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New Technology Research & Development Program
Grant Contract 582-5-65591-0007

Task 10 Deliverable Report
Final Report

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Final Project Report

Task # 10

Prepared for the
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Converter Technology Inc.

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Prepared by:
Ray Kammel
Converter Technology Inc.
155 Factory Road
Michigan Center, MI 49254-1009
(517)764-3800 Phone
(517)764-2020 Fax
raykammel@convertertechnology.net

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I. Summary of Tasks and Work Performed

I.1 **Overall Project Summary**: This project summary addresses issues of prime concerns relating to the retrofit of diesel trucks and buses in the state of Texas with emphasis on achieving the highest NOx reduction through EGR. The tasks identified in this project relates to Texas market assessment and inventory, how the technology can contribute to the goals of the state implementation plan, retrofit hardware construction and testing, and mobile data acquisition system development. Prime task is the EGR mapping at various engine loading conditions and various EGR injection strategies with a limit on total fuel penalty of 5%. Final task targeted verification with EPA or CARB with attainment of necessary durabilities and formal emission testing.

The project, being extensive in scope, experienced delays and cost overruns during implementation due to various factors, mostly out-of-control as outlined in this report. However, the results of the major/primary tasks demonstrated the capability of achieving NOx reduction in the order of 63% and at fuel penalty of about 4.6% based on the AVL 8-mode test cycle, which is equivalent to results to be obtained from engine transient cycle testing. First round of testing data on a dump truck on-the-road demonstrated good results in terms of NOx reduction, and still low smoke opacity under almost all truck driving conditions up to 60mph.

Durabilities for EPA verification on-the-road started in January, 2007. However, due to low usage in summer time, the required durabilities will necessitate additional time on the road, currently estimated to last 3-4 more months.

I.2 **Summary of Accomplishment by Task**

I.2.1 **Task #1: Texas Market Assessment**: This is a comprehensive study on the retrofit of on-road diesel engines with emphasis on counties eligible for TERP funding. The study was performed by Good Company Associates and reviewed by CTI. The report identifies engine population by manufacturer and model years, the prevailing NOx emission standards and vehicle classifications. Retrofit scenarios were identified for selected vehicles and the corresponding emission reductions. A critical factor was identified in the mileage accumulation per year since it varies significantly dependent on the application. Quarry trucks could accumulate 100,000 miles per year. For a given retrofit kit, the economics of emission reduction in dollars per ton of NOx removed could substantially vary according to mileage. The study also highlights the cost effectiveness of retrofitting old high polluting engines provided that the remaining life span justifies the cost of retrofit.

I.2.2 **Task #2: Emission Reduction and Compliance with Texas SIP**: This report is based on PM and NOx reductions using CTI's technology. It outlines implementation strategy with emphasis on mobile sources and eligible vehicles in targeted areas with emphasis on NOx and VOC's reductions. Due to EPA verification being limited initially to one single engine family, the scope of

retrofit implementation is restricted. However, this first engine is popular in metropolitan areas and also with municipalities. Upon market acceptance, CTI intends to amend verification in the future for additional engine families. The report identifies 3 engine families having large population. It also addresses practical aspect of retrofit, manufacturing ramp up and retrofit centers in Texas.

I.2.3 **Task #3 Design of Retrofit System for CAT 3406B&CAT 3126 engines:** Design work began on the initial engine selected at the onset of the project, CAT3406B. Upon contacts in Houston, this engine was not popular with public municipalities. Upon further explorations, CAT 3126 engine was selected due to its popularity in urban applications. The design was updated for the new engine. The design activities addressed the particulate converter, the oxidation catalyst and the EGR system. Mobile Data Acquisition System Design is also addressed for subsystems, components and calibration. The Mobile Data Acquisition System is used for measuring emissions, performances and collecting various exhaust data on the road. A post-processor is used to generate reports on emissions, engine operating conditions and related performances of engine, vehicle in time domain.

A major rework took place at the end of 2005 to upgrade the particulate converter from reverse pulse-jet option to incineration option. This was prompted by the issues raised by CARB during the verification process on the handling of particulate matter and collection in storage tank. CTI concluded that complying with new requirements and regulations by the California Dept. of Toxic Substance Control would cause diversion of the project and requires additional costs that could not be justified. The work on the incineration option, which alleviates such issue, continued through 2006. This option is most attractive since the hardware size was dramatically reduced. The new design continued to have all major advantages similar to the pulse-jet option. Mostly, incineration is a slow process and no appreciable rise in exhaust temperature was observed in lab testing or on road testing.

I.2.4 **Task #4 Construction of Converter System, EGR, Data Acquisition System**: CTI constructed 2 particulate converters based on the reverse pulse jet strategy, followed by to using incineration and particles centrifugal separation for the CAT 3406 engine. Two converters were constructed for the CAT 3126 engine based on incineration. 4 EGR valves were constructed for the CAT 3406 and two for the CAT 3126 engine. 3 mobile data acquisition systems were constructed and tested. The new converter option required a power supply with pulse-width modulator, and a total of 8 were constructed for testing. Two are dedicated for the CAT 3126. All hardware necessary for installation were assembled and installed on the first truck to accumulate the 1000 hours durability. A second retrofit kit will be installed on a second truck to accumulate about 100 hours durability.

I.2.5 **Task #5 EGR Mapping for 60-70% NOx Reduction**: Mapping for EGR injection strategy is based on studying various EGR injection rates at selected

steady-state operating modes. The modes selected are based on what is known as the 8-AVL modes, which can predict with a reasonable degree of accuracy the resulting NOx reduction during a federal transient emission testing. The definition of the 8-AVL modes, weighing factors, and the resulting NOx reduction as a function of EGR injection ratio as well as the fuel penalty are outlined in a detailed testing data and evaluation form. A NOx reduction of 63% can be achieved in a composite mode through the low-pressure EGR system, and the corresponding fuel penalty is limited to 4.3%. Testing was done on CAT 3406 engine and the same injection strategy is extended to CAT 3126.

I.2.6 **Task #6 In-House Emission Testing**: Detailed and elaborate in-house emission testing was carried out on EGR mapping followed by extensive testing on the incineration process. The EGR mapping was performed for 12 steady-state modes of engine operation. The details of mapping tests and the strategy selected for EGR injection is outlined. Incineration tests were performed in a lab environment and on-the-road. Incineration is a complex mechanism, however, NO_2 presence in the exhaust in small quantities emerged as the primary mechanism helping with the incineration. This worked in conjunction with electric pulsed-DC power (12 to 24V) applied to incinerator only where the need arises, and is engaged automatically. CTI performed extensive R & D work on the incineration process to investigate the process, mainly on the electrical-assist mechanism. Now, a combination of occasional temperatures of 300°C, small amount of NO_2 in the exhaust (from Diesel Oxidation Catalyst) and pulsed electric power are the mechanisms contributing to effective incineration.

I.2.7 **Task #7 On-The-Road Emission Testing and Durabilities**: CTI filed an application for PM and NOx verification with EPA through RTI. On-the-road testing started in January, 2007, to accumulate durabilities of 1000 hours. The truck selected is a city truck in Jackson, Michigan, and CTI received their cooperation with testing. Two trucks were selected. These trucks, however, do not operate on a daily basis since they are for road maintenance and repairs. The accumulated hours are running slow. Reaching the 1000 hours would extend the road testing to the end of September, 2007, at least.

CTI collected data on the road using the Smart-2000 plus mobile data acquisition system every 2 seconds. Data was sorted by categories, such as engine microprocessor data, exhaust data and emission data. Further details are provided in the report. The collected data illustrates the effect of EGR opening on NOx reduction for a given engine operating condition. A post-processor has been developed and selected test data has been further evaluated. CTI will continue to collect data on-the-road.

I.2.8 **Task #8 Acoustical Design and Measurements**: CTI has not performed the acoustical testing at Walker Manufacturing yet. CTI is in dialogue with the company relating to joint venturing and acoustical tests and is expecting to perform these tests in the next few weeks.

I.2.9 **Task #9 Verification with EPA**: CTI filed an ETV application for verification with EPA for the combined PM and NOx reduction system. A copy of the ETV application, and a copy of the statement of work, has been submitted to TCEQ. Due to delays encountered in the project, verification testing will not commence until October, 2007. CTI will inform TCEQ on progress, testing and results.

II. System Highlights and Performances

The low-pressure exhaust gas recirculation for the retrofit of diesel trucks is a viable strategy provided that certain conditions are satisfied. The major issue relates to having a particulate control system working effectively to meet the challenge of increased PM, HC and CO emissions. The particulate converter system, along with a diesel oxidation catalyst, is capable of having a reliable subsystem to meet the challenge and reduce emissions from base-line values.

The NOx emissions reduction can reach 63% at a fuel penalty of 4.3%, based on the AVL 8-mode testing. The low-pressure EGR is stripped virtually of all particles before entering the engine air intake and sub-cooled. These virtues are necessary to minimize EGR, shortcomings on engine performance such as oil contamination and loss of peak power. This is especially relevant over high-pressure EGR systems, which are dominant in most OEM applications due to its packaging advantages.

It is our conclusion that a low-pressure EGR injection strategy as outlined in this project is an effective strategy that can be used in retrofit of trucks and buses in Texas. This strategy offers low capital costs, reduction of PM, low maintenance and operating costs as well as other benefits especially when compared to other alternatives such as SCR strategy. The verification has to extend to other engine families as well as non-electronic diesel engines having high NOx emissions to be effective in achieving the goals of the state implementation plan.

III. Summary of Problems and Delays

Due to the nature of the technology being new and radical, as well as a broad and diversified scope for the project, CTI encountered numerous problems and difficulties resulting in delays and cost overruns. However, the project main targets and goals have been accomplished. The following summarizes the main problems encountered, resolution, and impact.

III1. **Verification of reverse pulse-jet particulate converter**: The reverse pulse jet option of our particulate system, which was developed at the onset of the project, encountered major regulatory difficulties during the verification process with CARB. The major difficulty is the classification of diesel soot collected in steel tank as “hazardous waste,” and the resulting compliance issues. After careful analysis, CTI concluded that resolving such regulatory compliances will result in

a major deviation in the scope of this project with unpredictable delays and cost overruns. The conclusion was to switch to the other option of the particulate converter design to be based on incineration. Development work on incineration lasted about a year to explore various boundaries. In conclusion, by far this was the major problem that resulted in significant delays and cost overruns. The incineration option is working, almost maintenance free and even more attractive than the reverse pulse jet option, especially from an operational point of view.

III2. **Selection of low-pressure EGR valve**: CTI expanded lots of efforts to locate EGR valves for the low-pressure EGR system. Unfortunately, almost all valves are high-pressure type. Initially, CTI built the first round of valves. That was a distraction from the scope of this project. Eventually, CTI located a valve supplier, and the new valves are functioning well.

III3. **Mobile data acquisition system**: The system initially was based on a portable emission analyzer that was used initially for about 6 months. Due to difficulties in obtaining reliable data, CTI switched to the "Smart 2000 Plus" mobile data acquisition system. This system is custom built to acquire data on the road in accordance with CTI needs. The system software development and debugging consumed more efforts than what is budgeted for. Most difficulties related to communication with engine microprocessor, developing data post-processor. Almost, most of these problems were resolved. However, some data scatters (unreliable) are still observed occasionally on data collected from engine microprocessor and emission sensors. Such data are screened and deleted.