Low-polluting, high-efficiency, mixed fuel/ natural gas engine for transport application

M. Gambino, S. Iannaccone & L. De Simio
Istituto Motori, Naples, Italian National Research Council, Italy

Abstract

Mixed fuel (MF) technology was the first way proposed for natural gas (NG) utilization in heavy-duty transportation. The unsolved problems of high levels of unburned hydrocarbons (THC) and the low amount of possible substitution of diesel oil with NG lead to the renouncing of this technology in favour of spark ignited full NG engines. In many situations, mixed fuel could represent the only way to access the environmental benefits connected to NG use in the transport sector. Therefore, a new generation of mixed fuel systems was developed and analysed the effects of intake throttling, catalytic exhaust gases and exhaust gas recycling (EGR). In the present paper, the influence of each component on performance and emissions is evaluated and the results on the regulated test, for a heavy-duty engine, are reported.
Keywords: mixed fuel, natural gas, emission reduction.

1 Introduction

Since the 1980s, mixed fuel technology was suggested as a realistic way for natural gas utilisation in heavy duty transport circulating in urban areas as an alternative to full natural gas spark ignited engines, not available at that time [1].

Although the unsolved problems of low percentage substitution of diesel oil with NG and high THC emissions, especially at low and medium loads, MF technology has been utilised thanks to the possibility of lowering particulate matter (PM) and exhaust toxicity. The MF technology was particularly suitable to overcome the inconvenience of the high costs of full NG conversion, retaining the possibility of switching to full diesel (FD) operation.

In a diesel-NG MF operation, a carburetted air NG mixture enters the cylinder and is ignited by means of pilot diesel oil injection, as in a compression ignition engine. Then the combustion propagates by means of different flame

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fronts in an almost homogeneous air fuel mixture. At light and medium load, the lean mixture does not allow a quick flame front propagation [2]. On the other hand, at high load knock could occur, caused by auto ignition of the end gas and enhanced by high intake temperatures and high levels of gas substitution [3]. Many methods have been proposed to improve mixed fuel behaviour, but no one is able to solve all the problems in all the operating range. For example, hot EGR have showed an optimum effect at a light load but cool EGR is better at a high load [4].

A sophisticated MF system is necessary to control the complex combustion process involved in these engines [5]. Nevertheless, a changing of the volumetric compression ratio, needed for more expensive spark ignition transformation, is not required for MF operation. Therefore, lower conversion costs are possible, because the disassembling of the engine is not necessary. Consequently, only external modifications have to be implemented to obtain the same levels of performance with lower emissions than the diesel engine. For these reasons the MF technology is particularly suited to reduce environmental impact (especially PM) from old urban transport diesel engines, even if these engines do not permit controlled injection timing and, in addition, the low injection pressure does not allow a good atomization of the small amount of the pilot.

In the present paper the effects of intake throttling, EGR, catalytic exhaust gasses after treatment, and MF operating condition have been analysed to find the optimum configuration of a prototype, in order to minimise the emissions with a negligible influence on performance. In addition, the target of reducing the toxicity with respect to the FD version was reached without great worsening in thermal efficiency.

2 Experimental apparatus

The experimental activity was carried out on a six cylinder heavy duty engine for bus application, whose main characteristics, in diesel mode feeding, are reported in Table 1.

Table 1: Main characteristics of IVECO 8360.46R engine.

6 cylinder in-line turbocharged	
Displacement	7.8 l
Bore x stroke	112 x 130 mm
Compression ratio	17.6 : 1
Rated power	166 kW @ 2050 rpm
Maximum torque	965 Nm @ 1250 rpm

A Borghi and Saveri FE 350S eddy currents dynamometric brake was used. A Ricardo volumetric flow meter was utilised for air flow measurement; a Micro Motion RFT 9739 Coriolì mass flow meter was used for NG consumption, while diesel fuel consumption was measured by an electronic integrated gravimetric system AVL MOD 730. The indicated in-cylinder pressure was acquired by an AVL Indiskop system.

The exhaust emissions were measured using the following analysers: Beckmann HFID MOD 404 for THC, Beckmann HCLA MOD 955 for NO_x, Beckmann NDIR MOD 880 for CO low concentration, Hartman & Braun Uras 10E for NO, CO_2, O_2 and CO high concentration, a partial-flow and partial-sampling dilution tunnel, designed at Istituto Motori, was used for PM collecting.

The conversion of the IVECO 8360.46R diesel engine to MF operation was carried out in Istituto Motori using a developing ETRA system. The schematic layout of the MF system is shown in Figure 1, while a detail of diesel quantity regulation apparatus is given in Figure 2.

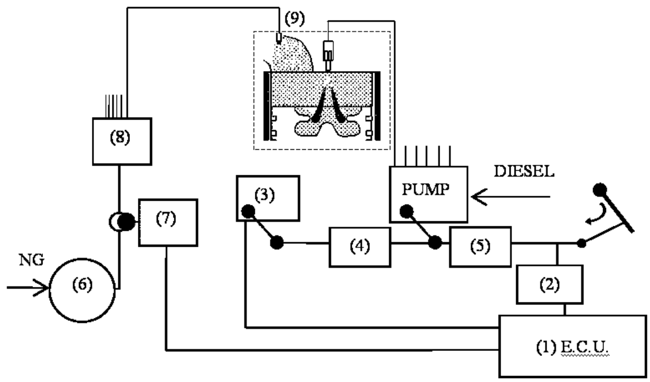

Figure 1: Schematic layout of the test installation.

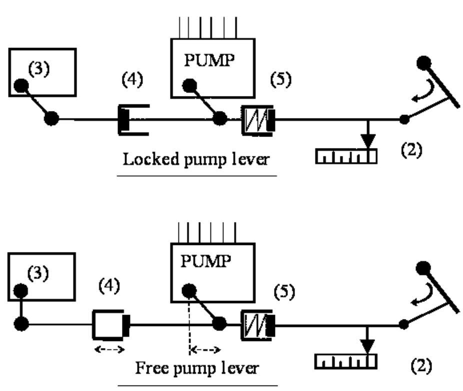

Figure 2: A detail of the regulation system for diesel fuel quantity.

In Figures 1 and 2 the same number indicates the same element, whose function is described below. The MF system is characterised by the installation of the following devices on the original diesel engine:

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1. an electronic control unit (ECU);
2. a transducer of linear shifting to determine the position of the accelerator, adopted by the ECU to regulate the quantity of diesel fuel and natural gas;
3. a stepper motor to control the quantity of diesel oil injected by the pump. It adjusts the position of the injection pump lever and is controlled by the ECU;
4. an adjustable stop, which acts on a telescopic rod between the mentioned stepper motor and the diesel injection pump lever, limiting maximum excursion of the pump (Figure 2), depending on the load and allowing the return to idle position;
5. an elastic element which allows the accelerator to move without a direct effect on the diesel injection pump;
6. a two-stage pressure reducer, which sets the natural gas feeding pressure;
7. a stepper motor which regulates natural gas admission (volumetric control) by ECU order. It acts on a shutter, modifying the passage section for natural gas;
8. a distribution system which feeds natural gas injectors in a continuous way;
9. six natural gas nozzles, one for each cylinder (continuous low pressure multi-point admission), installed close to the intake valve, connected to the mentioned distributor by gum pipes.

The ECU software sets diesel fuel and natural gas quantities on the basis of the values of two principle variables: engine speed and accelerator position. Mixed fuel operation can only be allowed at a speed higher than idle, setting NG and diesel stepper motors to optimise performance and emissions.

The high oxygen excess, typical of low load MF operation, is responsible for high THC emissions. To face this problem, a motorised throttle valve was installed at the intake of the engine. In Figure 3 the valve and the related throttle position (TP) sensor are shown.

THC decreasing, due to the throttling operation, was counterbalanced by an expected NO_x increasing for the higher combustion chamber temperature. For this reason a three-way catalyst was used.

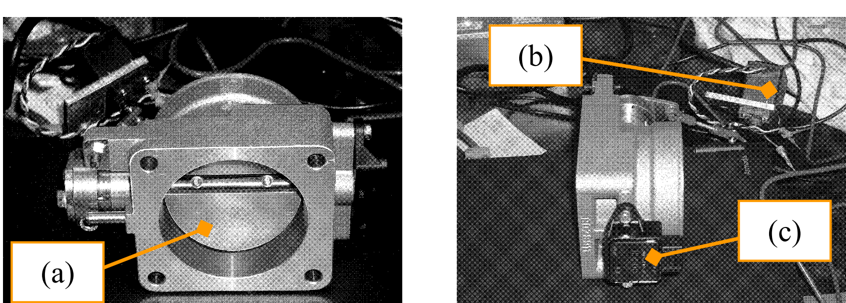

Figure 3: (a) throttle valve, (b) electric motor, and (c) throttle position sensor.

To optimise low load combustion and knocking resistance, a high-pressure route EGR apparatus has been designed and realised, (schematic of Figure 4). The exhaust gas is taken upstream of the turbine (b in Figure 4) and is added into the intake manifold downstream of the throttle valve (a in Figure 4).

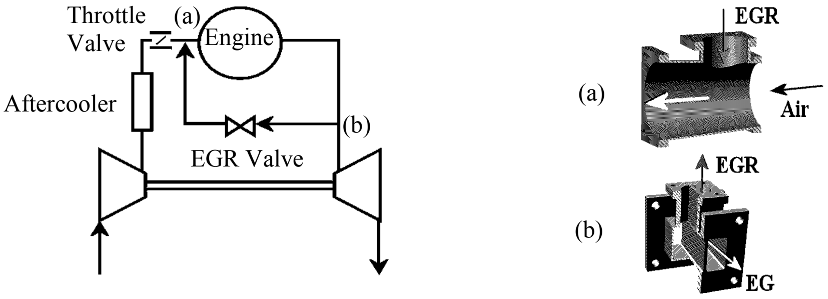

Figure 4: High-pressure route EGR system.

3 Experimental results

3.1 Un-throttled operation

Generally THC and CO emissions from MF engines are very high, principally due to very lean operation [2, 6]. According to the literature, substantially the same result was obtained with the first un-throttled configuration tested in Istituto Motori. In Table 2 FD and MF emissions at 1250 rpm are compared, at different diesel and NG relative quantity, at low (250 Nm) and medium load (500 Nm).

Table 2: Preliminary tests on IVECO 8360.46R FD and MF engine, without throttle valve.

	Speed rpm	**Torque Nm**	**Diesel %**	**NG %**	**THC ppm**	**CO ppm**	**NO_x ppm**	**O_2 %**
FD	1258	245	100	0	118	400	479	15
MF	1260	250	57	43	1820	1900	393	14.9
MF	1260	230	38	62	2680	2400	349	14.8
FD	1260	510	100	0	88	136	750	10.8
MF	1260	510	49	51	1500	1200	741	11
MF	1261	520	34	66	1680	1200	919	10.6
MF	1259	510	18	82	1930	1175	995	10.7

THC and CO emissions are largely higher (about one order of magnitude) with MF operation in every test condition. In particular, at low load, both THC and CO increased at higher NG percentage in MF, while NO_x resulted slightly

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lower. At medium load, a different behaviour can be noted. In this case, THC and NO_x increased with NG percentage, while CO was almost constant. This could be explained with better combustion at medium load because of lower oxygen excess in the NG/air mixture.

Therefore as a first step, a motorised throttle valve was installed at the intake, in order to control air admission and consequently enrich the mixture to run with the right oxygen quantity in each operating condition.

3.2 Throttled operation

Some tests were carried out varying NG percentage and throttle valve position. The results are shown in Table 3.

Table 3: Preliminary tests on IVECO 8360.46R FD and MF engine, with throttle valve.

	TP deg	speed rpm	torque Nm	diesel %	NG %	THC ppm	CO ppm	NO_x ppm	O_2 %
FD	93	1243	257	100	0	95	182	520	13.9
MF	93	1246	305	24	76	2690	2000	440	13.4
MF	17	1242	250	20	80	1790	1240	880	9.6
MF	13	1242	215	21	79	1280	1200	1030	6.4
MF	13	1242	260	18	82	930	8900	1170	3.8
FD	93	1247	480	100	0	77	264	885	10.5
MF	93	1245	480	33	67	1670	1180	1260	10.24
MF	30	1245	470	33	67	1390	1000	1630	9.1
MF	23	1244	480	33	67	1290	1200	1840	7.4
MF	19	1245	450	33	67	940	2900	1970	5.0
MF	18	1242	495	12	88	720	3700	2500	3.6
MF	18	1245	485	13	87	690	5900	2600	3.3
MF	18	1243	510	10	90	600	9500	2640	2.9

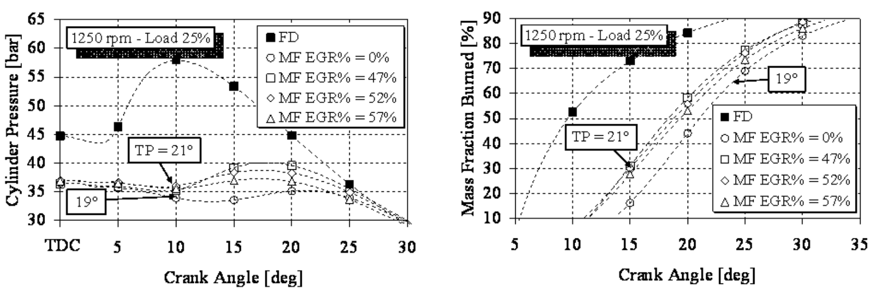
FD and MF emissions were compared at low and medium load: better results for THC, CO, NO_x emissions in FD operation were found. It is important to note that THC in MF operation decrease at lower throttle position, for the related air/fuel reduction, even if they result at least about one order of magnitude higher than in FD. In these conditions, a better combustion has been obtained but, as expected, NO_x emissions are greatly increased. On the other hand, lower oxygen availability causes a consistent CO increasing. Therefore throttling gives advantages in terms of combustion quality (low THC and high NO_x), but obviously, a CO and PM increase has to be expected.

3.3 EGR and three-way catalyst

To decrease high emissions from MF, a three-way catalyst (TWC) could be used, and consequently a stoichiometric mixture should be assured. However, throttling (until stoichiometric) could be limited (especially at low load) by bad combustion quality, due to low compression pressure, which compromises pilot auto-ignition. Therefore, an EGR system was developed in order to improve engine performance at stoichiometric throttled low load operating conditions.

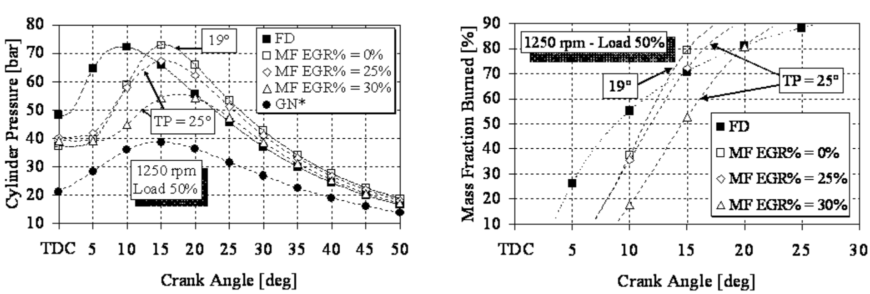
At low load, peak pressure (Figure 5a) and mass fraction burned (Figure 5b) are always lower (at EGR% varying from 0 to 57%) for throttled MF operation, even if injection timing is the same. Anyway a little combustion speed increasing with EGR, respect the condition without EGR (Figure 5b), allowed a slightly higher peak pressure due to an early pressure cycle development, (Figure 5a).

At medium load a better combustion was obtained as shown in Figure 6a, where pressure cycles in FD and MF are reported. Nevertheless throttled MF operation without EGR has a lower pressure than FD before ignition, the same peak pressure is reached, indicating a very high MF combustion speed. In fact, in MF mode, several ignition points (one for each injector hole) generate as many flame fronts, giving a very fast heat release rate.



(a) (b)

Figure 5: Cylinder pressure and mass fraction burned at FD and throttled MF operation, 1250 rpm, 250 Nm.



(a) (b)

Figure 6: Cylinder pressure and mass fraction burned at FD and throttled MF operation, 1250 rpm, about 500 Nm. (* six-cylinder 9.5l IVECO 8469.21 compression ratio 10:1).

This could represent a problem for knocking resistance at high power levels, because of the greater intensity of the pressure wave on the unburned mixture fraction (end gas). To contrast this effect, tests at different EGR percentages were carried out. Appreciable lower peak pressure and lower mass fraction burned were observed at EGR fraction increasing, (Figure 6a,b), for the effect of inert gas that, reduces combustion speed.

Anyway MF pressure cycle, also with EGR, is much higher than a dedicated SI NG one, (Figure 6a), also taking into account the difference of displaced cylinder volume and compression ratio. Therefore, the homogeneous air/NG mixture is greatly stressed towards knock in a MF engine. Consequently, maximum performance has to be limited to save engine reliability.

Emissions measured in MF with EGR and TWC show a general great THC and CO oxidation, while NO_x high conversion efficiency can be observed only at medium and high load, (Table 4). It should be noted that catalyst oxidation action is effective also in FD because of the presence of the catalyst installed for MF, while there is no effect on NO_x reduction for the great amount of oxygen, typical of a diesel exhaust.

Great EGR percentages allow a lower THC formation because of higher inlet mixture temperatures permitting a better flame front propagation. From an optimum EGR%, a further EGR% grove determines a THC increase due to combustion quality decay. NO_x decreasing in the cylinder is related to the lower maximum combustion temperature and inferior local probability of fuel molecule to react with oxygen. This is due to the increment of inert gases mass, and it is also the cause of CO increasing.

Table 4: Emissions in MF with TWC and EGR.

	TP deg	**EGR %**	**speed rpm**	**torque Nm**	**diesel %**	**NG %**	**THC g/kWh**		**CO g/kWh**		**NO_x g/kWh**	
							b*	a*	b*	a*	b*	a*
FD	WOT	0	1251	261	100	0	0.7	0.3	1.5	0.0	7.3	7.0
MF	19	0	1240	261	26	74	15.2	1.4	9.8	0.0	7.1	6.8
MF	21	47	1251	296	21	79	7.4	2.9	7.4	0.0	0.6	0.4
MF	21	52	1247	280	24	76	5.9	0.6	14.4	0.0	0.3	0.3
MF	21	57	1247	281	24	76	5.8	1.5	32.2	0.0	0.3	0.1
FD	WOT	0	1253	446	100	0	0.4	0.1	0.5	0.0	7.6	7.4
MF	19	0	1234	532	9	91	3.9	0.2	33.4	0.3	19.1	17.6
MF	25	23	1246	452	14	86	1.8	0.5	25.4	0.0	4.1	3.0
MF	25	30	1251	425	17	83	4.6	2.4	36.2	0.0	1.4	0.4
FD	WOT	0	1251	698	100	0	0.5	0.1	2.3	0.0	7.0	6.8
MD	26	9	1250	600	11	89	3.9	0.1	32.5	0.0	9.1	0.9
FD	WOT	0	1258	900	100	0	0.4	0.2	8.3	0.1	7.7	7.4
MF	WOT	<1	1249	773	8	92	2.9	0.1	31.1	0.1	15.2	0.6

b* = before catalyst; a* = after catalyst

3.4 13 mode results

The above optimisation tests indicated that low load conditions cannot be positively performed in MF neither at low nor at high speed. For this reason, the engine control was implemented for operating in MF only at medium and high power levels. At low power (from idle to 25% of the maximum load) engine performed in FD.

For this reason the European R49 cycle (13 mode) [7], was carried out in a double modality (named MF'): points 1 (idle), 2, 3, 7 (idle), 11, 12, 13 (idle) in FD, while, in MF, points 4, 5, 6, 8, 9, 10, the most influent on emission calculation. In Table 5 MF' results are compared with those of a non-catalysed FD engine. Fuel consumption on energy basis, also reported in table, shows that NG contribution is about half.

The diesel NO_x-PM trade-off was largely overcome with MF' operation with a great decrease of both NO_x (from 6.5 to 2.6 g/kWh) and PM (from 0.26 to 0.07 g/kWh). Minor differences were found for THC and CO, while TE (Total Efficiency) resulted lower for MF'. Lower maximum power (about 10%) of the MF engine necessary to avoid knocking, decreased the weighted power calculated on the 13 mode cycle.

Table 5: 13 mode results.

	Power kW	THC	CO	NO_x g/kWh	CO_2	PM	TE %	Diesel % (energy based)	NG % (energy based)
FD	68	0.6	2.2	6.5	727	0.26	37	100	0
MF'	59	0.4	1.4	2.6	651	0.07	32	50	50

4 Conclusion

An old heavy-duty diesel engine for urban bus application has been transformed into MF, retaining the possibility of the FD mode. To optimise combustion development and emission control, a throttle valve, a three-way catalyst and an EGR system have been installed, in order to run as close as possible to stoichiometric conditions. In particular, emissions in MF at medium loads, have been drastically decreased with respect to FD. The result has been obtained reducing diesel oil supply, until 8%, in favour of high NG percentage.

A bad MF combustion, at low load, and knocking, at high power levels, occurred. For these reasons, 13 mode cycles have been performed fuelling the engine in FD at idle and very low load, and in MF at medium and high load, the most influent on total emission amount. In any case, the optimisation, according to this strategy, has allowed a relevant emission reduction. In particular, typical diesel NO_x-PM trade-off was greatly decreased (NO_x 60% and PM 73%), and THC and CO resulted about 35% lower in MF. The over all energy consumption on 13 mode cycle is about the same for NG and diesel oil, with a total efficiency only 14% lower for MF operation. These results demonstrate the potential to reduce emissions from old heavy-duty diesel engine with a developing electronic control system for MF operation.

Notation

CO_2	Carbon dioxide	NO_x	Nitrogen Oxides
ECU	Electronic Control Unit	PM	Particulate Matter
EG	Exhaust Gas	TDC	Top Dead Center
EGR	Exhaust Gas Recycling	TE	Total Efficiency
EGR%	EGR rate	THC	Total Hydrocarbon
FD	Full Diesel	TP	Throttle Position
MF	Mixed Fuel	TWC	Tree Way Catalyst
NG	Natural Gas	WOT	Wide Open Throttle

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