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ABSTRACT

This paper describes the development of an emissions upgrade kit for the DDC 6V-92TA MUI bus engine manufactured by the Detroit Diesel Corporation (DDC). It incorporates three components: a base engine upgrade kit, a diesel oxidation catalyst and an electric demand turbocharger. A particulate matter level of 0.09 g/hp-hour has been demonstrated and certification is currently being sought at the 0.1 g/hp-hour level under the US EPA's Urban Bus Rebuild/ Retrofit Program.

INTRODUCTION

Diesel engines remain in widespread use because they are reliable, durable, easy to maintain, inexpensive to operate and are more fuel efficient than any other option. They are also low emitters of so-called greenhouse gases. Unfortunately, diesel engines have relatively high levels of particulate emissions (PM) and visibly contribute to airborne pollution. For this reason, the US EPA has focused much attention on PM emissions from diesel buses which operate in large metropolitan areas. Because diesel engines typically have a long lifetime, the EPA has mandated that pre-1994 model-year bus engines must incorporate low emission equipment at the time of an engine rebuild. The primary requirement of the EPA Urban Bus Rebuild/ Retrofit program [1] is to meet a 0.1 g/hp-hour PM emissions level, depending on the availability of certified equipment. This paper reports on one such retrofit kit, applicable to the 6V-92TA MUI engine, which has been developed by the Detroit Diesel Corporation (DDC) in conjunction with its emissions technology partners. In addition to upgraded base engine hardware, the kit employs a novel high response electric demand turbocharger (EDC) and an advanced technology diesel oxidation catalyst.

DDC 6V-92TA MUI EMISSION UPGRADE TECHNOLOGY

DDC ENGINE UPGRADE KIT - The Detroit Diesel 6V-92TA MUI engine was first certified for use in urban bus applications in 1979 and remained in production thorough 1989. Emission upgrade technology was introduced in 1990 and has been continuously developed by DDC to the point of US EPA Certification (for 25 percent PM reduction),which was obtained in October of 1995. Upgrades have been designed to be incorporated at regularly scheduled engine overhauls and to give bus operators the flexibility to standardize their engine build. As shown in Figure 1, upgrades include a turbocharger, an upgraded scavenger blower assembly, 1989-standard fuel injectors and current production pistons, piston rings and cylinder liners. Specific hardware combinations are offered based upon crankshaft rotation (right hand or left hand rotation), engine power output (based upon fuel injectors size) and the orientation of the engine in the bus (43 degree tilt, 15 degree tilt or upright).

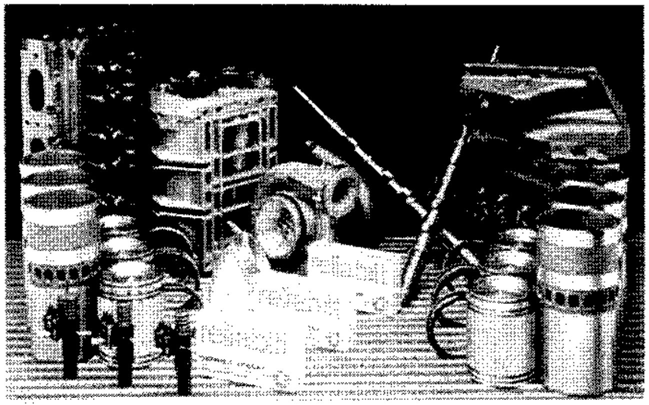

Figure 1: DDC 6V-92TA Engine Emissions Upgrades

Testing at DDC has shown that PM from a two-cycle engine is approximately half soot (carbon) and half organic compounds (Volatile Organic Fraction, VOF). (The introduction of low sulfur diesel fuel has reduced any PM contribution from sulfate production to less than a few percent of the total.) As shown in Table 1, upgrading the base engine significantly reduces PM. Soot is reduced by improved combustion resulting from modifications to the fuel injectors and air system and the improved cylinder components reduce oil consumption and hence VOF.

Additional reductions in both PM components have been achieved using a diesel oxidation catalyst to reduce VOF and an electric demand turbocharger (EDC) to reduce soot. The catalyst offers the advantages of low-cost, proven durability and of being a passive component which is easy to install. The EDC allows intake boost pressure to be achieved much more rapidly than for a conventional turbocharger, so that the period of low-boost during acceleration is largely overcome.

ELECTRIC DEMAND TURBOCHARGER -

The EDC (Figure 2) is provided by Turbodyne Systems Inc. and consists of a low-inertia centrifugal compressor installed ahead of and in series with the engine turbocharger. A bypass valve prevents any intake restriction once the turbocharger has spooled-up. The EDC is driven by a high-torque, brushless DC motor, drawing a peak current of 300 amps and is controlled by an engine interface controller. To reduce vehicle battery demand, the controller deactivates the EDC after 8 seconds or once an airbox pressure of 54 kPag is achieved. Activation is triggered by the input signal to the engine governor, which ensures that response is rapid and repeatable. The system achieves a boost pressure of 20 kPag even before the engine speed rises significantly above idle. The EDC has a multiplier effect, because EDC air also flows through the turbine of the engine turbocharger, which in itself causes it to accelerate more rapidly. Bench testing has demonstrated that the EDC reaches full pressure within approximately 0.4 seconds, which is about 5 times faster than a conventional turbocharger.

DIESEL OXIDATION CATALYST -

The diesel oxidation catalyst (DOC) is provided by Engine Control Systems Ltd. and has also been EPA certified to yield 25 percent PM reduction. Washcoat and precious metal loadings have been specially developed to control VOF, to be durable at high temperature and inhibit sulfate formation [2].

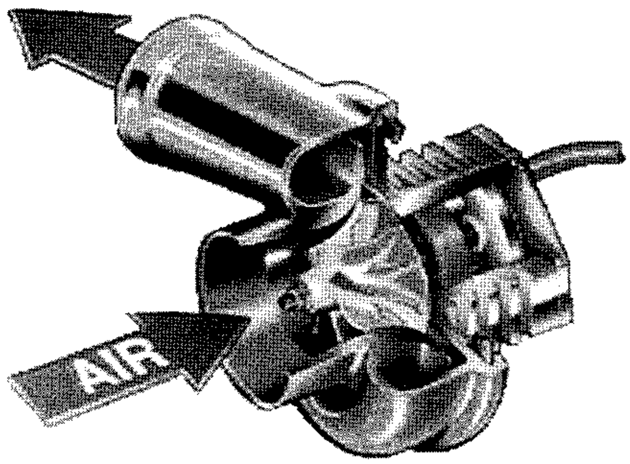

Figure 2: Turbodyne Electric Demand Turbocharger

The catalyst is typically provided as a muffler/catalyst combination. Because excessive back pressure can significantly degrade both engine and emissions performance, designs have been carefully optimized to have low backpressure. Figure 3 shows data obtained at Connecticut Transit on a 1990 bus with a DDC 6V-92TA DDEC II engine. Results were obtained at rated speed and full load, at transmission stall and for free acceleration. All tests are seen to meet the DDC specification for back pressure not to exceed 10 kPa.

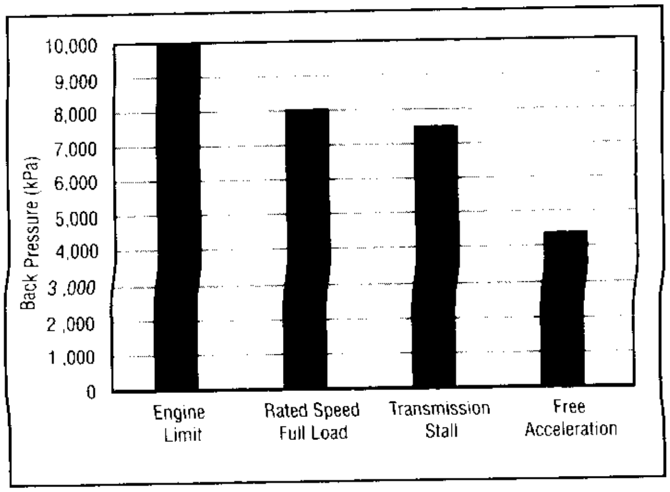

Figure 3: Muffler/Catalyst Backpressure Validation Test

EMISSIONS AND PERFORMANCE TESTING

The test engine was a 1986 DDC 6V-92TA MUI bus engine (V6, two-stroke, direct injected and turbocharged, with aftercooling and gear driven Roots blower for scavenging), producing peak power of 207 kW at 2100 rpm, and nominal peak torque of 1139 N-m at 1200 rpm. The engine is shown with the EDC installed in Figure 4.

Emissions and performance testing were conducted in a transient test cell at Southwest Research Institute. The test cell incorporates a full flow constant volume sampling system (CVS) for dilute measurement of both gaseous and particulate emissions. During steady-state performance testing, intake air flow was measured using a laminar flow element. All tests were conducted using a diesel test fuel meeting the specifications required for post-1994 low-sulfur emissions grade 2-D diesel fuel.

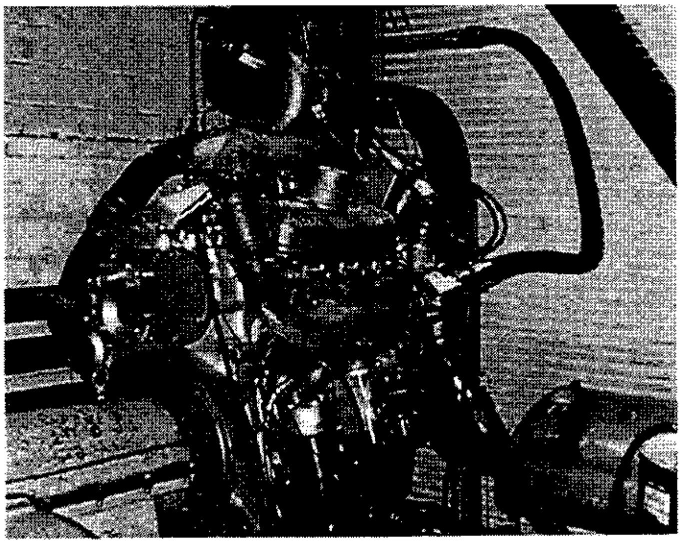

Figure 4: Test Engine with TDC installed

Emissions were measured over the US EPA heavy-duty transient cycle following procedures outlined in CFR Title 40 Part 86 Subpart N for heavy-duty diesel engines. Emissions of hydrocarbons (HC) were measured using a heated flame ionization detector (FID). CO and CO2 emissions were measured from proportional bag samples using NDIR instruments and NOx emissions were measured using a chemiluminescent instrument. Total particulate matter (PM) was determined by collecting particulate on a set of 90mm Pallflex filters via a double dilution technique. Particulate filters were analyzed for VOF using direct filter injection gas chromatography [3], and for sulfates via ion chromatography.

For EDC testing, electrical power was battery supplied (in normal vehicle operation it is supplied from the alternator). EDC current and voltage were continuously monitored and were used to calculate the total energy consumed over the transient cycle. This was subtracted from the engine work in deriving brake-specific emissions (and brake-specific fuel consumption). Typical EDC energy consumption was between 0.45 and 0.52 kW-hour, while total engine work was 15 kW-hour over the transient cycle (3.0 - 3.5 percent).

RESULTS AND DISCUSSION

Prior to the start of emissions testing and development, the test engine was rebuilt to incorporate the DDC emissions upgrade kit components. The rebuilt engine was then operated for 125 hours over a standard DDC durability cycle. An emissions test sequence, consisting of one cold-start and two hot-start transient tests, was run following the break-in to establish emissions and performance for the engine with the upgrade kit alone. Regulated transient emissions test results are given in Table 1, while particulate composition data based on filter analyzes is given in Table 2. Included in Table 1 are baseline emissions generated from a 1979 DDC 6V-92TA that was rebuilt using original components. A comparison between the baseline and the upgrade kit shows substantial reductions in particulate emissions, likely resulting from improved oil control and improved engine air flow. CO emissions were also significantly lower, but NOx emissions were increased with the upgrade kit, although the NOx level remained well within the applicable emission standard of 10.7 g/hp-hour. Filter analysis results with the upgrade kit indicated that about 45 percent of the particulates were composed of volatile organic compounds, of which 60 percent were due to unburned lube oil.

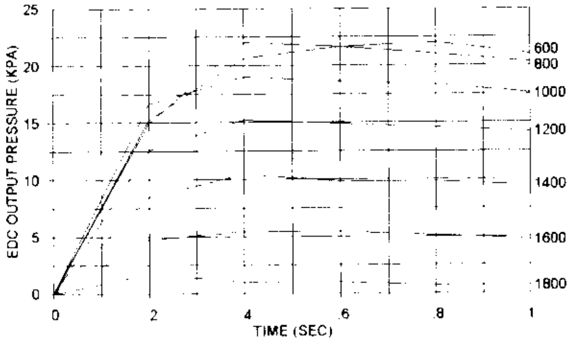

Figure 5: EDC Closed Throttle Pressure Response

The EDC was installed following completion of the baseline testing. Several tests were run in order to quantify the performance of the EDC. Figure 5 shows the transient response of the EDC installed on the engine. This test was performed using the test cell dynamometer to set engine speed at 200 rpm increments between 600 rpm and 1800 rpm with the throttle closed, and then triggering the EDC manually. At all engine speeds and air flows, the EDC was able to reach full pressure output within 0.4 seconds, and generally reach 75 percent of full pressure within 0.2 seconds. This rapid response is critical for the EDC to function as a means to compensate for turbocharger lag.

Table 1: Transient Emissions Test Results

Configuration	Test Type	Transient Emissions (g/hp-hr)				BSFC (lb/hp-hr)	Work (hp-hr (1))	Ref. (hp-hr)
		HC	CO	NOx	PM			
Baseline	**Composite**	**0.5**	**3.7**	**7.4**	**0.530**	**0.464**	-	-
Engine Kit	Cold	0.4	1.7	9.3	0.184	0.470	20.4	21.3
Engine Kit	Hot	0.5	2.0	9.8	0.191	0.454	20.7	21.3
Engine Kit	Hot	0.5	2.0	9.6	0.195	0.447	20.8	21.3
Engine Kit	**Composite**	**0.5**	**2.0**	**9.7**	**0.190**	**0.457**	**20.7**	**21.3**
Engine Kit+EDC	Cold	0.4	1.1	9.7	0.158	0.477	19.8	21.1
Engine Kit+EDC	Hot	0.5	1.0	10.5	0.146	0.466	20.1	21.1
Engine Kit+EDC	Hot	0.5	1.1	10.3	0.154	0.462	20.2	21.1
Engine Kit+EDC	**Composite**	**0.5**	**1.0**	**10.4**	**0.148**	**0.468**	**20.0**	**21.1**
Engine Kit+EDC+Catalyst	Cold	0.1	0.4	9.5	0.094	0.476	19.7	21.0
Engine Kit+EDC+Catalyst	Hot	0.1	0.4	9.8	0.090	0.462	20.2	21.0
Engine Kit+EDC+Catalyst	Hot	0.1	0.4	10.2	0.088	0.460	20.1	21.0
Engine Kit+EDC+Catalyst	**Composite**	**0.1**	**0.4**	**9.8**	**0.091**	**0.464**	**20.1**	**21.0**

The output pressure of the EDC at various air flow levels is shown in Figure 6. The maximum boost available from the EDC was about 20 kPag, and this level of boost was available until just under 200 cfm of engine air flow. At this point, EDC output pressure declined linearly with increasing engine air flow until between 425 to 450 cfm above which the EDC was unable to provide additional boost pressure. At this point the bypass valve in the EDCsystem opens to prevent it from restricting engine air flow. In addition, the EDC was de-energized at this point to conserve power.

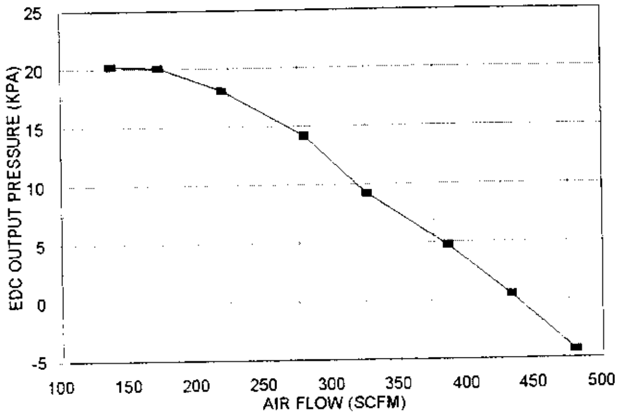

Figure 6: EDC Pressure vs Flow Performance

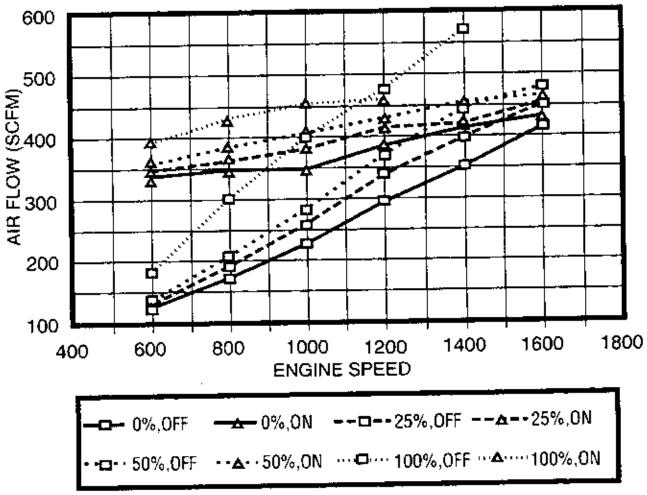

Figure 7: Engine Airflow with and without EDC

Figure 7 shows engine air flow with the EDC on and off at various speed and load points. Measurements were made by setting engine speed and load with the EDC off and measuring air flow; then triggering the EDC manually and measuring air flow again. The data show a significant increase in engine air flow at all loads up to about 1000 rpm, and in part load air flows up to about 1200 rpm. A crossover point occurs at about 450 cfm where the EDC does not improve engine air flow, which is consistent with data given in Figure 6. This point is the shut off point for the EDC controller. The switching is actually accomplished by means of a pressure sensor in the intake air box. Based on the air flow and pressure data the switch was adjusted to turn off the EDC at 54 kPag of air box pressure.

Subsequent transient cycle calibration runs were performed with the EDC installed to determine the optimum system configuration. The DDC 6V-92TA MUI engine normally employs a mechanical throttle delay mechanism in order to compensate for turbocharger lag and hence prevent the emission of large amounts of smoke during the initial stages of acceleration. The time delay for the test engine in its stock configuration when the engine was fully warm is roughly 6 seconds from wide-open-throttle command to the actual full opening of the fuel control rack. With the EDC installed, it was found that this delay could be reduced by roughly 2 seconds, which was accomplished by resetting the mechanical delay, while still maintaining the full emission benefits of the EDC as detailed in Tables 1 and 2. This resulted in improved throttle response and slightly improved transient cycle work, which helped to partially compensate for the work required to power the EDC. All test configurations with the EDC installed also included this recalibration of the throttle delay mechanism. The improved throttle response is anticipated to provide improved vehicle acceleration performance when the system is installed in buses.

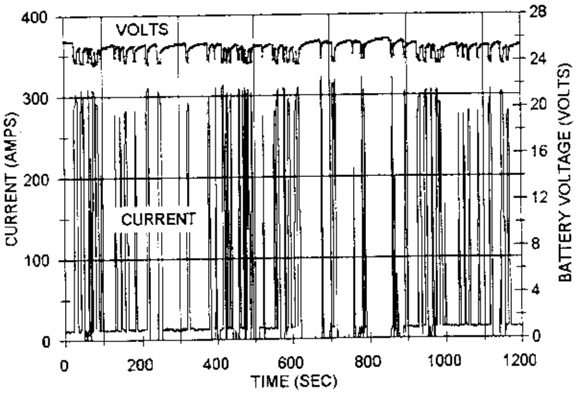

Figure 8: EDC Current and Voltage

The current and voltage requirements of the EDC during a typical transient cycle are shown in Figure 8. When not triggered by the electronic controller, the EDC operates in an "idle" mode, drawing about 10 amps of current. This mode aides in EDC response because the compressor does not have to be started from a complete stop when triggered, thus overcoming startup inertia. When the controller triggers the EDC, the current draw quickly rises to 300 amps, driving the EDC at full speed and maximum airflow until shut off by either the airbox pressure switch, or an 8 second safety timeout. This equates to a 7 kW power requirement during full speed operation. During transient cycle operation, the EDC was always shut down by the pressure switch, and therefore was never on for more than a few seconds.
The average power draw for the EDC during the entire transient cycle was actually about 1.5 kW. This equated to about 0.5 kW-hour of work, or roughly three percent of the total work produced by the engine during the transient cycle. It should be noted that this calculation does not account for alternator efficiency, as an alternator was not used during either baseline or retrofit hardware testing.

Composite transient emissions are shown in Figure 9 for all test configurations. It should be noted that the work values shown for configurations with the EDC installed have been corrected for the power used by the EDC during the transient test. The data shows significant reductions in both CO and PM, 50 percent and 22 percent respectively, with the EDC installed and operating. These reductions are likely due to improved in-cylinder mixing and combustion during accelerations due to the increased air flow provided by the EDC at low engine speeds. NOx emissions were slightly higher with the EDC, possibly as a result of slightly higher in-cylinder temperatures caused by improved combustion at lower engine speeds. The reduction in particulate emissions was not, however, enough to reduce particulates to below the 0.1 g/hp-hr target of the Urban Bus Rebuild/Retrofit Program, without the assistance of an aftertreatment device such as an oxidation catalyst.

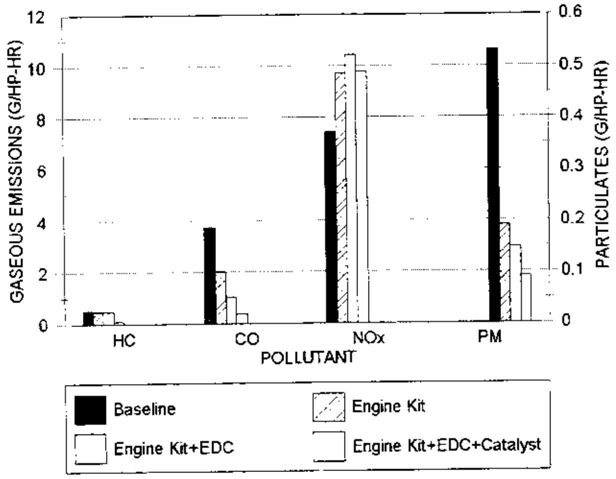

Figure 9: Gaseous Emissions Test Results

Table 2: Particulate Emissions Test Results

Configuration	Test Type	Total PM (g/hp-hr)	VOF (g/gp-hr)			Non Volatiles (g/hp-hr)
			Total	Fuel & Other	Oil	
Engine Kit	Cold	0.184	0.085	0.043	0.042	0.099
Engine Kit	Hot	0.191	0.078	0.027	0.052	0.113
Engine Kit	Hot	0.195	0.074	0.027	0.047	0.120
Engine Kit	**Composite**	**0.190**	**0.079**	**0.029**	**0.050**	**0.111**
Engine Kit+EDC	Cold	0.158	0.084	0.044	0.039	0.074
Engine Kit+EDC	Hot	0.146	0.085	0.043	0.043	0.061
Engine Kit+EDC	Hot	0.154	0.078	0.040	0.037	0.076
Engine Kit+EDC	**Composite**	**0.148**	**0.085**	**0.043**	**0.042**	**0.063**
Engine Kit+EDC+Catalyst	Cold	0.094	0.028	0.020	0.008	0.066
Engine Kit+EDC+Catalyst	Hot	0.090	0.041	0.029	0.013	0.049
Engine Kit+EDC+Catalyst	Hot	0.088	0.030	0.020	0.009	0.059
Engine Kit+EDC+Catalyst	**Composite**	**0.091**	**0.039**	**0.027**	**0.012**	**0.051**

Figure 10 shows the breakdown of composite particulate emissions for all test configurations. These results indicate that the reductions in PM observed with the EDC were entirely within the non-volatile component. This is consistent with the idea that the EDC improves fuel/air mixing and hence combustion, at lower engine speeds. VOF emissions, which are composed largely of unburned lube oil and fuel, are essentially unaffected by the EDC. This shifts the PM composition toward higher VOF and creates an environment which is more favorable for a diesel oxidation catalyst.

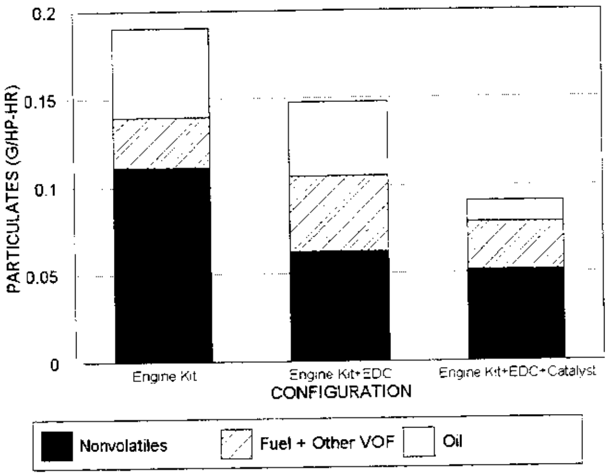

Figure 10: Particulate Emissions Test Results

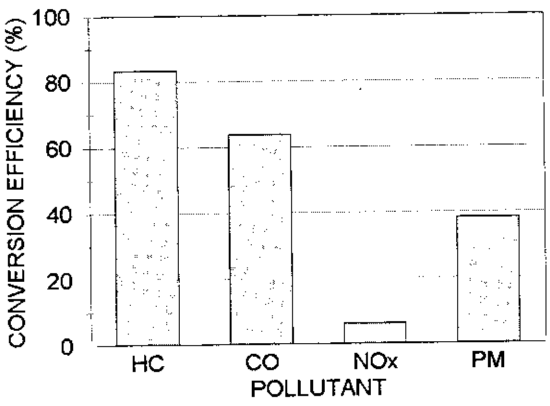

Figure 11: Catalyst Conversion Efficiencies

The muffler/catalyst was installed on the engine and aged for 20 hours prior to any testing, in order to stabilize its performance. Conversion efficiencies with the EDC installed are show in Figure 11. The catalyst was able to oxidize nearly 40 percent of the remaining engine-out particulates and almost 55 percent of the VOF component. This reduction, combined with that already produced by the use of the EDC, was successful in achieving the regulation target of 0.1 g/hp-hour.

The particulate composition data in Figure 10 confirms that the reduction occurs mostly in the VOF component. Large reductions of HC and CO emissions were also observed, which is an additional benefit from the catalyst. NOx emissions were largely unaffected, although a small reduction was noted. This was most likely due to the small increase of backpressure which results in an increase in internal exhaust gas recirculation.

FIELD EVALUATIONS

Although the US EPA's Urban Bus Rebuild/Retrofit Regulation does not require any durability or in-service testing, DDC has conducted extensive field trials. DDC began field trials of the retrofit system in July of 1997. To date, eight complete systems have been installed in buses and are operating daily in regular revenue service at four major US transit agencies. These field trial units have almost 40,000 miles of customer service and have performed without any major failures and have not required any in-use maintenance or repairs. The highest mileage unit has operated over 13,000 miles with no system failures. In addition, field trial fleets have reported no loss in drivability or vehicle performance and somewhat better fuel economy.

One focus of the field evaluations has been to address any concern with the impact of the EDC on the engine electrical system. The majority of DDC urban bus installations use the Delco-Remy 50dn alternator rated at 270 or 300 amps. The field trial evaluation units have been equipped with the Delco-Remy 50dn alternator rated at 270 amps and to date, no problems of any kind have been encountered with the buses' electrical systems. DDC has data logged one installation, which indicated that the EDC is active in the high speed mode for only approximately 10 percent of the time and that the average current draw is around 35 amps.

CONCLUSION

By combining available technologies in an optimized system, the most stringent PM emissions target of 0.1 g/hp-hour set by the US EPA for rebuilt engines, has been achieved on a mechanically controlled diesel engine. The kit is straightforward to install, is durable and in no way compromises the performance or driveability of the engine. In addition to meeting the PM standard, the system achieves 80 to 90 percent reductions in CO and HC emissions.

ACKNOWLEDGEMENTS

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