EXPERIMENTAL DETERMINATION OF VEHICLE EMISSION FACTORS OVER MULTIPLE DRIVING CYCLES IN URBAN AND EXTRA URBAN AREAS, FOR MODELING SIMULATION OF SOLUTIONS ADOPTED WITHIN PLANS FOR AIR QUALITY CONSERVATION AND IMPROVEMENT

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INTRODUCTION

Air quality standards attainment in urban areas is an issue of growing interest for Public Administration. Amongst feasible measures, provisions on vehicle traffic can be designed and verified by math simulating models where emission factors represent real operating conditions.

The Regione Emilia-Romagna[14], aiming at a deeper knowledge on the driving condition effects on vehicle emissions, founded a research program in order to obtain emission factors for modelling simulation and data as guideline in environmental policies and air quality improvement plans.

The experimental study, carried out at EniTecnologie[15], has taken in consideration the city buses in urban areas *(F. Alberici, S. Florio* 2003*)*, heavy and light duty vehicles for both goods and people transportation on motorways *(F. Alberici, S. Florio* 2005*)*. The study has been based upon cycles representing the real driving conditions.

TEST METHOD

The current emission regulations for heavy duty (HD) engines (buses and trucks) require to measure engine emissions at the test bed through standard cycles (steady state or transient). In the present work emissions have been measured at the chassis dynamometer.

By this way the heavy duty vehicle emissions are calculated in g/km and can be compared with those coming from light duty vehicles. In addition, modelling implementation is facilitated as absolute emissions can be calculated starting from the trip mileage.

The used method does not ask to replace current HD regulations, but it may be a useful integration of them. Further on, a vehicle test on the chassis dynamometer is less expensive and much less complex than a test on engine at the test bed.

Field tests

The real driving conditions have been recorded from a variety of vehicles, under different traffic situations. A speed recorder has been installed on the test vehicles running in urban and extra-urban traffic. More than 50 hours have been recorded over further than 3000 km using several vehicles (from buses in urban service to passenger cars on the motorway).

Test cycles

The data processing has established the typical driving cycles for the situation under trial and eight test cycles have been thus obtained. They represent the driving patterns in the town of Bologna area. Table 1 presents the test cycles main characteristics.

The bus cycles n.1 and 2 have been obtained on the same bus-line at different times, while cycle n. 3 represents the downtown conditions with smooth flowing traffic.

The cycles truck n. 3 and LVD n. 2 simulated a 2% slope meaning a higher load road curve. They represent a portion of Bologna-Firenze motorway.

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[14] The Administrative Department of the Bologna region
[15] The ENI Corporate Technology Company

Cycle		Length (km)	Durat. (s)	Av. speed (km/h)	Max. speed (km/h)	Share of idle (%)	Traffic conditions
Bus	1	1,836	1200	5,5	30	43	suburban rush-hours
	2	4,877	1227	14,3	42	29	suburban flowing
	3	4,154	1268	11,8	50	36	urban flowing
Truck	1	17,796	1140	56,2	69	2	motorway flowing
	2	3,706	1100	12,1	63	25	Motorway rush-hours
	3	11,897	1400	38,3	66	2	motorway flowing (slope 2%)
LDV	1	17,643	1280	49,6	127	14	mix flowing /rush-hours
	2	17,929	1380	46,8	104	13	mix flowing/rush-hours (sl. 2%)

Tab. 27; Data of the Test Cycles.

Test vehicles

Six buses have been selected for this study on urban cycles. They represent the 1996-2002 (Euro 2 - Euro 3) model years with the addition of an old pre-Euro 0 bus (MY 1980). Two trucks and four light duty vehicles have been tested on motorway cycles. Trucks differ in engine size and power. The light duty n.1 was a land rover, n. 2 a delivery van, while n. 3 and n. 4 were passenger cars. The vehicles technical data are given in Table 2.

	Vehicle / Emiss. class	MY	Engine displ. (l)	Max. power (kW)	Combustion system
Bus	n.1 / Euro 2	1999	7,7	162	diesel TC ME
	n. 2 / Euro 2	1997	7,7	162	diesel TC ME
	n. 3 / pre-Euro 0	1980	10,3	153	diesel TC ME
	n. 4 / Euro 3	2002	6,7	205	diesel TC IC EL
	n. 5 / Euro 2	1996	6,8	162	diesel TC ME
	n. 6 / Euro 3	1999	6,7	205	diesel TC IC EL
Truck	n. 1 / Euro 1	1995	6,2	166	diesel TC
	n. 2 / Euro 1	1994	14,2	309	diesel TC
Light Duty	n. 1 / Euro 3	2001	2,5	90	diesel TC EL
	n. 2 / Euro 2	1999	2,8	64	diesel NA ME
	n. 3 / Euro 2	1999	1,9	77	diesel TC CR
	n. 4 / Euro 2	1996	2,0	81	gasoline PFI TWC

TC: turbo charged — PFI: port fuel injector
CR : common rail — TWC: three way catalyst
IC : intercooler — ME: mechanical control
NA : naturally aspirated — EL: electronic control

Tab. 2; Test vehicles characteristics

Test procedures and measurement equipment

A microwave sensor (Doppler effect) has been used to measure the vehicle speed at real operating condition. A data logger acquired data for subsequent elaboration.

Buses and tracks have been tested in the heavy-duty test facility on a chassis dynamometer using a partial flow exhaust-gas sampling system based on the splitter concept (Fig. 1). As a result emissions are expressed in term of mass per driving distance (g/km). The light duty vehicles have been tested on a conventional emission test laboratory with a CVS system.

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Fig. 1; Partial flow sampling system

The HD chassis dynamometer has a roller diameter of 1,59 m, a power absorption capacity of 300 kW and can simulate 18000 kg of inertia.
The regulated emissions have been measured using an analyzer set conforming to the current regulation for light duty vehicles (Dir. 91/441/CEE).
A number of certain unregulated emissions measurements has been also carried out:

- one-ring aromatic hydrocarbons by CG;
- aldehydes by DNPH sampling and HPLC analysis;
- polycyclic aromatic hydrocarbon (PAH) collected on PM filter (gas phase sampling for gasoline vehicle) and analysed by HPLC.

All diesel vehicles have been tested using the same diesel fuel batch of current market quality.

TEST RESULTS

On each experimental point (vehicle/cycle), at least three test repetitions (up to five in some cases) have been carried out. As a consequence, each result is the average of at least three values.

Regulated emissions

Results are presented in three groups based on the vehicle type: bus, truck and light duty (LDV). Table 3 shows buses emissions on the three test cycles.

		Buses					
	Test Cycle	1 Euro 2	2 Euro 2	3 < Euro 0	4 Euro 3	5 Euro 2	6 Euro 3
CO (g/km)	1	5,36	9,07	9,93	7,57	5,07	10,14
	2	3,00	3,58	4,84	3,91	2,35	8,74
	3	3,04	4,86	8,35	4,61	2,94	10,75
HC (g/km)	1	5,29	5,48	8,98	1,36	1,05	1,39
	2	2,69	1,94	2,78	0,51	0,42	0,28
	3	2,71	1,92	3,61	0,49	0,51	0,28
NOx (g/km)	1	34,09	31,06	56,18	21,54	33,48	23,39
	2	14,92	12,98	33,01	9,81	15,05	11,60
	3	17,95	17,16	42,46	12,43	17,30	14,17
PM (mg/km)	1	1040	1200	2630	620	900	540
	2	580	550	950	400	550	450
	3	550	660	1410	350	730	590

Tab. 3; Buses: regulated emissions

As expected, emissions show a strong dependence from engine technology (Fig. 2): the old bus n. 3 (pre Euro 0) gives PM emissions five times higher with respect to Euro 3 buses (n. 4 and 6). In a similar way, NOx emissions are twice as higher.

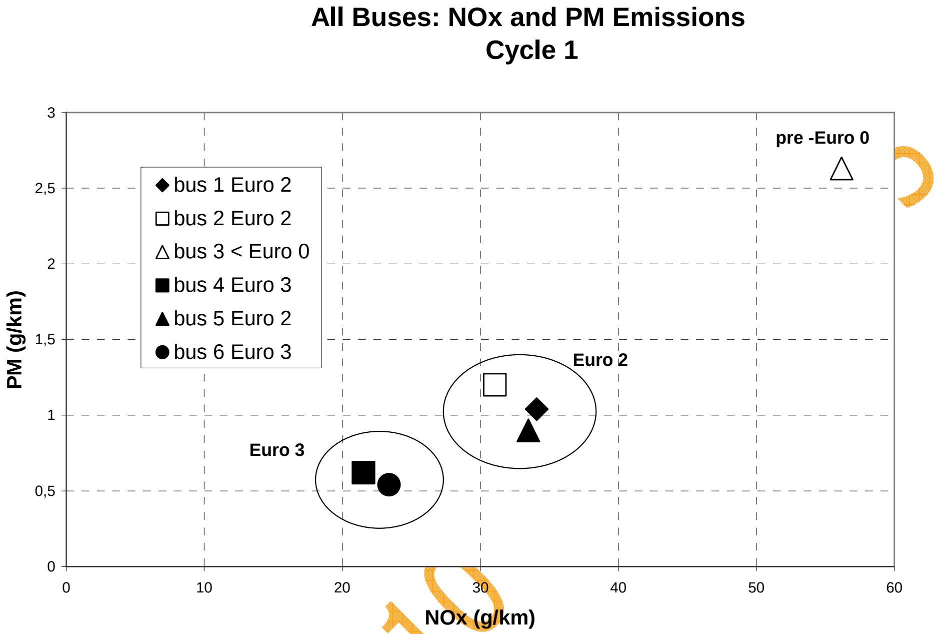

Fig. 2; Bus emissions: engine technology effect

The cycle profile depends on traffic condition, and also has a strong influence on emissions as reported in Fig. 3. Heavy traffic conditions cause an emissions increase of about the 100% in both NOx and PM.

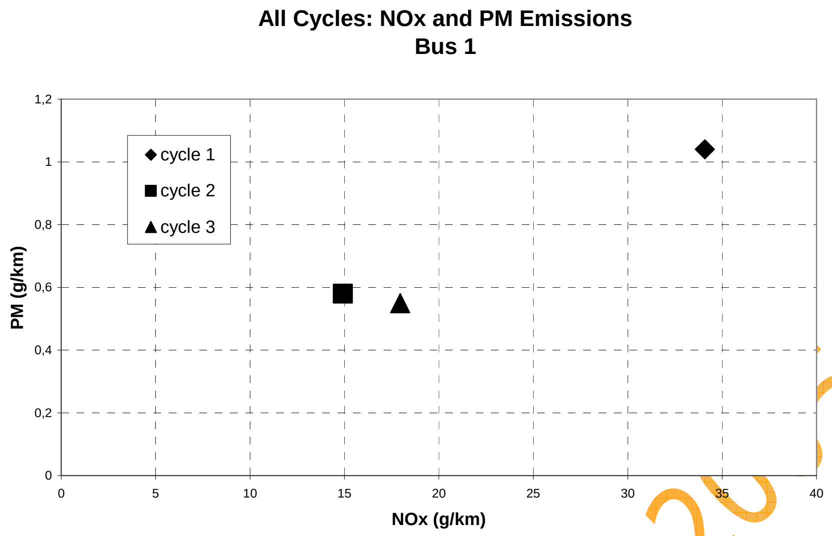

Fig. 3; Bus emissions: driving cycle effect

The truck regulated emissions over the test cycles are reported in Table 4.

		Trucks	
	Test Cycle	1 Euro 2	2 Euro 2
CO (g/km)	1	1,31	1,23
	2	4,32	4,53
	3	2,66	1,98
HC (g/km)	1	0,44	0,72
	2	1,80	3,17
	3	1,32	1,52
NOx (g/km)	1	7,49	7,91
	2	17,01	15,23
	3	12,95	12,79
PM (mg/km)	1	366	362
	2	1002	1373
	3	510	685

Tab. 4; Trucks: regulated emissions

As well known, the most critical emissions of diesel engines are the NOx and particulate.
Fig. 4 reports the two trucks emissions, where the cycle influence can be observed: three times higher PM and twice higher NOx in congested traffic compared with flowing conditions.

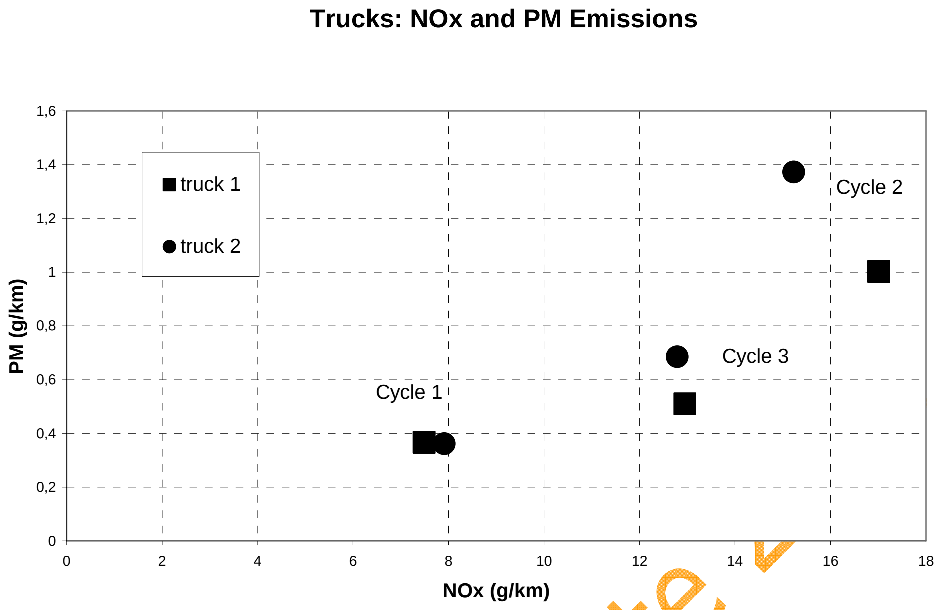

Fig. 4; Truck emissions: driving cycle effect

Test results for LD are reported in Table 5. The PM of the gasoline LDV (n. 4) has not been measured because of its extremely low level.

		Light Duty Vehicles			
	Test Cycle	LD 1 Euro 3	LD 2 Euro 2	LD 3 Euro 2	LD 4 Euro 2
CO (g/km)	1	0,24	0,14	0,17	2,43
	2	0,22	0,09	0,11	0,34
HC (g/km)	1	0,07	0,04	0,03	0,03
	2	0,06	0,02	0,02	0,01
NOx (g/km)	1	2,46	1,13	1,18	0,06
	2	2,49	1,30	1,69	0,04
PM (mg/km)	1	46	35	22	nd
	2	28	35	20	nd

Tab. 5; Light Duty vehicles: regulated emissions

Fig. 4 presents the NOx-PM emissions of the LDV tested. The vehicle influence is clear: the land rover shows about twice higher NOx emissions than the remaining LDVs. The diesel passenger car shows PM emission 40% lower than the delivery van.

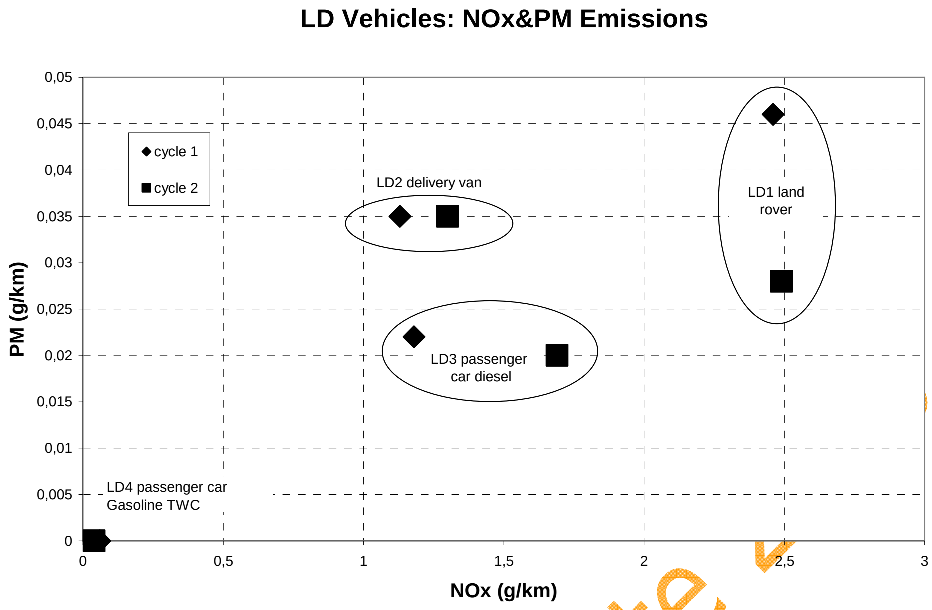

Fig. 5; Vehicle technology and cycle effect on LDV emissions

Unregulated emissions

The following unregulated compounds have been measured:

- BTEX: one ring aromatic hydrocarbon (Benzene, Toluene, Ethylbenzene and Xylenes);
- Aldehydes: formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, crotonaldehyde, MEK+butyraldehyde, benzaldehyde, valeral+cycloexanone, hexaldehyde;
- PAH: fluoranthene, pyrene, chrysene, b(a)anthracene, b(b)fluoranthene, b(k)fluoranthene, b(a)pyrene, db(a,h)anthracene, b(g,h,i)perylene.

The total sum is reported for each compound. Table 6 reports the buses unregulated emissions.

		Buses					
	Test Cycle	bus 1 Euro 2	bus 2 Euro 2	bus 3 < Euro 0	bus 4 Euro 3	bus 5 Euro 2	bus 6 Euro 3
BTEX (mg/km)	1	58,5	72,4	78,5	17,8	23,9	25,1
	2	23,7	21,7	27,4	5,4	9,5	5,7
	3	28,5	31,7	45,5	7,1	11,2	8,2
Aldehydes (mg/km)	1	274,7	254,4	363,2	176,9	165,5	183,7
	2	112,7	139,4	125,7	63,3	63,7	88,5
	3	137,3	111,9	158,2	82,5	88,2	84,8
PAH (µg/km)	1	428,6	570,3	1071,1	338,2	335,3	240,4
	2	224,1	243,5	405,3	254,8	173,6	153,5
	3	178,5	107,3	715,3	147,8	266,5	46,3

Tab. 6; Buses: Unregulated emissions

As previously observed for regulated emissions, engine technology has a dominant effect on unregulated emissions. Fig. 6 shows a reduction of about 65% for BTEX, 50% for Aldehydes and 80% for PAH switching from pre- Euro 0 to Euro 3 buses. Traffic conditions have a sound effect on this type of emissions, as well.

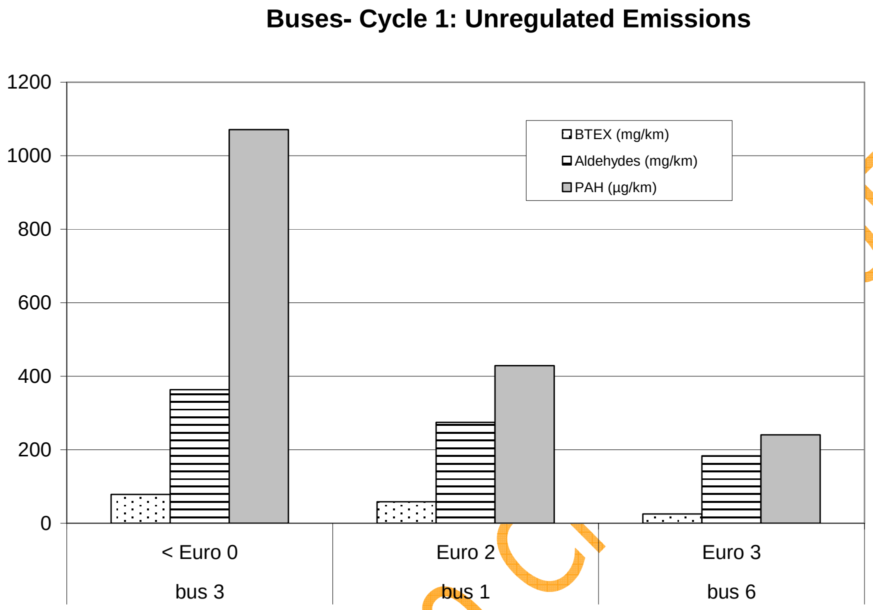

Fig. 6; Engine technology effect on unregulated emissions

Table 7 and 8 report results on truck and LDV tested.

		Trucks	
	Test Cycle	truck 1 Euro 2	truck 2 Euro 2
BTEX (mg/km)	1	13,0	12,2
	2	27,8	59,3
	3	22,2	21,1
Aldehydes (mg/km)	1	62,2	46,6
	2	225,2	274,3
	3	153,3	162,3
PAH (µg/km)	1	66,0	58,4
	2	356,8	210,9
	3	158,1	84,0

Tab. 7; Trucks: unregulated emissions

		Light Duty Vehicles			
	Test Cycle	LD 1 Euro 3	LD 2 Euro 2	LD 3 Euro 2	LD 4 Euro 2
BTEX (mg/km)	1	1,2	1,5	0,4	15,8
	2	1,0	0,7	0,3	13,5
Aldehydes (mg/km)	1	29,9	23,7	10,0	5,4
	2	75,0	20,7	8,1	6,6
PAH (µg/km)	1	6,7	2,5	3,5	3,1
	2	4,3	3,5	2,7	7,8

Tab. 8; Ligth Duty Vehicles: unregulated emissions

CONCLUSIONS

This paper presents emission results from a number of different vehicles on a chassis dynamometer tests with cycles representing real driving conditions.
Several field tests have been run with different classes of vehicle (bus, truck and LDV) to record speed and gear data at the typical traffic conditions of the city of Bologna.
The representative test cycles have been implemented in a laboratory under controlled conditions in order to obtain emissions inventories for air quality studies.
Experimental results have shown a strong pollutants dependence on cycle and engine technology: congested traffic conditions can increase PM and NOx emissions of 100% for buses in the suburban cycle. Euro 3, compared to Euro 2 buses, show a PM reduction from 25 to 45% and a NOx reduction in the range of 25÷30% (depending on the cycle).
Unregulated emissions (BTEX, Aldehydes and PAH) also depend on cycle and vehicles technology. A comparison between Euro 3 and Euro 2 buses shows a reduction in the range of 20÷70%, depending on the pollutant compound and cycle, while switching from congested to flowing traffic conditions provides a reduction in the range of 35÷75% for unregulated emissions.
The conducted research has generated a large number of emissions data for the different vehicle technology over multiple driving cycles. Emission factors of different test vehicles can be compared because all emissions are calculated in g/km.
The research program results have consistently improved knowledge on emissions, with can be usefully employed in future Quality Planning and related assessment.

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