A Fleet Test to Study the Effects of Detergent Additives on the Performance of Bus Diesel Engines

Dr. L. Tartakovsky, Dr. M. Gutman, Dr. Y. Kirzhner
& Prof. Y. Zvirin
Internal Combustion Engines Laboratory,
Research Center for Energy Engineering &
Environmental Preservation,
Faculty of Mechanical Engineering,
Technion- Israel Institute of Technology,
Haifa 32000, Israel

ABSTRACT

Many fuel detergent additives are now available commercially, and in some countries they are in regular use. The objective of the present study was to demonstrate the positive role of diesel fuel detergent additives in realistic driving conditions of the buses in Israel. The paper describes a fleet test with ten buses, which ran one month on normal fuel, and then another month on the same fuel with a detergent additive. This was a second stage of an extensive on-going research program aimed at reducing exhaust emissions of in-use diesel vehicles by improving the fuel quality. The main conclusion drawn from the analysis of the test results was that the use of the detergent additive to the fuel led to a significant reduction of injector nozzle fouling. The introduction of the additive did not lead to any negative side effects during the test, such as increased wear, corrosion, etc.

1. Introduction

Public transportation in Israel is based almost entirely on diesel vehicles (buses, taxis, and trucks). Therefore, it is essential to attempt finding ways to reduce pollutants' emission from diesel engines (in-use as well as new). One option to advance in this direction is to use reformulated diesel fuel (called also premium or low-emission), and additives play a key role in improving its quality.

An important property of the reformulated diesel fuel is its detergency, which is essential for maintaining good performance of the engine between periodic servicing. The use of detergent additives, that has become widespread in Europe during the last decade, was evoked by problems of injector nozzle fouling (or coking). Nozzle coking, induced by thermal degradation of fuel and crankcase lubricant components, and worsened by hot combustion gases. This results in slower initial combustion and pressure rise delay in the cylinder with subsequent increased rate and higher peak pressures, [1]. These effects cause increased engine noise, emission of pollutants and fuel consumption. Detergent/dispersant additives containing surfactants can prevent deposit formation ("keep-clean"), as well as remove detrimental deposits already formed ("clean-up") in fuel injectors, and thus yield and ensure good spray pattern characteristics, and maintain engine performance and pollutants emission at best levels possible for in-use engines, [1-4].

A range of substances is now suitable as detergent additives for diesel fuel: Amines, Imidazolines, Amides, Fatty Acid, Succinimides, Polyalkylene Succinimides, Polyalkyl Amines and Polyether Amines, [2-5].

The positive role of the detergent additives has led many automobile manufacturers to recommend their use in diesel fuel. For example, the French motor industry has set specific requirements for high quality fuels, and these include fuel detergency performance for injector nozzles. The European Automobile Manufacturers Association also supports the use of injector cleanliness additives, [5].

Evaluating the performance of detergent/dispersant additives is an important aspect in the development of good quality products for use. Care must be taken when selecting additives in order to avoid any problems created by adverse side effects resulting from their addition to the base fuel, [6]. Such side effects can appear because of incompatibility between the added ingredients and the base fuel, or corrosivity. Examples of detrimental effects are water and oil emulsification, deposit formation in critical areas of the engine and fuel system, corrosion, etc. Therefore, engine tests must be conducted for evaluating the improvements provided by the additives and ensuring that no adverse side effects occur.

Two recognized test methods are mainly employed now for performance evaluation of detergent additives: in Europe, the test is based on the widely used Peugeot XUD 9 1.9 l light duty IDI diesel engine, [7], and in the U.S. on the Cummins L-10 engine, [8]. The latter is increasingly becoming accepted as the standard for performance evaluation of detergent additives for controlling nozzle fouling in DI engines.

Many fuel detergent additives are now available commercially, and in some countries they are in regular use. The objective of the present study was to demonstrate the positive role of diesel fuel detergent additives in realistic driving conditions of buses in Israel.

The paper describes a fleet test with ten buses, which ran one month on normal fuel commercially sold in Israel (base fuel), and then another month on the same fuel with a detergent additive. This was a second stage of an extensive on-going research program aimed at reducing exhaust emissions of in-use diesel vehicles by improving the fuel quality. The first stage included the development of a screening test method for evaluation and selection of detergent additives, [9].

2. Fleet Test Methodolgy

The fleet test was performed with ten Mercedes buses of the Egged Transportation Cooperative, listed in Table 1. The entire work was carried out jointly with the company staff.

Two series of tests were conducted, where each of the ten buses ran its regular line (i.e., same roads and driving cycle), about thirty days with the base (normal) diesel fuel (specifications in Table 2), and then for about thirty days with a detergent additive to the fuel (same batch). New nozzle injectors were installed at the beginning of each of these two test periods. Their coking rate was determined by air flow measurements before and after the test in an experimental laboratory apparatus constructed according to the ISO-4010 Standard , [9,10].

Prior to the two series of tests, the engines were tuned to manufacturers' specifications and all routine checks and tuneups were performed. In two buses, the oil was changed at the start, and samples were analyzed chemically and by spectroscopy at the end of each period. The samples were taken immediately after idle operation, in order to ensure homogeneity. Smoke level measurements were performed at the start and end of the test by the following procedures: (a) with both Hartridge and Bosch smokemeters, at steady state, full load, and 85% of rated engine speed (according to the Israeli Standard test method); (b) at free acceleration, according to the 72/306/EEC test procedure, using the Hartridge smokemeter.

Table 1: Fleet test -- buses and engine types (Nos. 1-3: interurban; 4-10: urban)

	Bus type	Engine type	Production year	Odometer start, km.	Covered distance, km	
					with base fuel	with additized fuel
1	0-303	0M-442	1991	527795	11057	13381
2	0-303	0M-442	1989	881729	11301	14751
3	0-303	0M-442	1990	627492	10816	14095
Average	**0-303**	**0M-442**	**1990**	**679005**	**11058**	**14076**
4	0-405G	0M-447hA	1992	169463	4307	3389*
5	**0-405G**	**0M-447hA**	**1991**	**192682**	**3999**	**5055**
6	0-405	0M-447h	1991	305883	6539	6967
7	0-405	0M-447h	1990	409115	6961	8157
8	0-405	0M-447h	1992	230836	6284	7334
9	0-405	0M-447h	1990	365994	5893	6995
10	0-405	0M-447h	1992	193212	5493	6962
Average	**0-405**	**0M-447h**	**1991**	**301008**	**6234**	**7283**

*) The bus operation was interrupted due to a failure unrelated to the test subject.

The fuel consumption of each bus was measured by recording fueling, done always from the same tank. Mileage was also monitored. The additive for the fleet test was selected after a careful examination of the results of the screening laboratory test described in [9]. The treat rate of the additive used in the fleet test was 300 mg/kg. It was introduced into the diesel fuel in the road tanker after mixing with a small amount of just prior to removal from the storage terminal of the batch to the refueling special tank for the tests.

Table 2: The base diesel fuel specifications

Density at 15°C, kg/l	0.841
Kinematic viscosity at 40°C, cSt	3.6
Flash point °C	65
Cold filter plugging point (CFPP), °C	+ 7
Cetane Index	54
Sulphur content, % wt	0.2
Distillation, °C	
Initial boiling point (IBP)	166
10%	216
50%	291
90%	346

3. Results and Discussion

The accumulated distances (mileage) traveled by buses in the fleet test and their averages for each bus model are given in Table 1. As shown in this table, distances accumulated by the buses operated with the additized fuel were 7% to 31% larger than those with the base fuel (due to logistics of the test organization). The average differences were 27%, 26%, and 17% for models 0-303, 0-405G and 0-405, respectively. The mileage accumulated by the interurban buses 0-303 was twice that of the urban models.

As explained above, the additive effectiveness was mainly studied by measuring the air flow rate, Q, through the injector nozzle. The relative change of Q between the start and end of the test (Δq, %), is used for this evaluation. Figure 1 shows the averaged results of Δq as a function of the injector needle lift for the base and additized fuels and for each bus model.

It is noted that under the same operating conditions, the level of nozzle fouling (amount of deposits) depends on the duration, or distance of travel. As seen in Table 1, it was longer with the additized fuel test than with the base fuel. In order to compare the results on a common basis, the flow rate reduction for the latter was corrected by:

$$\Delta q_b = \Delta q_m \; S_a/S_b,$$

where : Δq_m denotes the measured relative reduction of Q (in %) and S_a and S_b are the accumulated traveled distances with the additized and base fuels (Fig. 1 includes both Δq_m and Δq_b). This simple relation stems from the approximation of linear deposit growth with time. It is known that the real behaviour is not linear, but progressive (thicker deposits for any elapsed time). Therefore, the results presented here are a lower limit, and the actual effect of the additive is more significant than that perceived from Fig. 1. Obviously, lower air flow reduction (Δq) during the test means a better state of the nozzle. As seen from the figure, and considering the above argument, the results clearly show that the detergent additive is, indeed, very efficient in preventing the accumulation of deposits (coking), and maintaining the nozzles clean.

It is important to note that for each of the injector nozzles of all the bus engines, the average air flow rates were improved (lower Δq) with the additized fuel. The max. reduction of Q was decreased by using the additive compared to the base fuel from 31% to 3% for bus model 0-303; from ~9% to ~1% for model 0-405, and from ~13% to ~1.5% for model 0-405G. The effectiveness of the additive in preventing nozzle fouling is more pronounced for the interurban buses, model 0-303. This is even more conspicuous than the results for the urban buses 0-405 and 0-405G because of the larger distances traveled during the test.

Table 3 shows the average results of the fuel consumption of the tested buses. These were defined and calculated by the following equation:

$$g = 100\ \Sigma G/S$$

where: g is the mean fuel consumption during the test, (l/100 km); ΔG is the total amount of fuel consumed by the bus during the test, either with the base fuel or the additized (l), and S is the respective total distance traveled (km).

Table 3: Average results of bus fuel consumption, g, (and variance, σ_n)

Bus model	No. of buses	Fuel consumption g, l/100 km;(σ_n)		Change of g, %
		Base fuel	Additized fuel	
0-303	3	40.3 (0.31)	40.2 (0.39)	- 0.25
0-405G	1	65.4	71.3	9.0
0-405	5	50.1 (0.78)	51.3 (1.32)	2.4

As can be seen from Table 3, very good repeatability in fuel consumption results was obtained for the buses of the same model, especially the interurban one (standard deviation, $\sigma_n < 1\%$). This can be explained by the similar and repeated traffic conditions of these buses. On the other hand, under urban traffic conditions, the driver's experience and driving style is a decisive factor in attaining appropriate engine operating conditions and, hence, they affect the fuel consumption.

The results (Table 3) show that the average fuel consumption of the interurban buses, running with additized and base fuels, remained almost the same. A slight tendency toward economy is observed with the additized fuel. For urban buses, the fuel consumption increased (2.4% for bus model 0-405 and 9% for model 0-405 -- double-wagon construction). However, it is noted that the test with the base fuel was performed during a cold period of the year -- from 13.2.95. to 16.3.95 -- while the test with the additized fuel was conducted from 14.3.95. to 19.4.95, in quite different weather conditions - in particular, many days with temperatures above 21°C. Therefore, the air conditioning (AC) systems were often functioning. It is obvious that the reason for the increased fuel consumption during the test with the additized fuel resulted from the higher ambient temperatures, and the operation of AC, especially for the double-wagon buses, model 0-405G, with two AC systems. The power required by the AC is a significant factor: 28KW for the 0-303 and 0-405 models, and twice-56KW for the 0-405G.

The smoke measurements were performed by the procedures described in Section 2. An example of the results for the interurban buses is given in Table 4. As shown, the smoke levels remain without change during the service when the bus runs with the additized fuel, contrary to a clear trend of smoke rising during the service with the base fuel. The accumulated distances traveled by the urban buses were not sufficient to obtain significant effects of the additive on smoke level changes.

Table 4: Average results of smoke measurements for interurban buses (model 0-303)

Test condition	Smoke level, HSU			
	Base fuel		Additized fuel	
	Before test	After test	Before test	After test
Full load	15	17	17	16
Free acceleration	11	13	15	13

As mentioned in Section 2, samples of the lubricant oil were examined in order to check whether the additive would cause detrimental side effects. The results of the oil spectral and chemical analysis are presented in Table 5. It is clearly shown that the changes between the values found with the additized and base fuels are minimal, and it is concluded that there is neither augmentation of wear and corrosion nor reduction of lubricant quality as a result of using the additive.

Table 5: Results of engine oil analysis

Sample identification	K.V. at 40°C cSt	K.V at 100°C cSt	TAN mg KOH /g	Water cont., % wt.	Contaminants Content, ppm											
					Ca	Al	Zn	Ni	Mg	Sn	P	Cr	Pb	Cu	Fe	Si
Bus 1, base fuel	101.2	12.24	2.90	0.11	2533	10	1261	1	585	1	974	2	6	2	17	36
Bus 1, additized fuel	87.8	12.14	2.20	0.10	2755	10	1224	0	613	1	975	1	6	18	18	23
Bus 2, base fuel	94.4	12.71	2.62	0.13	2838	10	1283	0	621	0	991	2	6	3	23	17
Bus 2, additized fuel	90.7	13.53	2.18	0.16	2573	10	1282	1	586	1	986	2	6	2	13	20

A decrease of the acidity (25-30%) is observed in the period of running with the additized fuel. The occasional increase of the Cu content does not indicate any enhanced wear, because this phenomenon would necessarily have been associated with increase of othemetals: Cr, Sn, Pb, Al, and Fe.

4. Conclusions

Based on the results obtained the fleet test, the following conclusions have been reached. For each of the buses involved in the test, the use of the detergent additive to the fuel led to a significant reduction of injector nozzle fouling. The air flow reduction levels (between start and end of the tests), decreased from about 31% maximum (with the base fuel), to about 3% (with the additized) for the interurban buses, and from 9÷13% maximum to about 1÷1.5% for the urban models. The differences in the accumulated levels of nozzle coking for urban and interurban buses are due to the different distances traveled.

Unfortunately, the results of the fuel consumption were substantially affected by the operation of the powerful AC systems, due to the rise of ambient temperature, and subject to weather fluctuations typical in the Israeli climate during this season. Nonetheless, the average measured values of fuel consumption were without change for the interurban buses, and increased by 2.4% and 9% for urban models (the latter is a double-wagon). It is important to note that despite the influence of the AC, the fuel economy of the interurban buses, which accumulated much larger distances than the urban buses, did not change. This was the result of sufficient reduction in nozzle fouling due to the detergent additive, that compensated for the aforementioned negative tendency.

The use of the detergent additive to the fuel suppressed the rising of the smoke levels during the test. The introduction of the additive did not lead to any negative side effects, such as increased wear, corrosion, etc.

Based on the results of this test, it is now planned to conduct a more extensive experiment with a fleet of about 300 buses for a longer period (not less than six months), in order to reach a decision for the policy pertaining to controlled additizing of the diesel fuel.

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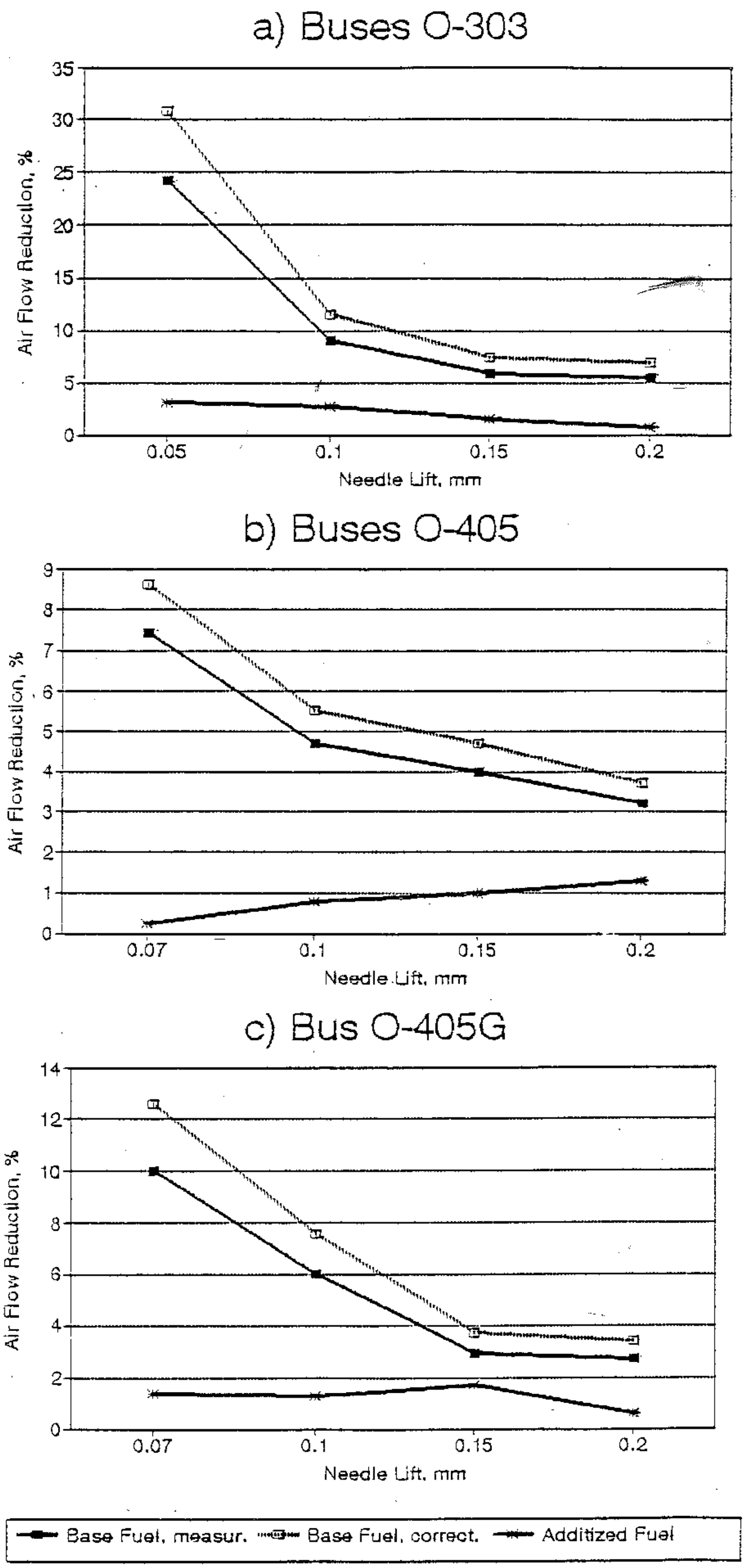

Figure 1: The averaged results of air flow reduction, Δq, through the injector nozzles.