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Experimental Evaluation of DOC Light-Off Behavior Using Secondary Fuel Injection

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ABSTRACT

Although most 2007 systems introduce the fuel for Diesel Particulate Filter (DPF) regeneration through in-cylinder post-injection, it is likely that 2010 systems will also need in-stream fuel injection to help avoid oil dilution and potential pre-mature engine wear. An active DPF regeneration system is evaluated, which applies various fuel injection techniques directly within the exhaust system upstream of the diesel oxidation catalyst (DOC). Diesel fuel is oxidized in the presence of a proprietary catalyst system, increasing exhaust gas temperatures in an efficient and controlled manner, even during low engine-out gas temperatures. This unique technology has been retrofitted on a Dodge Ram Diesel pick-up truck and evaluated on a chassis dynamometer and in real-world operation conditions. These evaluations demonstrate the capability of the technology to operate within transient conditions, offering continuous filter regeneration capabilities regardless of the duty cycle. Such benefits reduce risks of overloaded filters and partially regenerated filters, while increasing system performance and reducing overall costs. An injector is applied within the exhaust stream to introduce algorithmically controlled amounts of diesel fuel which is chemically reacted using a proprietary low-temperature catalyst. This study outlines the geometries applied to the exhaust system, describing the methods used within engine and chassis dynamometer evaluations to generate the transient control algorithms, including the measured variables. The operating performance of the system during various driving conditions, including on-board emissions measurements, is also documented. Additionally, DOC performance is compared with traditional platinum and palladium-based DOCs, quantifying improvements over current applications.

INTRODUCTION

Diesel Particulate Filters (DPF) applied within 2007 vehicles resolve PM emissions through effective trapping of the soot particles. Periodically these trapped particles must be burned or they continue to accumulate and increase backpressure, reducing engine performance and eventually resulting in system failure. The periodic burning of the soot on command is referred to as “active regeneration”, and it requires external energy inputs and controls since the necessary temperature, nearly 600^{o}C, is otherwise not achieved.

A typical means of obtaining this energy is through the use of the on-board fuel and an exothermic catalytic process. Fuel is injected into the exhaust stream and its energy is chemically released, increasing the exhaust stream temperature to enable DPF regeneration. Often, a Diesel Oxidation Catalyst (DOC) is used to produce these reactions, functioning as a catalytic burner. Many variables affect this process, and transient conditions, which are typical of many real-world applications, pose control challenges. Fuel injection strategies affect system response. Although 2007 systems apply in-cylinder injection (pulsing of fuel within the cylinder during the exhaust stroke) 2010 systems may need to apply injections within the exhaust system, particularly if the DPF is downstream of the urea SCR catalyst. Another critical characteristic of such catalytic systems is light-off behavior, which determines the systems capability to initiate the exothermic reaction.

LIGHT-OFF BEHAVIOR

Light-off (LOF) behavior and performance of catalytic burner systems is not only a function of catalytic formulation, coating density etc., but also of operating conditions. LOF is generally defined as the temperature, at which the conversion rate of gaseous constituents reaches the 50% level (T50). The DOC components used in this work consisted of Cordierite flow-through monoliths, coated with Active-X™ washcoat material (2g/in^{3} loading) and platinum catalyst (see Table 1). Active-X is a proprietary washcoat powder supplied by AirFlow Catalyst Systems which provides low temperature T50 values for CO and hydrocarbons (i.e., below 200^{o}C). Figures 1 and 2 show the HC and CO, light-off curves, respectively, for core samples with similar formulations to those used in the engine tests below. These light-off curves were measured on a synthetic gas reactor (SGR) with a standard gas mixture typically used in such tests (10% O_2, 4% CO_2, 5% H_2O, 100 ppm CO, 30 ppm propylene, 30 ppm propane, 100 ppm NO – balance N_2) and a space velocity of 50Khr-1. The hydrothermal aging was done in air -10% H_2O for 10 hours at 700^{o}C and a space velocity of 25Khr-1.

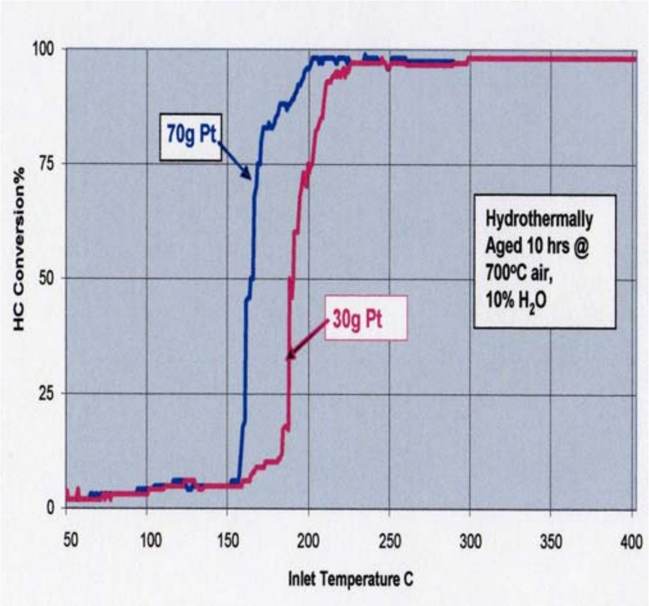


Figure 1: Hydrocarbon Conversion

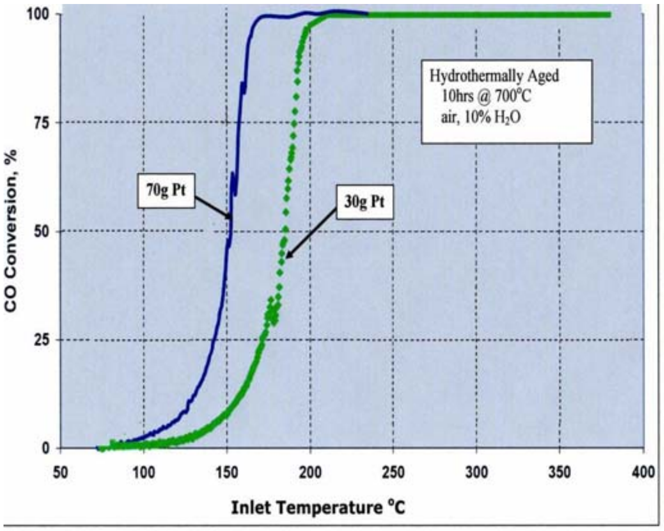


Figure 2: CO Conversion

The LOF in exhaust systems with secondary fuel injection is similar to the self-ignition process in diesel combustion. The exhaust gas temperature is a significant LOF parameter, but not the only one necessary to describe the complete chemical kinetic response.

The chain of thermodynamic and thermo-kinetic sequences here can be summarized as follows:

- Injection of fuel, followed by dispersion, atomization and separation into droplets
- Heating of droplets during the travel downstream in the exhaust, causing partial evaporation of external layers
- Mixing of the fuel and exhaust gases
- Initiation of thermo-kinetic reactions with increasing reaction rates depending on the concentration and temperature distributions
- Progressive chain reactions with significant exothermic heat release

This last state will be described as self-ignition or light-off.

Impact factors of LOF to be considered in two groups:
Design related:

- Layout of catalytic formulation and coating
- Physical and chemical fuel properties
- Fuel injection methods

Operating condition related:

- Operating load and exhaust gas temperature
- Exhaust (or intake air) mass flow rate and O_2 concentration
- Momentary heat capacity of boundaries and magnitude and direction of local wall/gas temperature gradients

Because of the complexity of the LOF and self-ignition mechanism an experimental evaluation methodology is applied. Details of the methodology used for LOF characterization of several DOC components and achieved results are described. The same methodology can also be used for exhaust burner systems with secondary fuel injection.

TEST SETUP

Test Vehicle and Setup

A Dodge Ram Truck (2004.5) with a 5.9L turbo diesel engine is used as the test carrier. The exhaust line is diverted to the right side of the vehicle to simplify access to the test components, as documented in Figure 3.

Steady state and transient driving conditions are simulated on a chassis dynamometer with 40” rolls using the road load profile given in Figure 4.

The performance criteria for the tested DOCs are:

- LOF temperature
- Exothermic release
- Secondary emissions

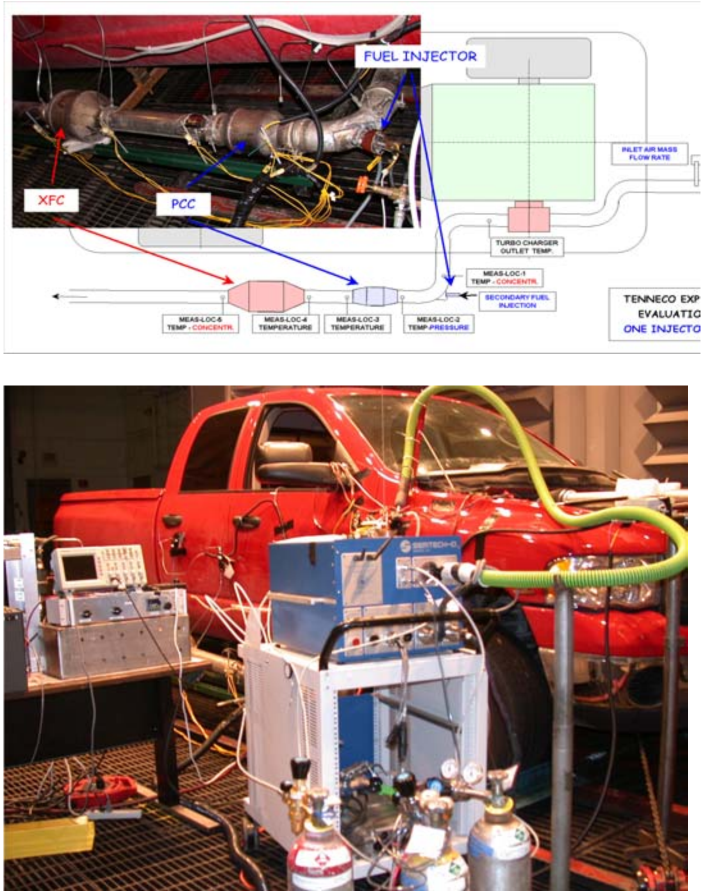


Figure 3: Test Setup

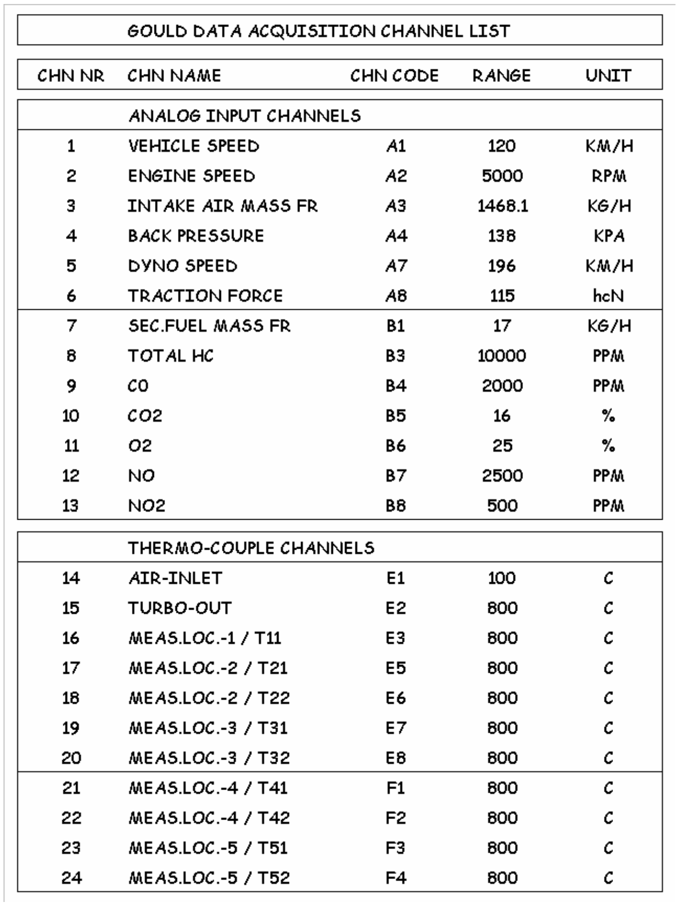
Measured Test Variables

A Gould DAstar system is used for data acquisition, and a data sampling rate of 10 Hz is applied for all channels. Exhaust emissions (raw concentrations) are measured using a Semtech-D mobile emissions analyzer from Sensors, Inc. Table 1 documents the data collected, including the respective channel, range, and units.

Test Parts

In this study four cordierite and one metallic DOCs are evaluated, with specific features given in Table 2.

Table 1: Measured Data Channels



GOULD DATA ACQUISITION CHANNEL LIST				
CHN NR	CHN NAME	CHN CODE	RANGE	UNIT
	ANALOG INPUT CHANNELS			
1	VEHICLE SPEED	A1	120	KM/H
2	ENGINE SPEED	A2	5000	RPM
3	INTAKE AIR MASS FR	A3	1468.1	KG/H
4	BACK PRESSURE	A4	138	KPA
5	DYNO SPEED	A7	196	KM/H
6	TRACTION FORCE	A8	115	hcN
7	SEC.FUEL MASS FR	B1	17	KG/H
8	TOTAL HC	B3	10000	PPM
9	CO	B4	2000	PPM
10	CO2	B5	16	%
11	O2	B6	25	%
12	NO	B7	2500	PPM
13	NO2	B8	500	PPM
	THERMO-COUPLE CHANNELS			
14	AIR-INLET	E1	100	C
15	TURBO-OUT	E2	800	C
16	MEAS.LOC.-1 / T11	E3	800	C
17	MEAS.LOC.-2 / T21	E5	800	C
18	MEAS.LOC.-2 / T22	E6	800	C
19	MEAS.LOC.-3 / T31	E7	800	C
20	MEAS.LOC.-3 / T32	E8	800	C
21	MEAS.LOC.-4 / T41	F1	800	C
22	MEAS.LOC.-4 / T42	F2	800	C
23	MEAS.LOC.-5 / T51	F3	800	C
24	MEAS.LOC.-5 / T52	F4	800	C

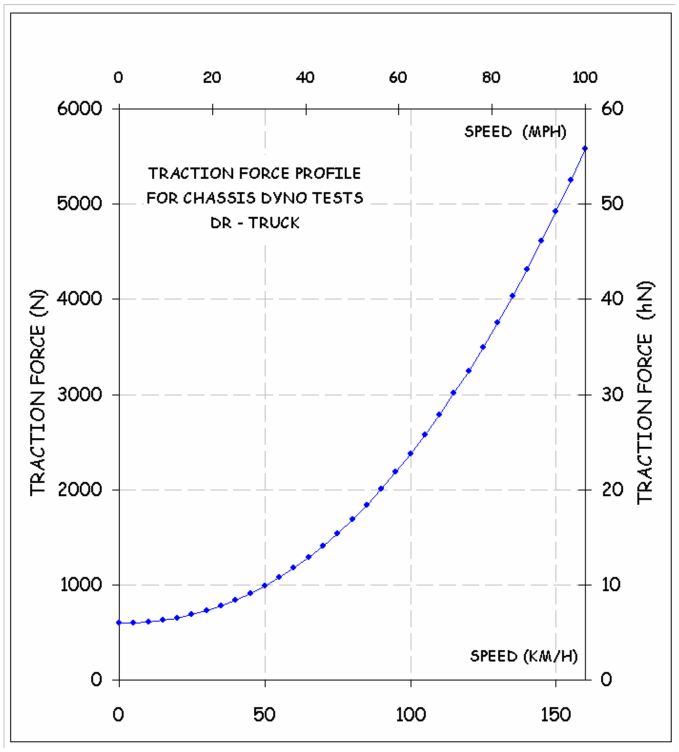


Figure 4: Road Load Profile for Dodge Ram Truck

Table 2: DOC Descriptions

Part #	1	2	3	4	5
Coater	Airflow Catalyst Systems			-----	-----
Substrate Material	Cordierite				Metal
PGM Loading (g/ft^3)	10	40	70	-----	-----
Cell Density	400 / 6.5				-----
Outer Diameter	6 "				9"
Length	6"				2"

Test Modes

Two drive profiles have been combined with two fuel injection modes:

- Test Mode #1 & 2: Ascending / descending constant speed steps between 40 to 90 km/h, with 10 km/h increments, and SF injection pulses of 60 sec. followed by 60 sec no-fuel sequences with a MFR at both 2 and 4 kg/h (Figure 5)
- Test Mode #3: FTP-72 cycle with continuous SF injection at a MFR of 2 kg/h (Figure 6)

Fuel Injection Equipment

Tests are performed with a manual PWM injection controller to create the fuel injection profiles given in Figures 5 and 6. The layout of the fuel injection equipment setup and its basic control method is illustrated in Figure 7.

PWM frequency and pulse width are adjusted independently to provide desired SF MFR.

An injector from a gasoline direct injection (GDI) engine is used because of its very fine droplet distribution, avoiding response effects to injector performance. Similar test evaluations can be applied to also evaluate injector performance and its positioning dependencies.

TEST RESULTS

Certain representative examples from test results are given in the following figures to illustrate the targeted performance features.

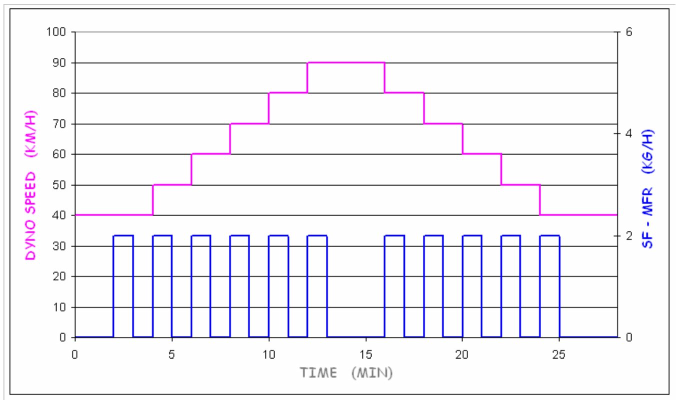


Figure 5: Test Mode #1

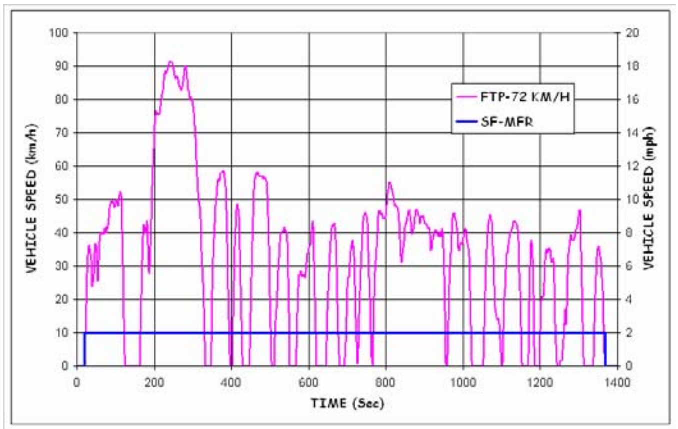


Figure 6: Test Mode #3

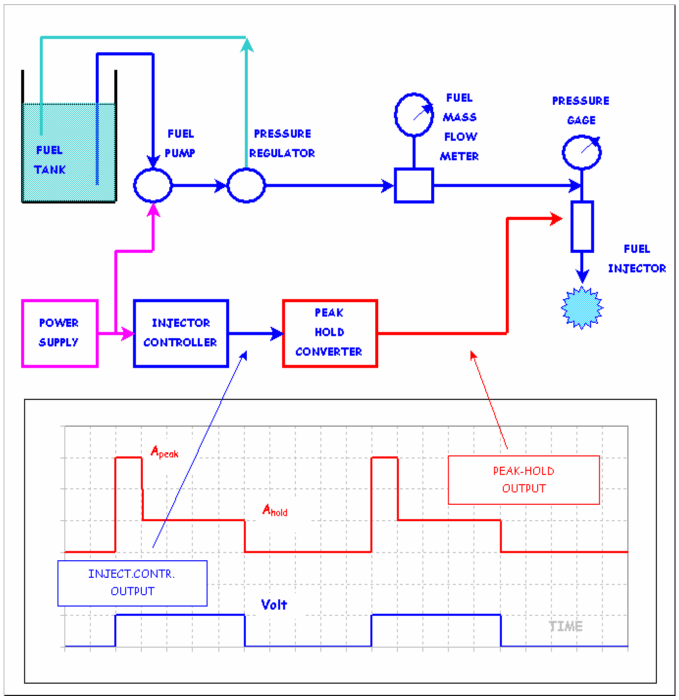


Figure 7: Fuel injection equipment Layout

Description of various labels used in the charts below:

Upper section:

T_turbo out	Turbo outlet temperature
T_dev in	Device (DOC) inlet temperature
T_dev out	DOC outlet temperature
Doc Skin	DOC skin temperature
IA-MFR	Engine intake air mass flow rate
Dyno Speed	Dyno (vehicle) speed

Lower Section

THC	Concentration
CO	Concentration
NO	Concentration
NO2	Concentration
CO2	Concentration
O2	Concentration
SF-MFR	Secondary fuel mass flow rate

Figure 8 illustrates a poorly performing DOC1, as evidenced by a lack of exothermic response during the first fuel injection point (T_**dev** in) at 230 C. Additionally, a THC peak of about 800 ppm exists as a result of its inability to react with the catalyst.

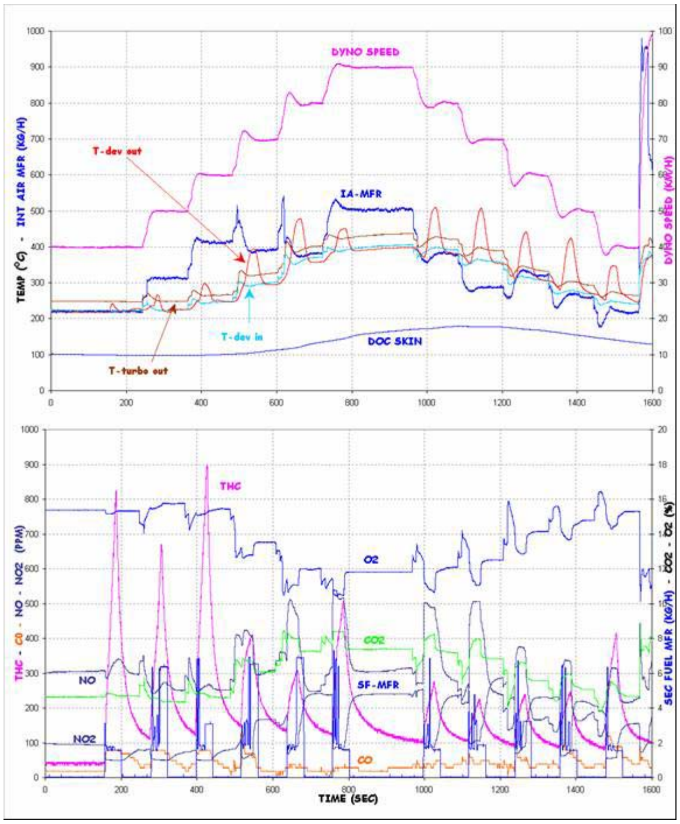


Figure 8: DOC1 with SF-MFR = 2 kg/h

Figure 9 illustrates a much better performing DOC3, since LOF at 230 C results in an exothermic response reaching 450 C with a corresponding THC peak of 350 ppm.

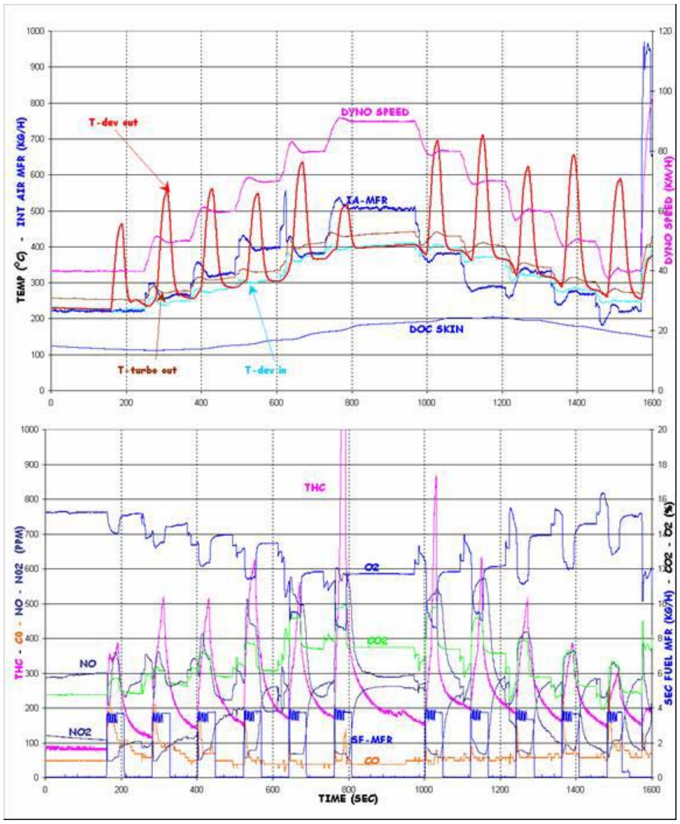


Figure 9: DOC3 with SF-MFR = 4 kg/h

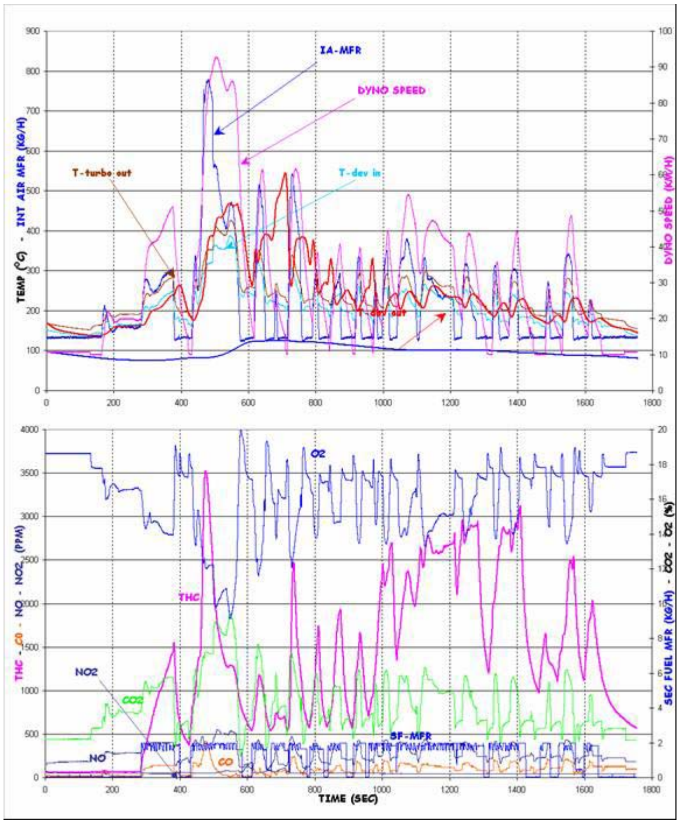


Figure 10: DOC1 in FTP-72 Cycle

Before starting the FTP-72 cycle, the exhaust temperature was stabilized at 20 km/h constant speed for 5 min. As seen in Figure 10, the maximum temperature (T_dev out) during FTP-72 cycle reaches 550C. THC levels peak up to 3500 ppm, demonstrating the inefficiency of the fuel usage caused primarily by low exhaust temperatures and little catalytic response.

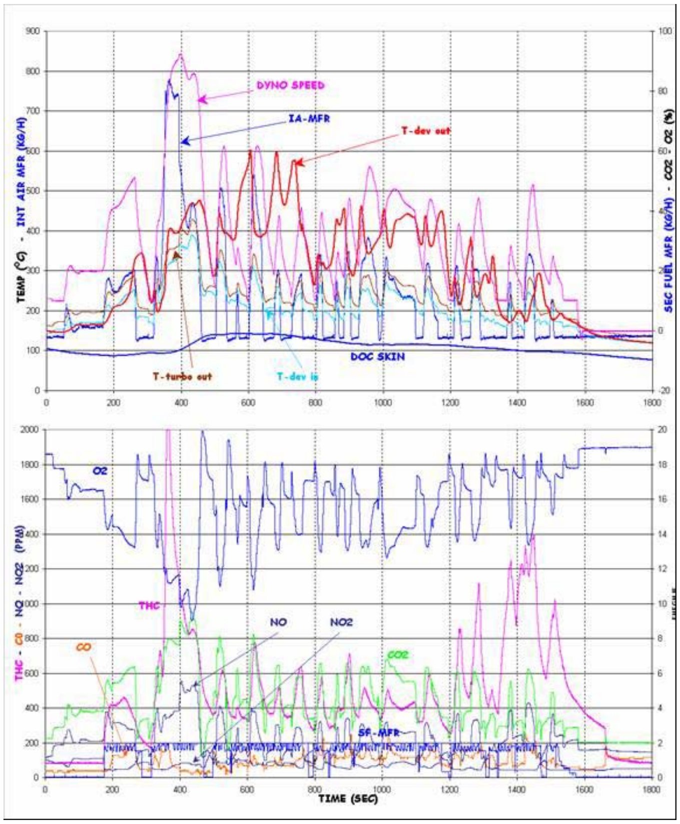


Figure 11: DOC2 in FTP72 Cycle

DOC 2 is accepted as a better performing DOC, since its maximum temperature during this test reaches 600^{o}C and THC peaks are only 200 ppm (Figure 11).

Figure 12 compares LOF peaks during test modes #1 and #2 at SF MFR of 2 (lower graph) and 4 kg/h (upper graph) for all five DOCs. As seen from this comparison most of the tested DOCs have a LOF peak at 230^{o}C (40 km/h) with varying exothermic responses. Decreasing the SF-MFR to 2 kg/h reduces the catalytic combustion response. This comparison reveals the superior performance of DOC 2 and DOC 3 compared with the others, creating greater exothermic responses (T_dev out), including significant benefits at lower inlet gas temperatures (T_dev in).

All DOCs performed better on the descending speed side of the test cycle, delivering significantly higher exothermic responses. This data is summarized in Figure 13. Such behavior is likely the result of elevated catalyst temperatures and improved droplet evaporation caused by the stored heat in the DOC and the surrounding metallic walls.

Quantitative results from steady state test mode #1 and #2 are shown in graphical form in Figure 14. As seen here, DOC2 and DOC3 deliver better performance based on their lower LOF temperatures, higher exothermic response, and lower THC values.

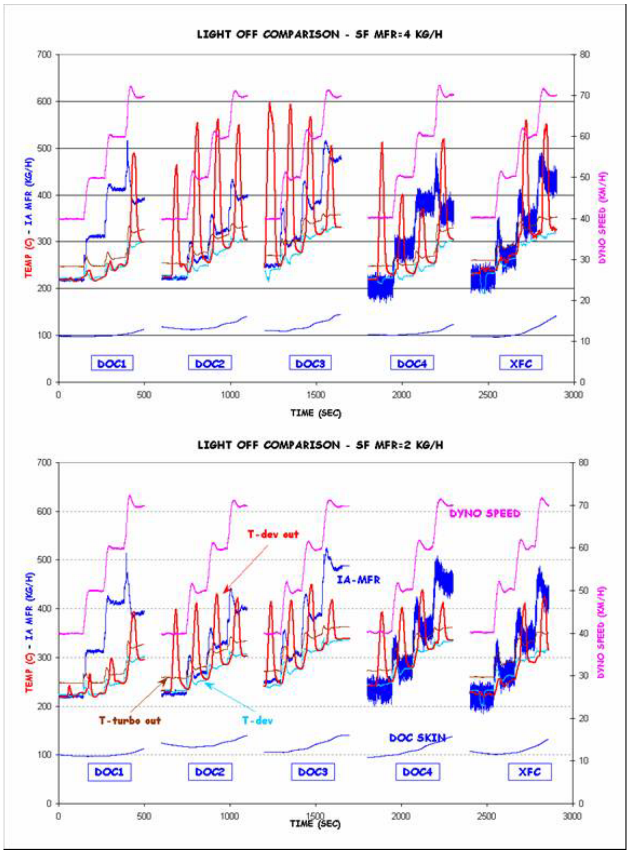


Figure 12: LOF comparison of all 5 DOCs

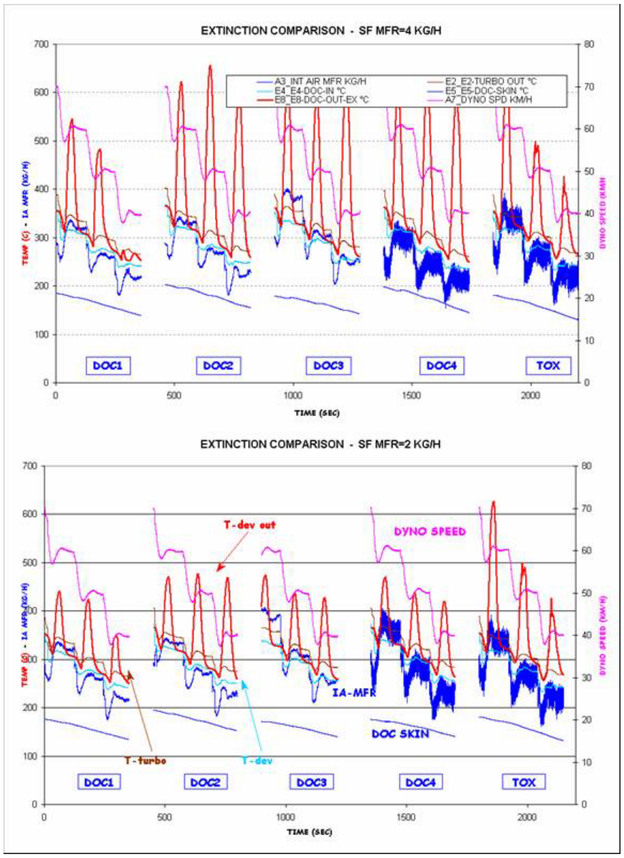


Figure 13: Extinction comparison of all 5 DOCs

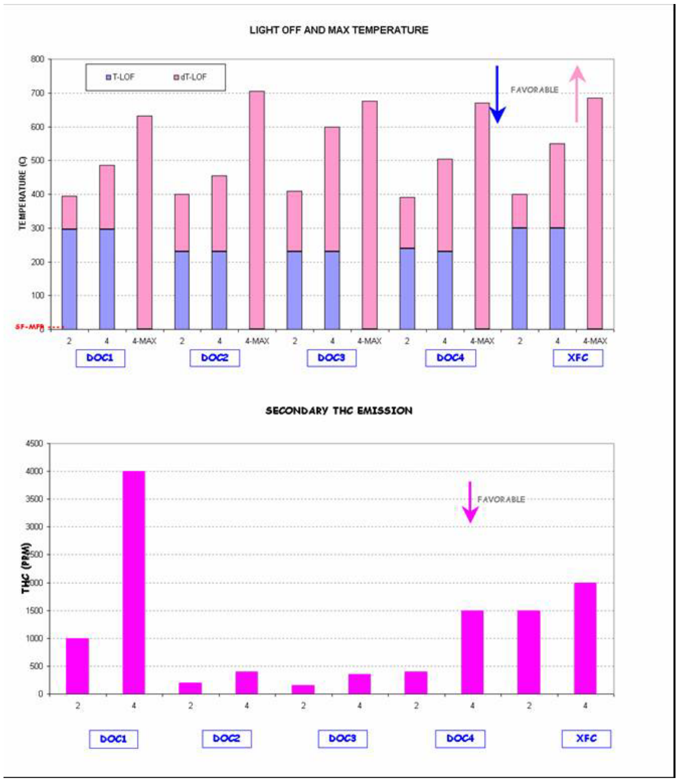
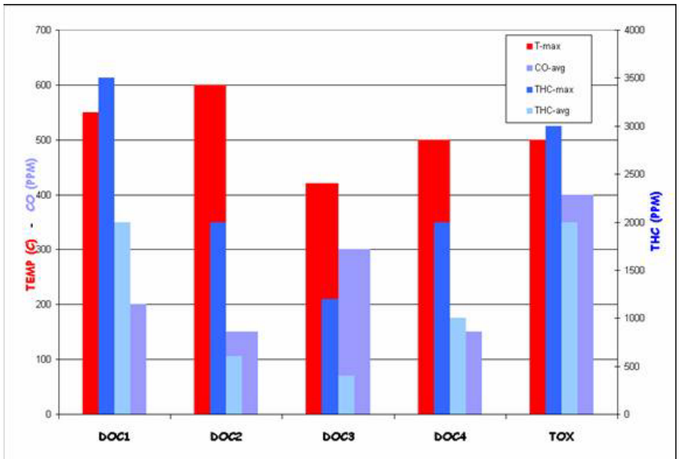


Figure 14: Steady-State LOF and THC Results



	SIMPLIFIED FTP-72			
	T-max	THC-max	THC-avg	CO-avg
DOC1	550	3500	2000	200
DOC2	600	2000	600	150
DOC3	420	1200	400	300
DOC4	500	2000	1000	150
TOX	500	3000	2000	400

Figure 15: Transient LOF and THC Results

Similar quantitative results from the transient test mode #3 are obtained by averaging and reducing the data

(Figure 15). It is clear that DOC2 performs better than the others based on its higher exothermic response as evidenced by its greater maximum temperature. It also has the lowest CO concentration, signaling its ability to successfully oxidize CO into CO_2. DOC2 also has one of the lowest THC responses, second only to DOC3, which is a result of its heavier Pt coating.

In summary, the results indicate that DOC2 and DOC3 provide the lowest LOF temperatures with highest exothermic response, as well as the lowest THC and CO emission levels. This trend is supported in all three test modes, including steady-state and transient evaluations. Therefore, in choosing an appropriate DOC for the secondary fuel injection active DPF regeneration system, DOC2 and DOC3 provide the greatest performance, and as always, cost trade-offs must be considered. Since DOC3 has 75% additional Pt loading, DOC2 is the likely choice since it can likely achieve reduced THC emissions with application-specific fuel injection control strategies.

CONCLUSION

Based on this study, the following can be concluded:

- The test methodology presented here can be used as a tool for application-specific selection of the best performing DOC formulation to be used with secondary fuel injection
- Secondary Fuel Injection can be successfully applied to support active regeneration, and the proposed test methodology can also be applied to optimize injector performance
- DOC2 is the preferred catalyst for this application since it provides the lowest LOF temperature, the greatest exothermic response, lowest CO emissions, and low THC emissions
- Ascending and descending constant speed steps simulate the impact of the thermal inertia of the tested parts in a simplified way
- Similarity between the steady state and transient mode results can be used as justification for using steady state test modes only for the pre-selection of multiple catalytic choices

Based on the results and conclusions of this study, the following are recommended:

- Apply this test methodology to aged DOCs to quantify and compare catalyst performance degradation
- Apply this test methodology to fuel injection products intended for use within diesel exhaust systems to evaluate effects of injector costs, spray performance, and its distance from the DOC
- Evaluate DOC performance with Pt loadings between those applied in DOC1 and DOC2 (between 10 and 40 g/ft3) to better assess cost and performance trade-offs, potentially further reducing costs

REFERENCES

1. SAE Paper 2006-01-1089
2. Others to be added

DEFINITIONS, ACRONYMS, ABBREVIATIONS

LOF: Light off behavior.

DOC: Diesel oxidation catalyst

DPF: Diesel particulate filter

PWM: Pulse Width Modulation

SF: Secondary Fuel Injection

MFR: Mass Flow Rate

THC Total hydrocarbons