

Low Cost LEV-III, Tier-III Emission Solutions with Particulate Control using Advanced Catalysts and Substrates

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ABSTRACT

A production calibrated GTDI 1.6L Ford Fusion was used to demonstrate low HC, CO, NO_x, PM (particulate mass), and PN (particulate number) emissions using advanced catalyst technologies with newly developed high porosity substrates and coated GPFs (gasoline particulate filters). The exhaust system consisted of 1.2 liters of TWC (three way catalyst) in the close-coupled position, and 1.6L of coated GPF in the underfloor position. The catalysts were engine-aged on a dynamometer to simulate 150K miles of road aging. Results indicate that ULEV70 emissions can be achieved at ~\$40 of PGM, while also demonstrating PM tailpipe performance far below the proposed California Air Resources Board (CARB) LEV III limit of 1 mg/mi. Along with PM and PN analysis, exhaust system backpressure is also presented with various GPF designs.

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INTRODUCTION

It is noble to be a good steward of our environment and resources. With this objective, governments have recently promulgated fuel economy in addition to further reductions in emissions standards. In Europe, Euro-6c emission standards will come into play in 2017 with a 95 g/km CO₂ fleet average by 2020. In the US, the LEV-III / Tier-III emission standards have been implemented with fleet fuel economy to improve from 35 to 52 mile/gallon by 2025. China will shortly be enacting laws that shall contain aspects of the European Union and US regulations. Realization of all these stricter standards will help to improve our environment and conserve resources.

The execution of these regulations will tax the vehicle manufacturer's resources. Vehicle manufacturers will need to consider many technologies: turbocharging, gasoline direct-injection (GDI), light weighting, electrification, lean GDI, and diesel powertrains. They will have to implement these solutions in a timely manner and design products that the customer can afford and prefer to drive.

In order to comply with the standards, many vehicle manufacturers have elected to introduce GDI engines with and without turbocharging. These powertrains provide both improved fuel economy and emission

performance [1,2]. Figure 1 shows the substantial growth of the GDI vehicles in Europe, China, and North America and the decline of multiport fuel injected (MFI) engines. GDI powered vehicles will grow from 15 million in 2015 to over 33 million in 2020. However, GDI engines have considerably higher particulate emissions than multiport fuel-injection engines [3] and vehicle manufacturers may need to consider aftertreatment particulate control such as GPFs. With respect to GPFs, manufacturers are concerned about higher exhaust backpressure causing loss of power, poorer fuel economy, durability, system layout, and added cost. Regeneration of the GPF during vehicle operation also needs to be considered.

Substrate and catalyst suppliers have addressed many of these concerns. Previous studies have investigated the impact of GPF substrate design on backpressure [5,6,7] when cell density, wall thickness, porosity, and diameter were varied. It was found that GPF diameter had the greatest impact on backpressure. Four different exhaust system layouts with GPFs have been considered, 1) a washcoated close-coupled GPF only, 2) a washcoated closed-coupled GPF behind a TWC, 3) a washcoated GPF in an underfloor position behind a close-coupled TWC, and 4) an uncoated GPF in an underfloor position behind a close-coupled TWC [7, 8, 9, 10]. In

general, in close-coupled applications, high porosity GPFs are used to maximize washcoat loadings in order to have sufficient catalytic activity and durability after aging. Low porosity GPFs can be used in underfloor locations with or without a catalyst coating applied. Benefits in CO and NO_x emissions were observed when adding a coated GPF to a production vehicle with the same total system PGM loading [8,9]. Vehicle durability studies with GPFs have been executed with interesting results [11,14]. It was observed that filtration efficiency of the GPF improved with aging while fuel economy (CO₂ emissions) was not affected despite a marginal increase in back pressure by the GPF. However, losses in vehicle peak power of about 1.5 - 2.5% were observed [7,10]. There have been significant studies investigating the need to regenerate GPFs [5,8,12,13]. In summary, the catalytic activity of a coated GPF reduces soot combustion temperatures while the presence of oxygen during fuel cuts promotes the oxidation of soot at lower temperatures. Boger et al. [13] stated, “the passive soot oxidation rates exceeded the rate at which engines emitted soot.”

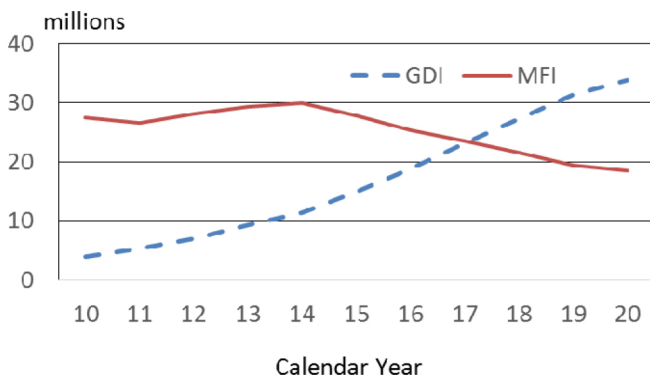


Figure 1. Global Gasoline Engine Technology Trend [4]

However, this is not to conclude that active regeneration may not be required after extended cool operation.

Arguably the US LEV-III and Tier-III emission standards are most demanding. The entire fleet, which encompasses vehicles <8500lbs, must average 30mg NMOG (non-methane organic gases) + NO_x (SULEV30) by 2025. The LEV-III regulations (and Tier-III) combine the NMOG and NO_x emissions and have various emission categories; ULEV70, ULEV50, SULEV30 and SULEV20, for example, to which the vehicle manufacturers can certify. Studies have investigated and estimated catalyst volume and PGM loadings required to meet the LEV-III emission regulations [14, 15, 16] based on current PZEV and BIN 4 applications. Based on current 4-cylinder vehicles, Ball et al. estimated that the best-in-class calibrated vehicles require \$89, \$98, and \$108 PGM for ULEV70, ULEV50, and SULEV30 applications, respectively. 6-cylinder and 8-cylinder applications were assumed to be 1.5 and 2.0 times the cost of that required for a 4-cylinder to meet each emission category, respectively. Supplemental catalyst technology developments for LEV-III can be found in references [17,18]. These catalysts are specifically designed for GDI engines and calibrations.

Most recently, high porosity/low mass cordierite substrates were developed for TWC catalysts [19,20]. These high porosity substrates are 30% lighter than current materials. As expected, the low mass of the substrates results in faster catalyst light-off and lower cold start NMOG emissions. Savings in PGM is predicted.

The goal of this work is to demonstrate LEV-III emissions with particulate control at low PGM usage with a current production PZEV calibrated GDI vehicle. The exhaust layout consisted of two close-coupled TWCs and an underfloor GPF. High and low porosity substrates with a designed three-way technology were evaluated in the close-coupled position at different PGM loadings. In the underfloor position, coated GPFs were varied by diameter and porosity and the porosity defined the washcoat loading. Results not only confirm the NMOG light-off advantage of the high porosity substrates, but improvements in NMHC and NO_x were realized throughout BAG 1 and 3 of the FTP. All GPF designs reduced particulate mass well below 1 mg/mile. As expected, GPF diameter coupled with material porosity/washcoat loading had the largest impact on system backpressure. Since the PGM loadings of the close-couple catalyst were varied, predictions in PGM loadings to achieve the various LEV-III categories are estimated.

EXPERIMENTAL

After-treatment Test Specimen Details

For the purposes of this evaluation, all original after-treatment components were replaced. For the substrate in the close-coupled position after the turbocharger outlet, the single catalyzed substrate was replaced with a series of two catalyzed substrates as shown in Figure 2. Two substrates each ½ of the total volume of the original substrate are used. These close-coupled substrate pairs will be referred to as CC1 (close-coupled catalyst 1) and CC2 (close-coupled catalyst 2).

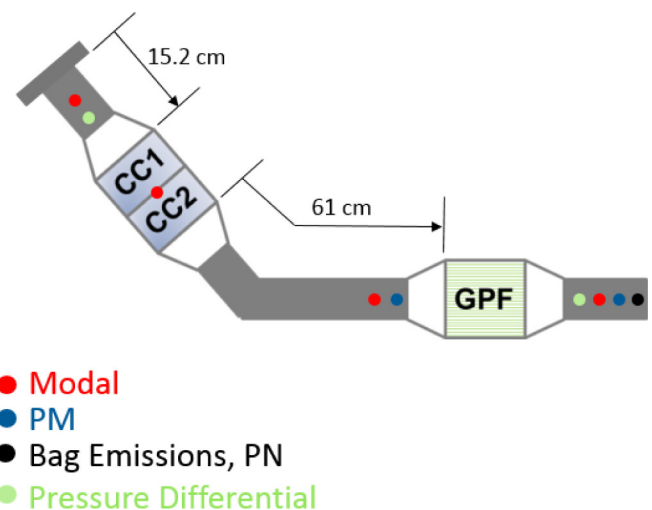


Figure 2. Graphic of new system architecture used for the experimental after-treatment components tested on vehicle. The original close-coupled catalyst was replaced with a split substrate pair, while the underfloor catalyst was replaced with a gasoline particulate filter.

This new system design allowed for direct comparison of standard porosity substrates to newly developed high porosity, low-mass substrates and for experimental hybrid solutions to be examined. [Table 1](#) shows bare, non-coated properties and part sizes of the substrates used in the experiment [19].

Table 1. Comparison of bare properties and part geometries for standard and high porosity substrates. Porosity and mean pore size were determined by mercury porosimetry.

	Standard Porosity Substrate (Celcor™)	High Porosity Substrate (FLORA™)
Cell Density (CPSI) / Wall Thickness (mil)	600/3	600/3
Porosity (%)	35	55
Mean pore diameter (μm)	4	4
Density of Matrix (g/L)	294	200
Part Size (in.)	3.54"x5.16"x2.5" (Oval)	3.54"x5.16"x2.5" (Oval)
Part Volume (L)	0.6	0.6

For the underfloor position, the typical TWC was replaced with a coated GPF as shown in [Figure 2](#) to demonstrate tailpipe particulate mass reduction through filtration in anticipation of future regulations.

Two different developmental cordierite-based GPF technologies were selected; a standard and a high porosity. The variation in porosity enables evaluation of different levels of washcoat loading (WCL). In addition, two different part diameters were selected, while keeping overall part volume the same. The variation in porosity, washcoat loading, and diameter were then measured on vehicle to determine their relative effect on filtration efficiency, system backpressure, and emissions performance. [Table 2](#) shows bare, non-coated properties of the gasoline particulate filters used in the experiment.

Table 2. Comparison of bare properties and part geometries for standard (GC) and high porosity (GC-HP) gasoline particulate filters. Porosity and mean pore size were determined by mercury porosimetry.

	Gasoline Cordierite (GC)		Gasoline Cordierite – High Porosity (GC-HP)	
Cell Density (CPSI) / Wall Thickness (mil)	200/8		300/8	
Porosity (%)	55		64	
Mean pore diameter (μm)	13		20	
Part Size (in.)	Ø4.66"x5.7"	Ø5.66"x3.9"	Ø4.66"x5.7"	Ø5.66"x3.9"
Part Volume (L)	1.6		1.6	

Catalyst Coating & Aging

The washcoat technology selected for the CC1 and CC2 catalysts has low mass but high thermal durability for fast light-off. Additionally, the low mass washcoat enables a meaningful application to highlight the performance differences between the standard and high porosity substrates. The washcoat loading on all of the CC1 and CC2 samples is equivalent. The GPFs were coated with a technology specifically developed for use on filters. For each GPF type, standard or high porosity, the maximum washcoat loading possible was used while

ensuring that the coating was contained entirely within the wall of the substrate to minimize backpressure effects. This led to washcoat loadings on the high porosity filter to be 3 times that used on the standard filter. Pd loadings on the CC1 catalysts were either 96 g/ft³ or 32 g/ft³ and the CC2 Pd loadings were either 32 g/ft³ or 10 g/ft³. Rh loadings were either 4 g/ft³ or 1 g/ft³ on both the CC1 and CC2 catalysts. The GPFs were Pd free, but contained either 6 g/ft³ or 2 g/ft³ of Rh. This large variance in PGM allows for the creation of an empirical model that can be used to calculate the optimal PGM loadings one could use to certify vehicles at emission levels from ULEV125 down to SULEV30.

All test systems were engine-aged to a FUL (full useful life) 150K mile condition using a 4-mode aging cycle for 75 hours. Each 4-mode cycle lasts for 60 seconds and the aging cycle is repeated 4500 times. The individual modes are: stoichiometric, rich, rich+air-injection, and stoichiometric+air-injection. Peak temperatures measured in the CC1 and CC2 catalysts were ~990°C while peak temperatures measured in the GPFs were ~880°C.

Vehicle Description

Vehicle hardware and calibration are critical to achieving low emissions at low PGM costs. The intent of this section is to provide detailed information to help understand how this vehicle operates and how the calibration enables the performance of the advanced substrates and catalyst leading to a low PGM cost solution.

The test vehicle used for these experiments is a 2013 Ford Fusion. It is equipped with a 1.6L GDI, turbocharged engine. The transmission is a traditional 6-speed automatic transmission with a torque converter. The engine features charge-air cooling, wide-range lambda sensor in the engine out position, independently variable intake and exhaust valve timing, and a single-stage electromechanical turbocharger. The rated output of this engine is 173 bhp @ 5700 RPM and 184 lb-ft. @ 2500 RPM, with EPA fuel economy values of 25/37/29 mpg (city/hwy/combined).

An Influx Technology Rebel XT data logger was connected to the diagnostic link connector (DLC) in the vehicle throughout all of the testing. It served to collect numerous SAE specified J1979 mode 1 parameter IDs (PIDs) used in quality control and characterization of the Fusion's advanced PZEV calibration. This application represents an advancement in emissions control technology for turbocharged 4-cyl. PZEV vehicles because it is not equipped with an air pump to assist in catalyst light-off during the cold start. The cold start and FTP+US06 lambda calibrations are summarized next.

The engine speed during the first idle / cycle 1 of the FTP is shown in [Figure 3](#). Notably in this calibration, the cold start engine flare is kept to a minimum. Average park-neutral engine speed is 1300 RPM, on average, with a drop to approximately 950 RPM after the shift to drive before the start of cycle 1. This represents a mid-level operating point in the 1st idle cold start for PZEV vehicles [14].

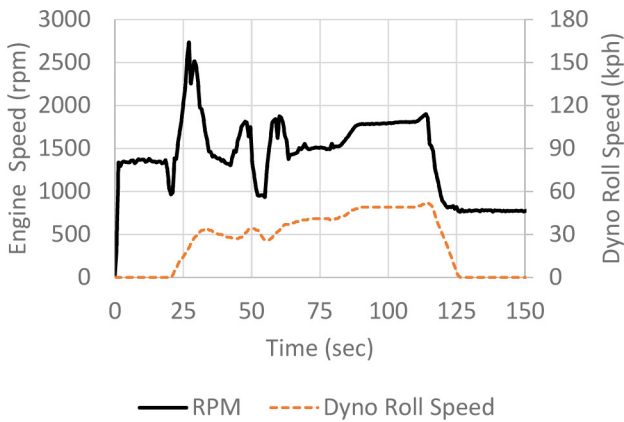


Figure 3. FTP Cycle 1 Engine Speed

Figure 4 shows ignition timing. It is noteworthy the Fusion powertrain is able to attain very aggressive levels of spark retard ($\sim 20^\circ$ BTC) in the first idle of the FTP. This can be attributed to the fact that DI fuel system and in-cylinder fuel and air mixing technology offers faster and more stable levels of combustion with more aggressive ignition timing, compared to PFIs. The aggressive timing offsets some of the light-off detriment the turbo introduces to the system by delaying the combustion process. The mass fraction of unburned fuel and air is increased with late spark plug firings, leading to a higher level of burning that takes place when the exhaust leaves the chamber and passes over the catalyst.

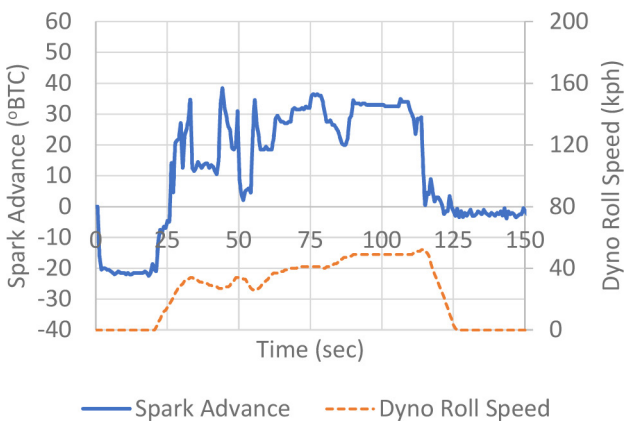


Figure 4. FTP Cycle 1 Spark Advance

As shown in Figure 5, the fuel system reaches closed-loop status at approximately 13 seconds after the engine starts. The application has fast warmup HEGO sensors that allow it to achieve closed-loop before the first cycle acceleration, similar to the vast majority of applications calibrated to meet PZEV or SULEV limits. Operating in closed-loop during the first cycle acceleration offers a distinct advantage in terms of minimizing engine-out emissions.

Figure 6 shows the FTP cycle 1 ECU commanded lambda and measured lambda. The measured value was achieved by means of installing a Bosch LSU wide range lambda sensor in the turbo-out exhaust position. The commanded value was collected from the ADL datalogger, PID 44, "Fuel/Air Commanded Equivalence Ratio" per the SAE J1979 specification, and is therefore a direct representation of what the calibration is attempting to achieve in terms of fuel

control. This application utilizes a wide-range engine-out lambda sensor, that reports the actual commanded lambda in closed-loop vs. a single value of $\lambda=1$ for control system with a switching engine-out sensor.

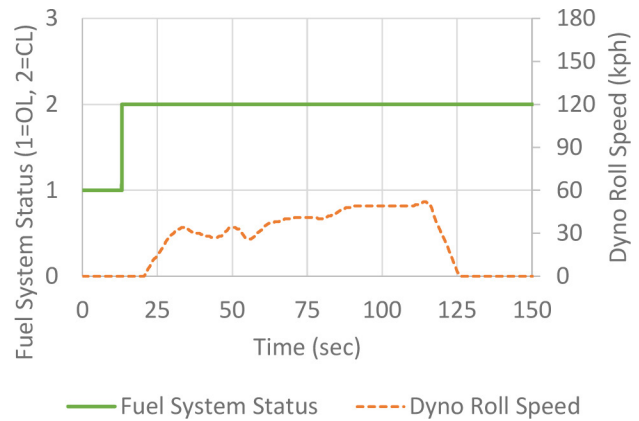


Figure 5. FTP Cycle 1 Fuel System Status



Figure 6. FTP Cycle 1 Engine Lambda

It can be observed that this particular calibration starts out and operates in a lean condition for the first 10 seconds, and then ramps towards stoichiometric throughout the remainder of the first 20 second idle period. As the temperature plots will show, this calibration strategy achieves a good balance of presenting enough late burn fuel energy to the catalyst to ensure a rapid light-off, while minimizing raw engine HC emissions before the catalyst is lit off.

Once closed-loop is achieved, the commanded lambda shows an attempted operation with amplitude and frequency of approximately 2.7% (basis commanded) and 2.1 Hz (basis measured), respectively. Average lambda is just slightly rich (0.5%), which is standard operating procedure for NO_x control for the overwhelming majority of lambda 1 calibrations [21]. The overall level of AFR control demonstrated by this application in cycle 1 is very good and serves as an excellent means for keeping emissions low.

Exhaust Temperatures

General exhaust temperature representations are shown in this section. Specific temperature comparisons between the standard and high porosity substrates are compared later in the results section. For