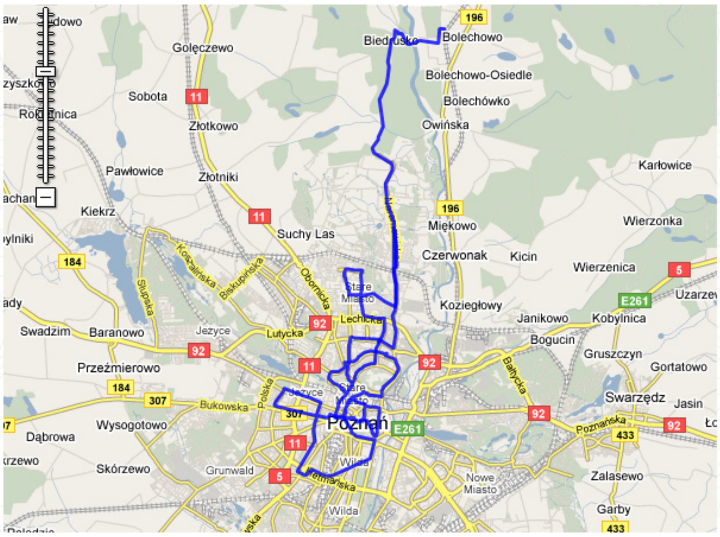

Fig. 1. A road portion (routes marked) used for the measurement of the buses emission level

Tab. 1. Technical data of the tested buses

Parameter	Conventional diesel bus	Hybrid Bus (diesel + electric)
1	2	3
Engine type	DAF PR 265	Cummins ISB 250
Displacement [cm^3]	9200	6700
Emission standard	Euro 4	Euro 5
Transmission	VOITH DIWA 86 4.5	ALLISON Ep50
Vehicle weight [kg]	16,700	17,800
Vehicle weight full load [kg]	21,200	22,000

For the measurement of the exhaust emissions the authors used a portable SEMTECH DS analyzer [9, 16] by SENSORS LTD (Fig. 2). The analyzer measured the fuel consumption and the exhaust emissions (Tab. 2) at the same time recording the exhaust mass flow. The exhaust gases entering the analyzer through a sensor maintaining the temperature of 191°C (Fig. 3) were filtered for particulate matter (diesel) and then the concentration of hydrocarbons was measured in a FID (flame ionization detector). Next, the exhaust gases were cooled down to a temperature of 4°C and the measurement of the concentration of NOx took place (non-dispersive method with the use of ultraviolet radiation that enabled the measurement of both nitrogen oxide and nitrogen dioxide), carbon monoxide, carbon dioxide (non-dispersive method with the use of infrared radiation) and oxygen (electrochemical analyzer). The data could be directly transferred to the analyzer central unit from the vehicle diagnostic system and the GPS.

Fig. 2. View of the testing device (Semtech DS for exhaust emissions tests) fitted in the bus

Tab. 2. Characteristics of the portable exhaust gas analyzer SEMTECH DS

Parameter	Method of measurement	Accuracy
1	2	3
1. Concentration of CO HC NOx = (NO + NO_2) CO_2 O_2 Sampling frequency	 NDIR – non-dispersive (infrared), range 0–10% FID – flame ionization, range 0–10,000 ppm NDUV – non-dispersive (ultraviolet), range 0–3000 ppm NDIR – non-dispersive (infrared), range 0–20% electrochemical, range 0–20% 1–4 Hz	 ±3% ±2.5% ±3% ±3% ±1%
2. Exhaust gas flow	Mass flow intensity T_{max} up to 700°C	±2.5% ±1% of the range
3. Pre-heating time	15 min	
4. Response time	$T_{90} < 1$ s	
5. Supported diagnostic systems	SAE J1850/SAE J1979 (LDV) SAE J1708/SAE J1587 (HDV) CAN SAE J1939/J2284 (HDV)	

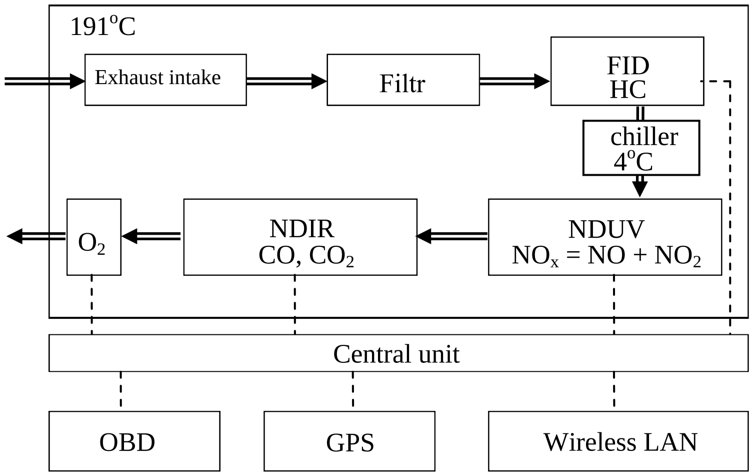

Fig. 3. Schematics of the portable analyzer SEMTECH DS – exhaust gas flow (══) and electrical connections (- - -) shown

3. Tests results and analysis

With the use of the portable system the emissions of CO, HC, NOx, CO_2 with 1 second interval were measured as well as the changes in the engine speed and torque– the parameters taken from the vehicle OBD (CAN SAE J1939) and used to calculate the emissions related to the unit energy of the engine. Example data recorded during the cruise are shown in Fig. 4. The ECU of the hybrid vehicle limited the torque of the diesel engine when the vehicle began to move – while accelerating up to the speed of 5 km/h the electric motor was used and the diesel engine remained idle (lower toxic emissions).

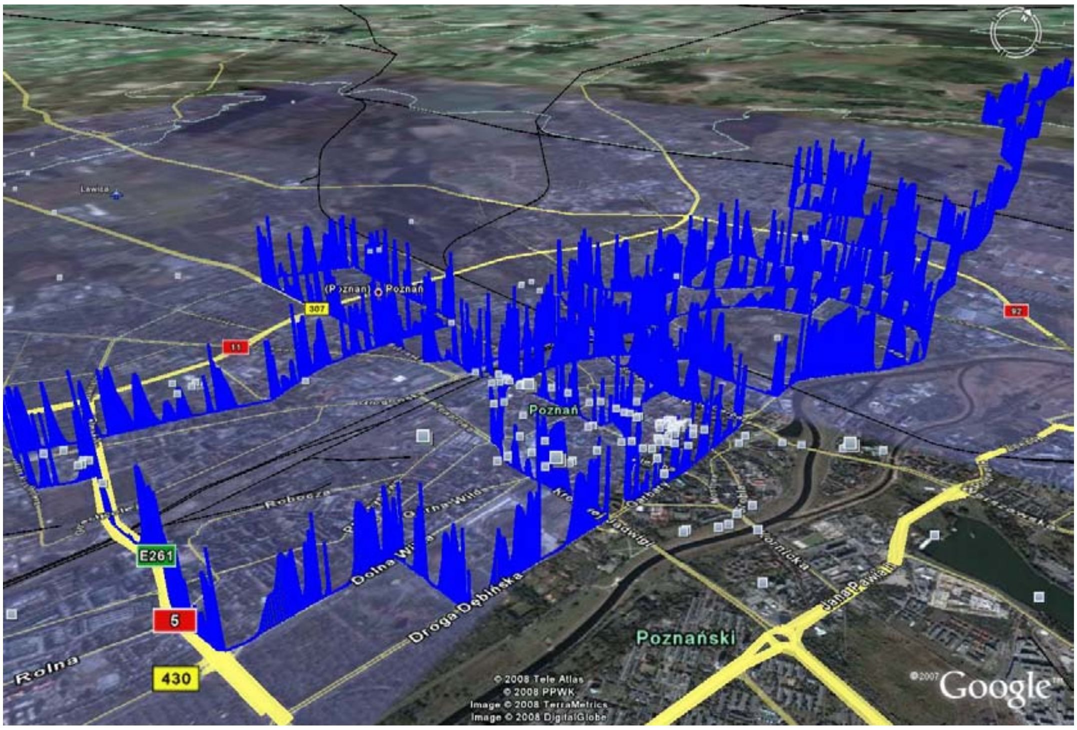

Fig. 4. Example measurement recording (CO_2 emission overlaid on the vehicle route during the emission tests)

The calculations of the time density characteristics for the engine parameters in the urban traffic revealed certain dependencies that characterize the share of given parameters of engine operation in the total cruise time (Fig. 5). For the hybrid bus a large share of the operating time falls within the engine operation range of 700–900 rpm and engine load of approximately 10%. For the bus with the conventional powertrain, over 2000 s (approx. 20% of the engine operating time, total engine operating time amounts to 10,200 s) of the engine operating time was 600 rpm and the engine load approximately 10%. The ranges of engine parameters used in the city traffic were: idle speed (for both of the tested buses) and the external characteristics operating range (maximum load for a given engine speed). At the same time, for the hybrid bus a higher share of part loads is more visible.

a) b)

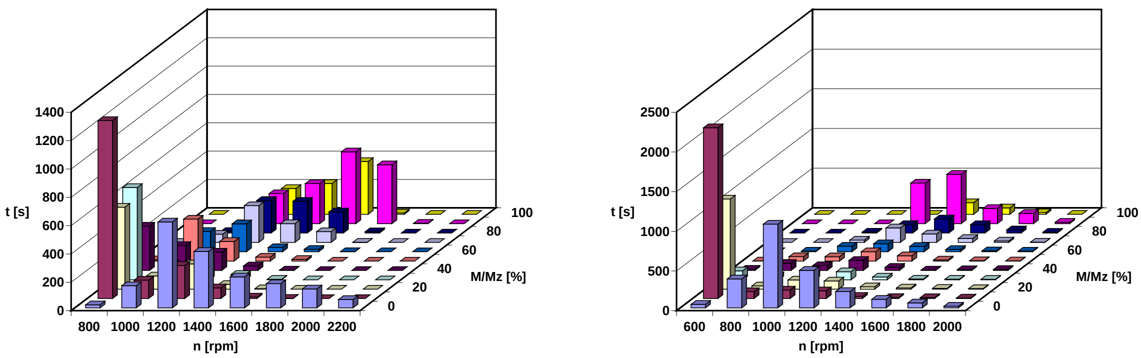

Fig. 5. Characteristics of the operating time density: a) hybrid, b) conventional diesel

The highest intensity of the CO_2 emission in the tested city traffic conditions we can observe for medium engine speeds and for the maximum engine torque (hybrid vehicle, Fig. 6a) and for the conventional diesel engine the CO_2 emission (fuel consumption) increases proportionally to the engine speed and engine load (Fig. 6b). The CO_2 emissions for the hybrid vehicle are approximately 20–30% lower than the analogical values for a conventional diesel vehicle. This could indicate a lower fuel consumption; the total fuel consumption is calculated with the use of this data as well as the share of the engine operation in given engine speed ranges and loads.

a) b)

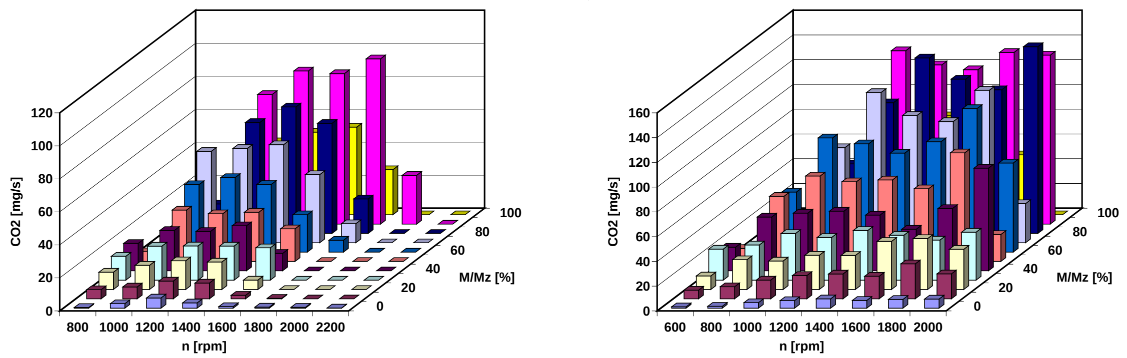

Fig. 6. Time density characteristics of the CO_2 emission: a) hybrid, b) conventional diesel

The maximum intensity of CO emission, given in milligrams per second, falls within the range of maximum engine loads and medium engine speeds (hybrid vehicle, Fig. 7a) and for the conventional vehicle this range is approximately 4–5 times wider (maximum for high loads and medium engine speeds, Fig. 7b). This mainly results from the differences in the engine capacity and the fact that for the hybrid vehicle medium loads are more frequently the case as compared to the conventional diesel engine, which operates at high loads for most of the time.

a) b)

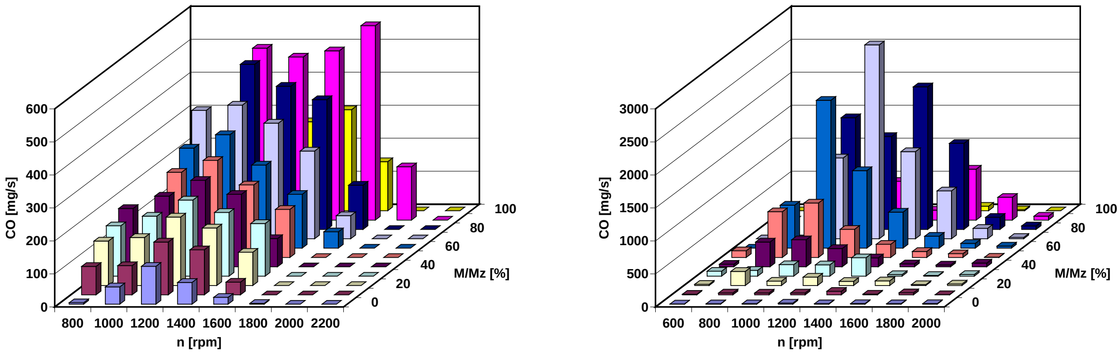

Fig. 7. Time density characteristics of the CO emission: a) hybrid, b) conventional diesel

The maximum values of the emission of hydrocarbons for both of the powertrains is similar (approximately 25–35 mg/s), yet, for the hybrid vehicle only the maximum values reach 25 mg/s (Fig. 8a); in the range of medium engine speeds and engine loads the values do not exceed 20 mg/s (Fig. 8b). For the conventional diesel vehicle there is a nearly linear dependence between the HC emission and the engine speed and load (the maximum is observed for the maximum values of the engine speed and load).

a) b)

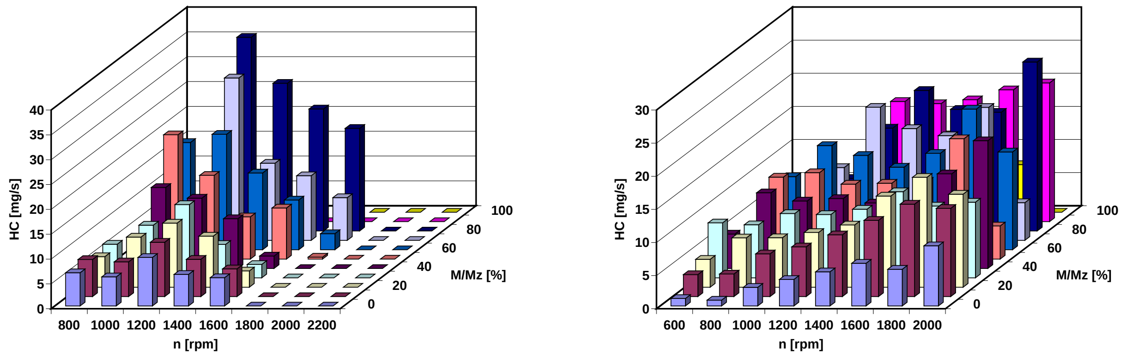

Fig. 8. Time density characteristics of the hydrocarbons emission: a) hybrid, b) conventional diesel

The area of elevated NOx emission in a hybrid vehicle (Fig. 9a) falls within the range of low engine speeds in the whole range of engine loads and the maximum engine speed and high engine load. This could be the effect of the application of selective catalytic reduction in this vehicle, where, at high exhaust gas temperatures the reduction of NOx occurs. For the vehicle with the conventional powertrain (no SCR) a linear growth of NOx emission is observed as the engine speed and engine load increase (Fig. 9b).

a) b)

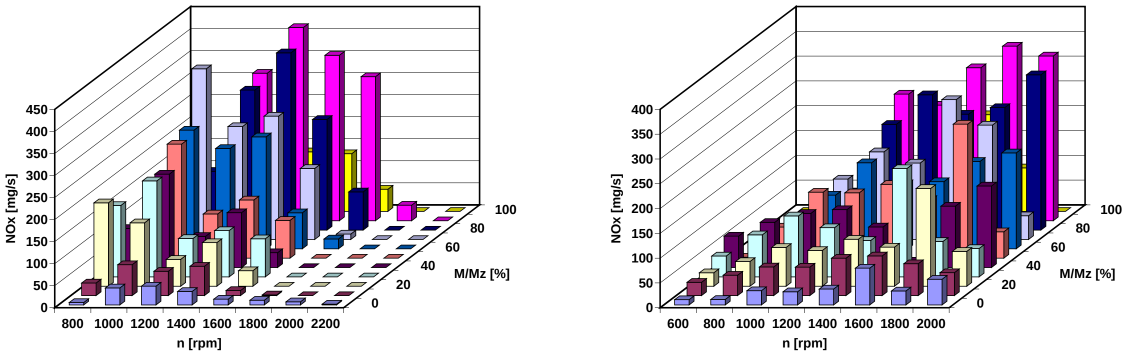

Fig. 9. Time density characteristics of the NOx emission: a) hybrid, b) conventional diesel

4. Comparison of the emission level of the tested engines

The emission intensity under real conditions was calculated with the help of the time density characteristics of the engine operation ($u_{n,M/Mz}$) and the characteristics of the emission intensity for a *j* toxic compound $e_j(n, M/M_z)$:

$$E_{real,j} = \sum_{n} \sum_{M/M_z} \left\{ u_{n,M/M_z} \cdot e_j(n, M/M_z) \right\}, \tag{1}$$

where:

$E_{real,j}$ – emission of a *j* toxic compound under real conditions,
n – engine speed,
M/M_z – relative engine load.

Knowing the effective power in each range (determined by the engine speed and load), the unit emissions of the toxic compounds were compared, related to the engine power during the whole test cycle. The following values were obtained for the hybrid bus: HC – 0.193 g/(kW·h), CO – 3.981 g/(kW·h), NOx – 2.711 g/(kW·h) and CO_2 – 570.2 g/(kW·h). For the conventional diesel bus: HC – 0.282 g/(kW·h), CO – 9.130 g/(kW·h), NO_x – 3.128 g/(kW·h) and CO_2 – 763.3 g/(kW·h). The above, when compared, discloses lower values for the hybrid vehicle: CO by 56.4%, HC by 31.8%, NOx by 13.3% and CO_2 by 25.3% as compared to the conventional power-train (Fig. 10).

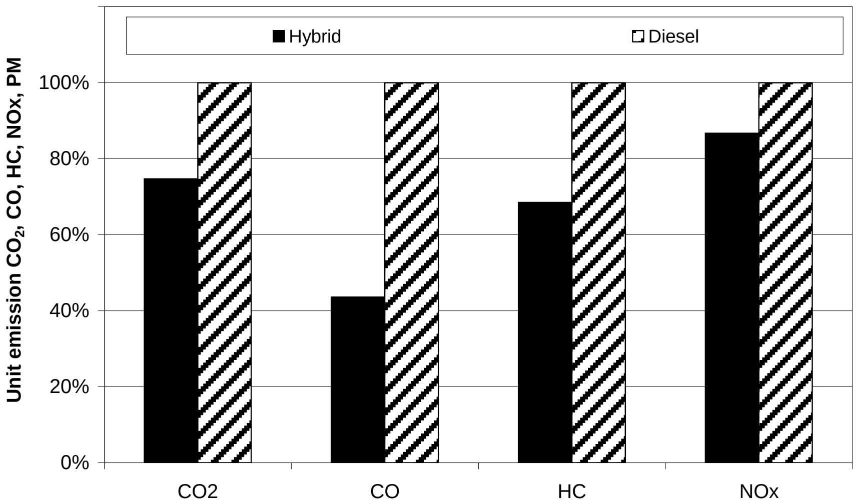

Fig. 10. Relative values of the unit emissions of toxic compounds during the on-road tests (hybrid and conventional diesel)

5. Engine emission level indexes

From the information presented in the paper such as the characteristics of the share of engine operation at given engine speeds and loads as well as the characteristics of emission intensity we can obtain the factor of multiplication of the increase (decrease) of the emissions under real traffic conditions as opposed to the values obtained during the homologation test. The emission index (for a given toxic compound) has been defined as follows [12]:

$$k_j = \frac{E_{real,j}}{E_{cycle(norm),j}}, \tag{2}$$

where:

j – toxic compound for which the emission index has been determined,
$E_{real,j}$ – emission intensity obtained under real conditions ([g/(kW·h)]),
$E_{cycle(norm),j}$ – emission intensity obtained in the ESC or ETC test ([g/(kW·h)]) or the boundary values adopted as permissible for a given emission standard.

The knowledge of the actual emission and the test emission (or the one compliant with the standard) may serve to determine the emission indexes of the toxic compounds of a given vehicle. If there is no information on the engine toxic emissions in the ESC or ETC test, we can adopt the permissible values according to the Euro emission standard which is binding for a given vehicle.

From the data included in Tab. 3 the emission indexes were obtained for each vehicle as they complied with different emission standards, hence the actual emission of a hybrid bus was compared with the emission values set out in Euro 5 (ETC test as the vehicle was fitted with an aftertreatment system) and the actual emission of the conventional diesel bus was compared with the emission values set out in Euro 4 and the ESC test as the engine was not fitted with aftertreatment systems other than Oxicat. Because the standard does not provide for the CO_2 emission level the unit CO_2 emission was converted into unit fuel consumption and then the mean overall efficiency of the engine was estimated in the whole road test ($\eta_{o\ Hybrid} = 0.48$, $\eta_{o\ Diesel} = 0.36$).

Tab. 3. Emission level under real traffic conditions and emission indexes obtained in the tests for the hybrid and conventional vehicle

Parameter	CO	HC	NOx	CO_2
1	2	3	4	5
Actual emission (hybrid) [g/(kW·h)]	**3.981**	**0.193**	**2.711**	**570.2**
Actual emission (conventional) [g/(kW·h)]	9.130	0.282	3.128	763.3
ESC test emission				
Euro 4 [g/(kW·h)]	1.5	0.46	3.5	–
Euro 5 [g/(kW·h)]	**1.5**	**0.46**	**2.0**	–
ETC test emission				
Euro 4 [g/(kW·h)]	4.0	0.55	2.0	–
Euro 5 [g/(kW·h)]	**4.0**	**0.55**	**2.0**	**–**
Emission index [–]	Hybrid bus			
ESC included	2.645	0.419	1.350	–
ETC included	0.993	0.351	1.350	–
Emission index [–]	Conventional bus (Diesel)			
ESC included	6.086	0.613	0.894	–
ETC included	2.282	0.513	1.564	–

The analysis of the emission indexes obtained for the two different buses (Fig. 11) shows that the hybrid bus has advantages in terms of both – fuel economy such as lower CO_2 emission and ecology such as lower emission indexes for CO and HC (lower than 1). This means that during its operation the bus releases fewer toxic compounds to the atmosphere than in the dynamic ETC test (in reference to a unit of energy). The emission index obtained for NOx amounts to 1.35 – this means that the emission of this compound during the road tests is 35% higher than in the ETC test. The emission indexes obtained for the conventional bus show that the emission of CO has been exceeded (more than 6 times) in the road test. The emission of the other toxic compounds does not exceed the boundary values set out in the Euro 4 standard. It should be noted that for the conventional bus the emission indexes were obtained through the data related to the Euro 4 standard and the ESC test.

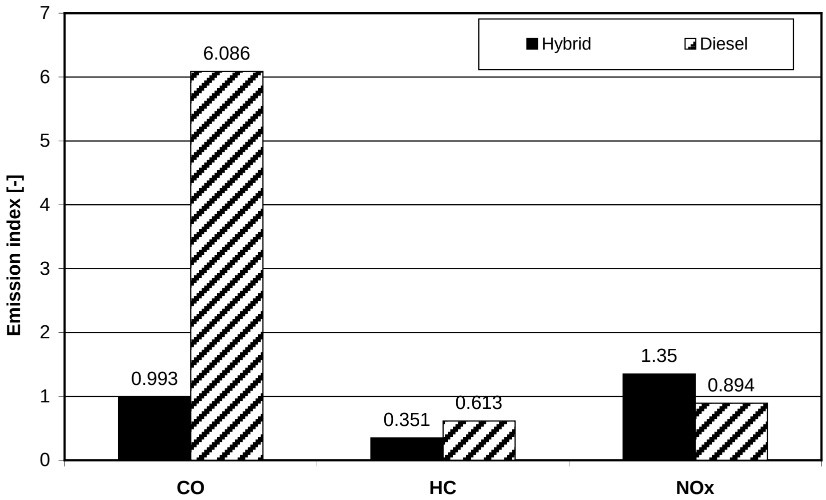

Fig. 11. Comparison of the emission index of the two buses in terms of real road emissions as opposed to the limits set out in the emission standards

6. Conclusions

A hybrid bus is more environment friendly because of a lower emission of CO_2 (fuel consumption) by 25% and a lower emission of other toxic compounds such as CO by 60%, HC by 30%, NOx by 15% as opposed to a conventional bus.

The analysis of the emission indexes shows that the emission values in the homologation test (ESC or ETC for a Euro 4 or Euro 5 vehicle) and the values in the real operation vary. For a conventional bus the differences of certain toxic compounds (as opposed to the emission set out in Euro 4 in the ESC test) are high and amount to: CO 6 times higher, HC 1.5 times lower and NOx emission similar. For the hybrid bus (opposed to the emission set out in Euro 5 in the ETC test) the following emission values were obtained under real traffic conditions: NO_x emission 35% higher, HC emission 65% lower and CO emission similar. The elevated NO_x emission during the tests can result from an inappropriate selection of the engine for this particular vehicle (an engine of higher capacity and power would be required so that it could more frequently operate on part loads).

The defined emission indexes could come in handy in the classification of vehicle fleets in terms of toxic emissions according to their year of manufacture, emission limit compliance, mileage or conditions of operation.

Literature

[1] AVL, *Current and Future Exhaust Emission Legislation*, AVL List GmbH, Graz 2007.

[2] Gao, Y., Checkel, M. D., *Emission Factors Analysis for Multiple Vehicles Using an On-Board, In-Use Emissions Measurement System*, SAE Technical Paper Series 2007-01-1327.

[3] Gao, Y., Checkel, M. D., *Experimental Measurement of On-Road CO2 Emission and Fuel Consumption Functions*, SAE Technical Paper Series 2007-01-1610.

[4] Greening, P., *European Light-Duty & Heavy Duty OBD – Legislative Update*, On-Board Diagnostic Symposium: Light and Heavy Duty, Lyon-Villeurbane 2007.

[5] Jehlik, H., *Challenge X 2008 – Hybrid Powered Vehicle On-Road Emissions Findings and Optimization Techniques: A 4 Year Summary*, Sensors 5th Annual SUN (SEMTECH User Network) Conference, 25-26.09.2008.
[6] Johnson, K., Durbin, T., Cocker, D., Miller, J., Agama, R., Moynahan, N., Nayak, G., *On-Road Evaluation of a PEMS for Measuring Gaseous In-Use Emissions from a Heavy-Duty Diesel Vehicle*, SAE Technical Paper Series 2008-01-1300.
[7] Khair, M., Khalek, I., Guy, J., *Portable Emissions Measurement for Retrofit Applications – The Beijing Bus Retrofit Experience*, SAE Technical Paper Series 2008-01-1825.
[8] Khalek, I., *Status Update on the PM-PEMS Measurement Allowance Project*, Sensors 5th Annual SUN (SEMTECH User Network) Conference, 25-26.09.2008.
[9] Korniski, T., Gierczak, C., Wallington, T., *Laboratory Evaluation of the 2.5 Inch Diameter SEMTECH® Exhaust Flow Meter with Gasoline Fueled Vehicles*, Sensors 4th Annual SUN (SEMTECH User Network) Conference, 22.10.2007.
[10] McCarthy, M., *Update on Light Duty OBD II*, On-Board Diagnostic Symposium: Light and Heavy Duty, Lyon-Villeurbane 2007.
[11] Merkisz, J., Pielecha, J., Gis, W., *Comparison of Vehicle Emission Factors in NEDC Cycle and Road Test*, APISCEU 2008, Beijing 2-6.11.2008.
[12] Merkisz, J., Pielecha, J., Gis, W., *Possibilities of Evaluation of Vehicle Emissivity with the use of OBD II System in Road Tests*, Better Air Quality (BAQ) 2008, Bangkok 12-14.11.2008.
[13] Quan, H., *ARB's Stockton Heavy-Duty Vehicle Laboratory and Portable Emission Monitoring System (PEMS) Activities*, Sensors 5th Annual SUN (SEMTECH User Network) Conference, 25-26.09.2008.
[14] Palocz-Andresen, M., *Completion of the OBD- with the OBM-(On-Board- Measurement)-Technology*, Predelli O.: Onboard-Diagnose II, Expert Verlag, Renningen 2007.
[15] Rapone, M., Ragione, L., Meccariello, G., *Characterization of Real-World Bus Driving Behavior for Emission Evaluation*, SAE Technical Paper Series 2007-24-0112.
[16] Shahinian, V. D., *SENSOR tech-ct Update Application Software for SEMTECH Mobile Emission Analyzers*, Sensors 4th Annual SUN (SEMTECH User Network) Conference, 22.10.2007.
[17] Sharp, C. A., Feist, M., *Results of the HDIUT Gaseous PEMS Measurement Allowance Program and Update on PM Program Status*, Sensors 4th Annual SUN (SEMTECH User Network) Conference, 22.10.2007.
[18] Zhao, F. F., *Technologies for Near-Zero-Emission Gasoline-Powered Vehicles*, SAE International, Warrendale 2007.