

Development and Testing of the Ultera® Dual Stage Catalyst System on Gasoline-Fueled Light Duty Vehicles (LDV's)

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ABSTRACT

All vehicles sold today are required to meet emissions standards based on specific driving cycles. Emissions standards are getting tighter and the introduction of real driving tests is imminent, potentially calling for improved aftertreatment systems. A dual stage catalyst system, with exhaust temperature control, can provide a robust solution to meet challenging modes of operation such as rapid acceleration and other heavy-duty transients. The Ultera® technology, developed and successfully implemented on stationary natural gas CHP (Combined Heat and Power) engines, introduces a second stage catalyst downstream of a three-way catalyst. Air is injected between the two stages to provide oxygen required for the second stage reaction that removes additional CO and NMOG. Critical to the process is to avoid the reformation of NOx. This is achieved by cooling the exhaust gas prior to the second stage, to a temperature range in which CO and NMOG oxidation is extremely effective, while no new NOx is created. The objective of this research was to apply this technology to vehicle engines, with the primary interest being gasoline-fuel, direct fuel injection, and more dramatic transient loading. Testing of a ULEV compliant light duty truck (LDT) and a European passenger vehicle was conducted using a chassis dynamometer. Optimization of control temperature and air- injection flow was studied. Also examined were customized catalyst formulations for enhanced hydrocarbon reduction. Results showed significant reductions of CO and NMOG, with no negative impact on NOx. There was also no measurable impact on fuel economy, but further study is required to include the parasitic loads of cooling and air injection in order to fully quantify the impact to mpg. Future development work can provide opportunities to further reduce NOx emissions through chemistry and integration with engine operation.

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INTRODUCTION

Growing concerns over public health effects of automotive-based pollution has compelled regulators to continue to lower the limits of acceptable criteria pollutants, in the United States, Europe, and around the World. The US EPA is now harmonizing their regulations with those of California, a state that suffers from some of the most severe smog, especially in the greater Los Angeles metropolitan area. These new US standards for passenger cars (PCs) and light duty trucks (LDTs) will phase in from 2015 to 2025, and require that by 2025, not only must a vehicle meet the lower standard for NOx and

NMOG in its class, but a manufacturer's light duty fleet average must also comply with today's SULEV (Super Ultra Low Emission Vehicle) standard [1]. SULEV is one of the strictest levels adopted by some of the cleanest cars on the market today.

Europe is also tightening vehicle emission regulations with the introduction of the Euro 6 directive in 2015. In fact in 2017, the European Union will begin introducing RDE (Real Driving Emissions) limits where the actual tested on-road emissions will be phased in to the regulations over time. Even those countries in EAMA (European Automobile Manufacturers Association), recognize

that there is a gap between laboratory emission testing and actual road emissions based on real world driving [2]. Initially in 2017, these regulations will only apply to new type approvals. However, by 2019, they will apply to all vehicles. European automakers are scrambling to determine how to comply with these tougher standards by 2019, particularly with smaller turbocharged engines. While diesel engines struggle with NO_x, gasoline engines have difficulties with carbon monoxide, NMOG, and particulates [3].

In order to maintain compliance as these targets aim lower, the industry continues the research and development efforts in the areas of advanced engine control strategies and exhaust aftertreatment systems. Much of this work has focused on reducing cold start emissions with advances in control strategies and close-coupled catalyst design. Significant progress has also been made with advanced three way catalysts, including high cell density substrates, catalyst coating, and precious metal impregnation [4].

The Ultera dual stage emission technology is an alternative tool to help meet these future regulation goals. Dual catalysts are a known method for expanding the AFR control window in order to attain acceptable emissions of both CO and NO_x, and were employed in some automotive applications in the 1980's. However, this concept proved to have the negative consequence of reforming NO_x in the second stage and fell out of favor when the emissions limits tightened over the years. However, the patented insight of this new dual stage concept is cooling the exhaust gas prior to the second stage, such that CO and NMOG oxidation are extremely effective, but no new NO_x is created [5]. This technology was originally developed for natural gas stationary CHP engines and provided a robust solution for continuous duty industrial applications [6]. The purpose of this research was to determine whether the technology could be applied to mobile engines fueled by gasoline.

TEST SETUP

The primary objective of this test demonstration was to verify that this technology, which has been repeatedly proven on stationary natural gas engines, could translate over to gasoline engines on vehicles. This technology is an aftertreatment system that is simple and non-intrusive and could be easily added to the external exhaust system of a vehicle. However, the unknown challenges on the vehicle application were 1) gasoline fuel as opposed to natural gas, 2) the dynamic control of a foot pedal resulting in dramatic control transients and 3) the impact on fuel economy.

Two light duty vehicles were tested on chassis dynamometer in order to validate the technology. These were:

Vehicle 1

This vehicle was a LDT (light duty truck) in the ULEV emission category, 2016 model year, 5.3L displacement, 8 cylinder, DFI (direct fuel injection) and a weight of 5500 lbs. With a V8 configuration, the engine had two close-coupled catalysts, 1 per exhaust manifold, and an underbody catalyst. No detailed information was available on the vehicle's catalysts (i.e. volume,

PGM (platinum group metal) loading, and composition) as this is proprietary OEM (Original Equipment Manufacturer) information. The odometer reading when testing commenced was 1,606 miles. This vehicle was compliant with the regulations LEV3 ULEV 125 [1] as shown in Table 1, which compares the FTP75 drive cycle test on the baseline vehicle to the certification standard.

Table 1. Vehicle 1 Baseline Compliance

	NMOG +NOx [g/mi]	CO [g/mi]
FTP75 Test Result	0.044	0.47
LEV3 ULEV 125	0.125	2.1
% of Standard	35%	22%

Vehicle 2

This vehicle was a European passenger car, 2015 model year, 1.2L turbocharged, DFI (direct fuel injection), CAC (charge air cooling) and a weight of 2500 lbs. With an inline 4-cylinder configuration, the engine had just a single underbody catalyst. No detailed information was available on the vehicle's catalyst (i.e. volume, PGM loading, and composition) as this is proprietary OEM information. The odometer reading when testing commenced was 7,800 miles. This vehicle was compliant with the Euro 6 regulations [7] as shown in Table 2, which compares the NEDC drive cycle test on the baseline vehicle to the certification standard.

Table 2. Vehicle 2 Baseline Compliance

	NOx [g/km]	NMHC [g/km]	CO [g/km]
NEDC Test Result	0.012	0.0001	0.009
EURO 6 – Class PI	0.06	.068	1.0
% of Standard	20%	0.1%	1%

The testing was done by AVL California Technology Center.

First standard test cycles were run on the baseline vehicle (without adding the second stage system) mainly to examine potential impact on fuel economy. Then the vehicle was outfitted with the exhaust cooling/air injection and second stage catalyst (from here on called second stage catalyst system for simplicity). This system was just incorporated into the vehicle OEM exhaust system by inserting it in between the underbody catalyst and the muffler. Referring to Figure 1, the exhaust heat exchanger was placed immediately after the underbody catalyst. This heat exchanger was equipped with an internal bypass butterfly valve that was controlled to maintain an exhaust temperature leaving the heat exchanger. The heat exchanger was cooled by a secondary radiator. The second stage catalyst had a volume of 261 in³, cell density of 300 cpsi (cells per square inch), and a total PGM commensurate with a commercially available underfloor catalyst. It was installed downstream of the heat exchanger. Air was injected in between the exhaust heat exchanger and the second stage catalyst. The hours on the OEM catalysts matched the same low mileage odometer readings of the vehicles (Vehicle 1 - 1606 miles, Vehicle 2 - 7800 miles), while the second stage catalysts were fresh.

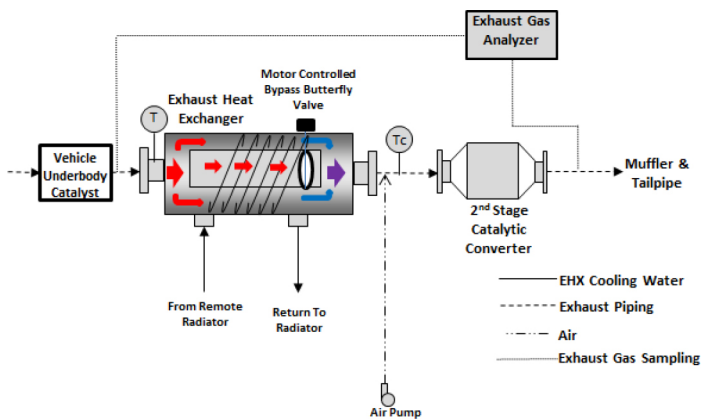


Figure 1. Dual Stage System Test Set-up

Emission samples were taken upstream of the second stage system and at the tailpipe. Each sample line was fed to a dedicated emissions test bench in order to obtain real time emissions before and after the new technology. These were state-of-the-art automotive certification analyzers that utilized the latest technology of exhaust measurement such as CLD (chemiluminescence detection) for NO_x and IRD (infrared detection) for CO.

Measurements were taken for NO_x, CO, THC, CH₄, O₂ and CO₂. NMOG, which is the mass emissions of non-methane hydrocarbons and oxygenated hydrocarbons, is calculated from the measurements of THC and CH₄. First, the concentration of NMHC (non-methane hydrocarbons) is calculated:

$$NMHC \text{ (ppm)} = THC \text{ (ppm)} - CH_4 \text{ (ppm)} \times r_{CH_4} \quad [8]$$

Where,

THC (ppm) - Measured concentration of THC (total hydrocarbons)

CH₄ (ppm) - Measured concentration of methane

r_{CH_4} - FID methane response factor = 1.11

Then NMOG is calculated from the mass of NMHC as follows:

$$NMOG \text{ [g]} = NMHC \text{ [g]} \times RAF \quad [8]$$

Where,

RAF - Reactivity Adjustment Factor = 1.04

The test results from both vehicles are presented in subsequent sections. Vehicle 1 was tested first, followed by Vehicle 2. Upgrades were made to the second stage system prior to the Vehicle 2 testing, so those results reflect improved hardware. Lastly, a laboratory study on alternative second stage catalyst formulations is discussed.

VEHICLE 1 TEST RESULTS

The primary objective of this test was to verify that the favorable performance of the technology, which has been repeatedly proven on stationary natural gas engines, could translate over to a gasoline engine on a vehicle. The first vehicle (Vehicle 1) tested was a light duty truck, with a direct injection gasoline engine, and a ULEV emission classification.

The US06 standard drive cycle was performed. This cycle encompasses a high speed/quick acceleration loop that lasts 10 minutes, covers 8 miles (13 km), averages 48 mph (77 km/h) and reaches a top speed of 80 mph (130 km/h). It includes four stops and a brisk acceleration rate of 8.46 mph (13.62 km/h) per second.

Table 3 presents the emission results for a typical US06 cycle. The CO reduction is 94%, reducing the emissions from 0.322 g/mile to 0.020 g/mile, which amounts to 2.5 grams of CO removed over the entire cycle. The NMOG reduction is 81%, from 0.005 g/mile down to 0.001 g/mile, amounting to 34 mg of NMOG removed.

Table 3. Typical Vehicle 1 US06 Drive Cycle Test Results

	CO	NMOG	NO _x	NMOG + NO _x
Pre – Second Stage Catalyst System				
Grams	2.609	0.042	0.047	0.089
grams/mile	0.322	0.005	0.006	0.011
Post – Second Stage Catalyst System				
Grams	0.160	0.008	0.041	0.049
grams/mile	0.020	0.001	0.005	0.006
Reduction Efficiency	94%	81%	12%	45%
Total Grams Removed	2.5	0.034	0.006	0.040
ULEV Regulation [g/mile]	9.6			0.14

Another objective of the test was to demonstrate the destruction of CO and NMOG without reforming NO_x. As shown in Table 3, this was the case at a setpoint control temperature of 375 °F. In fact, the NO_x actually decreased for a combined NO_x and NMOG decrease of 45%.

The last row presents the current EPA regulation for this vehicle, which is a ULEV (Ultra Low Emissions Vehicle). As shown, this vehicle is easily in compliance even without this technology. However, as the regulations are moving towards cleaner fleets in the US, and with the upcoming RDE legislation in Europe, technology that continues to reduce tailpipe emissions has significant value.

Graphical data is helpful to illustrate the system's effectiveness across the entire drive cycle. Figure 2 presents the CO concentration in ppm upstream of the second stage system. Also shown on the graph is a representation of the US06 cycle using the vehicle speed [km/h] in order to illustrate the driving pattern with various transients, high acceleration, and deceleration events. As shown, there are various spikes in CO, particularly when accelerating. Figure 3 presents the tailpipe CO, after the second stage system, which shows that the CO is nearly eliminated across the US06 cycle, except for a moderated spike near the end of the cycle.

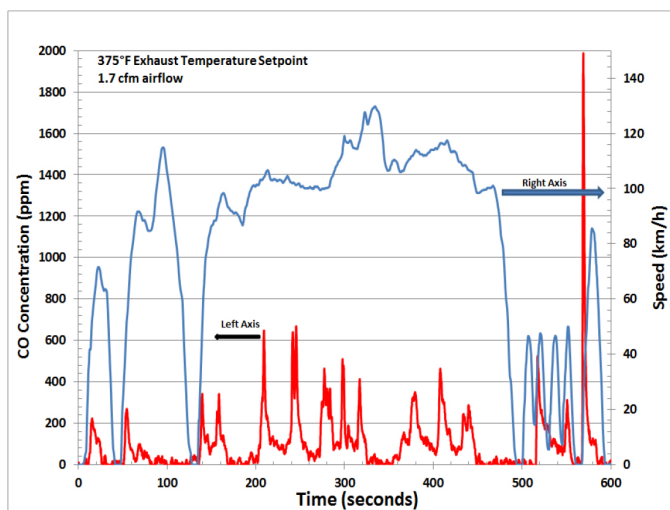


Figure 2. CO Concentration - US06 Drive Cycle - Pre Second Stage System, Vehicle 1. Red line indicates CO concentrations in ppm (left axis) while blue line shows the vehicle speed in km/h (right axis)

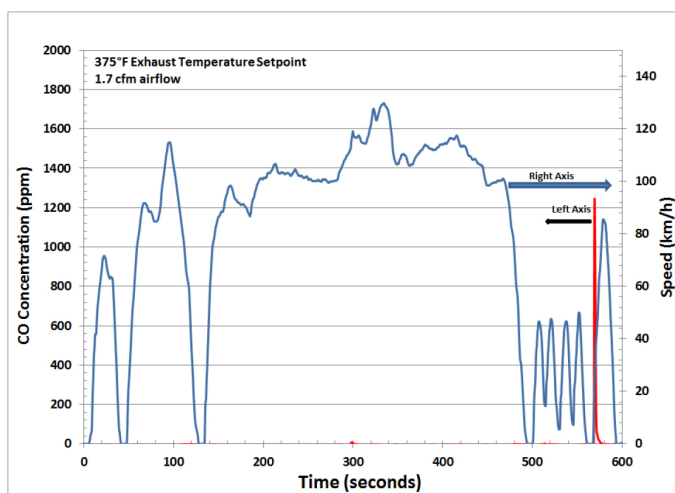


Figure 3. CO Concentration - US06 Drive Cycle - Post Second Stage System, Vehicle 1. Red line indicates CO concentrations in ppm (left axis) while blue line shows the vehicle speed in km/h (right axis)

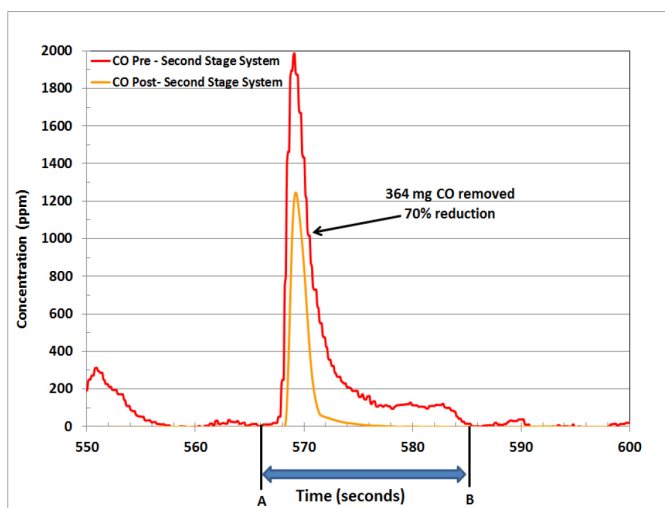


Figure 4. CO concentration in the last acceleration spike observed in the US06 cycle in Figures 2 and 3 without (in red) and with (in orange) the second stage system, Vehicle 1.

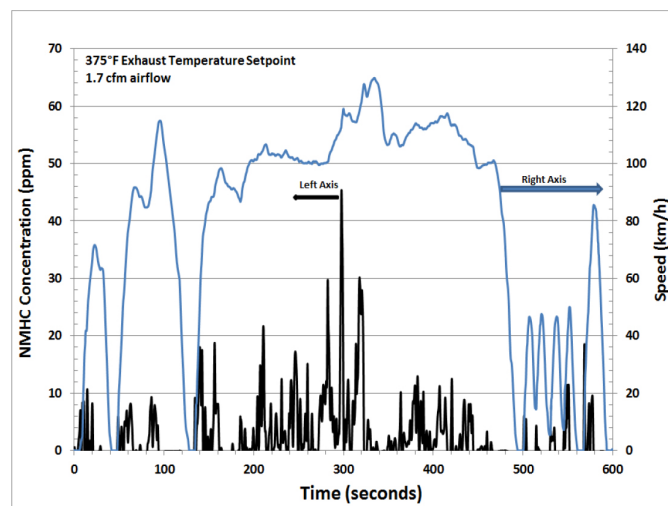


Figure 5. NMHC Concentration - US06 Drive Cycle - Pre Second Stage System, Vehicle 1. Black line shows NMHC concentration in ppm (left axis) while blue line depicts the vehicle speed in km/h (right axis)

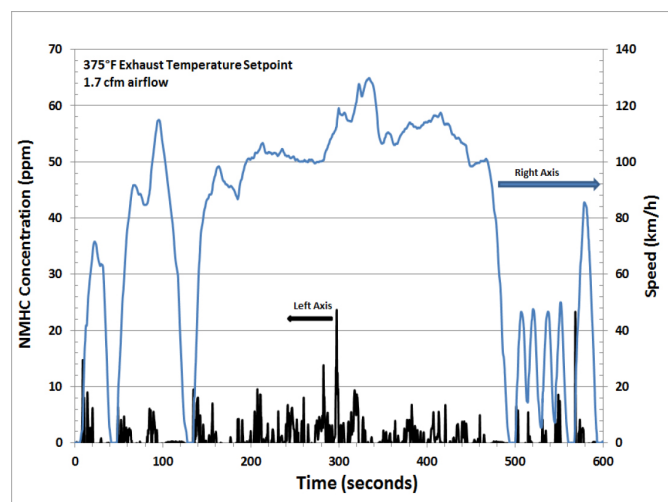


Figure 6. NMHC Concentration - US06 Drive Cycle - Post Second Stage System, Vehicle 1. Black line shows NMHC concentration in ppm (left axis) while blue line depicts the vehicle speed in km/h (right axis)

The second stage system did not completely eliminate this last spike. However it did significantly reduce the area under the spike, which represents the mass concentration. Figure 4 is a graph of the CO concentration, before and after the second stage system, during the large acceleration spike at the end of the US06 (i.e. between time A and B). The area under each curve is the mass of CO in milligrams and was calculated using the measured fuel and air flow from time A to time B. The pre-second stage system mass was 522 mg and the post-second stage system mass was 158 mg. Therefore, the weight of CO removed by the second stage system during this event was 364 mg or 70%. Figure 4 depicts this reduction.

Figure 5 presents the NMHC (Non-Methane Hydrocarbons) concentration throughout the drive cycle upstream of the second stage system. It is important to note that NMHC is plotted here, since NMOG can only be represented as a mass. Figure 6 presents the NMHC at the tailpipe, illustrating the reduction of this pollutant by the system.