Title
In-Use Gaseous and Particulate Emissions from a GDI Vehicle With and Without a Gasoline Particulate Filter (GPF)

Author
Zhang, Jinwei

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In-Use Gaseous and Particulate Emissions from a GDI Vehicle With and Without a Gasoline Particulate Filter (GPF)

A Thesis submitted in partial satisfaction
of the requirements for the degree of

Master of Science

in

Chemical and Environmental Engineering

by

Jinwei Zhang

June 2018

Thesis Committee:
Dr. David Cocker, Chairperson
Dr. George Karavalakis
Dr. Kelley Barsanti

The Thesis of Jinwei Zhang is approved:

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Committee Chairperson

University of California, Riverside

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ABSTRACT OF THE THESIS

In-Use Gaseous and Particulate Emissions from a GDI Vehicle With and Without a Gasoline Particulate Filter (GPF)

by

Jinwei Zhang

Master of Science, Graduate Program in Chemical and Environmental Engineering
University of California, Riverside, June 2018
Dr. David Cocker, Chairperson

There is currently widespread concern about the in-use nitrogen oxides (NOx) and particulate matter (PM) emissions of gasoline direct injection (GDI) vehicles, which have dynamically penetrated into the US passenger vehicles market and are expected to eventually replace the less fuel efficient port fuel injection (PFI) vehicles. Although GDI engines are knows to significantly improve fuel economy and lower greenhouse gas emissions (GHG) when compared to PFI engines, they produce higher PM emissions due to the direct spray of gasoline into the combustion chamber. This leads to locally rich, diffusion-governed liquid fuel combustion that enhances PM formation. Gasoline particulate filters (GPFs) are introduced as an effective strategy to reduce the

tailpipe PM mass and the number of ultrafine particles under a range of driving conditions and at the same time meet California's PM mass emission standards.

For decades, dynamometer based measurements of vehicle emissions have been the standard for verifying the engine, but average test driving cycles do not provide the full range when driving on road or accurate estimates of typical power demands on the vehicle's engine. This has led to the introduction of real world driving emission (RDE) test and portable emissions measurement systems (PEMS). PEMS is becoming an important regulatory device.

The objective of this study is to examine the PM mass, PM soot (PM soot means black carbon and this is the majority of PM mass), particle number (PN), and gaseous emissions of a current technology GDI vehicle during on-road testing with and without a catalyzed GPF. Testing was performed on three routes with different topological characteristics, representing urban, rural, highway and mountain driving conditions. The vehicle was tested triplicate in downtown Los Angeles, Mt. Baldy, and in San Diego. The results of this work are discussed in the context of the impact of GPF and driving patterns on tailpipe PM, PN, gaseous emissions and fuel economy.

The results showed statistically significant filtration rate up to 99% for PMsoot emissions by employing catalyst GPF instead of traditional TWC catalyst, statistically significant reduction for total PM, PN and a statistically significant decreasing trend for NO_x emissions for most driving conditions, no statistically significant for CO, CO_2, THC, and NMHC emissions, no measureable impact was found for fuel economy indicates that there is no back pressure issue. With all these beneficial performances we conclude that catalyzed GPF is a reliable strategy for GDI vehicle emission control.

Research regarding a traditional GPF without a catalytic washcoat has been done before and this study aims to reinforce previous findings and see if a catalytic washcoat along with real world driving changes anything seen before. In previous works, most of the market sale GPFs didn't achieve as high of a reduction efficiency as the state of art catalyzed GPF utilized in this study. Additionally this catalyzed GPF solved the back pressure issue that was found by Tasuku et al [1] on 2012. This study is one of the first in this field that simultaneously measured a catalyzed GPF's impact on both gaseous and particulate emissions during real world driving tests, however, similar research was done by Joachim et al [2] in 2017 in Europe. Their work showed similar PM and PN reduction and decrease trend for gaseous emissions, but their GPF reduction efficiency for PM is not as significant as our GPF. With this study the Manufacturers of Emissions Controls Association can optimize the catalyzed GPF to reach maximum efficiency and create stronger regulations for gasoline vehicle emissions.

Key words: Catalyzed gasoline particulate filter (GPF).

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Acronyms and Abbreviations

SCAQMD .... South Coast Air Quality Management District

CARB..California Air Resources Board

EPA ....Environmental Protection Agency

MECA ....Manufacturers of Emissions Controls Association

CE-CERT..College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)

GDI .... Gasoline direct injection

PFI …... Port fuel injection

GHG ….. Greenhouse gas emissions

GPF .... Gasoline particulate filter

DPF .... Diesel particulate filter

FTP-75..Federal Test Procedure

HWFET .... Highway Fuel Economy Test

SFTP..US06 Supplemental Federal Test Procedures

CH_4 .... Methane

OC .... Oxidation catalyst

TWC..Three way catalyst

CO ....carbon monoxide

CO_2..carbon dioxide

FID ....flame ionization detector

UV ....ultra-violet

NDIR...non-dispersive infra-red

NH_3 ....ammonia

NO_x..nitrogen oxides

OEM..original equipment manufacturer

RDE ....Real Driving Emissions

PM..particulate matter

PM2.5...ultra-fine particulate matter less than 2.5 µm (certification gravimetric reference method)

PN ....particle number

RPM ....revolutions per minute

THC..total hydrocarbons

NMHC..non-methane hydrocarbons

UCR ....University of California at Riverside

FE...Fuel economy

SD ....San Diego

LA ....Los Angeles

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1. Introduction

Air pollution has become a topic issue for human society. With a continuously developing of automotive and transport industry, the amount of passenger vehicles has rapid grown worldwide. Vehicle exhaust emissions, including primary and secondary aerosol emissions resulting from normal day driving has become a serious health problem especially near roadway and in urban area. Since pollutants emitted by motor vehicle is shown to be the main source of urban air pollution by recent air quality measurements and studies, researches and predictions related to vehicle exhaust emissions have significant value to human society. Worldwide governmental agencies and research institutions, have realized the importance of pollution limits and carried out more stringent regulations year by year to force and supervise the industrial companies and automotive manufacturers to find ways to reduce pollutions from vehicle exhaust. [1-3]

The United States (U.S.) and the European Union (EU) have adopted many standards for vehicle pollutions and fuel economy. The Corporate Average Fuel Economy (CAFE) requires all manufactures in the US to meet 54.5 miles per gallon fleet average by 2025 for all newly built passenger vehicles and trucks. The requirements for the EU is a fleet average of no greater than 130g/km of CO_2 emissions adopted in 2011. California Air Resources Board (CARB) and U.S. Environmental Protection Agency (EPA) have implemented California LEVIII and U.S. Tier 3 regulations Federal Test Procedure (FTP-75) test cycle since 2015 and 2017 respectively and California LEVIII is the updated version of current California LEVII, with particulate matter (PM) maximum exhaust standard reduced to 3 mg/mile instead of 10 mg/mile standard. This is a 4-year step for 2017-2021 model vehicles where all vehicles must certify to LEV III regulation to gain market selling permit. Additionally a stricter PM limit of PM less than 1 mg/mile standard will be enforced starting from 2025.The EU has similar mandates called Euro Stage 6 particle number (PN) limit for dyno test and Real Driving Emissions (RDE) since September 2017, the former limits of $6*10^{12}$ particles/km released from September 2014 reduced by 90% to a new standard of $6*10^{11}$ particles/km. This exhaust limit is valid for both passenger vehicles and light duty trucks with diesel engines. The EU also has gaseous emission regulations and is listed below. [4-8]

Table 1 LEVIII emission standards for all passenger vehicle

	NMOG+NOx (g/mi)	CO (g/mi)	HCHO (g/mi)	PM (g/mi)
LEV160	0.160	4.2	4	0.01
ULEV125	0.125	2.1	4	0.01
ULEV	0.070	1.7	4	0.01
ULEV	0.050	1.7	4	0.01
SULEV	0.030	1.0	4	0.01
SULEV	0.020	1.0	4	0.01

Table 2 Euro 6 Emission Standards

Parameter	Unit	Value
THC	mg/km	100
NMHC	mg/km	68
NO_x	mg/km	60
CO	mg/km	1000
PM	mg/km	4.5
PN	#/km	$6.0*10^{12}$

SULEV- Super Ultra Low Emission Vehicles. NMOG - non-methane organic gases. HCHO-formaldehyde.

Facing the stricter vehicle exhaust emission standard and for the purpose of getting better fuel economy, gasoline direct injection (GDI) engine technology is introduced into the engine and automotive manufactures market, which has significantly penetrated the U.S. passenger vehicles market and is expected to eventually replace the less efficient traditional port fuel injection (PFI) engine technology. GDI engine directly sprays gasoline into the combustion chamber instead of port fuel injection spark ignition, which leads to higher fuel economy and higher power output, and helps the goal to reduce CO_2 emissions. With a rapid development of GDI engine technology, market occupancy of GDI vehicles has risen up to 60% by 2016 in U.S. passenger vehicle market and will continuously grow in the future. [9]

Although GDI engines are known to significantly improve fuel economy, output, increase torque, and exhaust lower greenhouse gas emissions (GHG) emissions compared to PFI engines, there is currently a widespread concern about the actual particulate matter and black carbon emissions of GDI vehicles. GDI engines produce higher PM emissions due to the direct spray of gasoline fuel into the combustion cylinder rather than port fuel injection, such that gasoline and intake air don't have sufficient time to evaporate and mix before combustion. This leads to locally rich, diffusion-governed liquid fuel combustion leading to increase pyrolysis and resulting in more PM and soot formation. Therefore the drawback of GDI engines is that they create more PM pollution, which has attracted attention of regulating agencies and requirements of PM emissions reduction. [11-12]

Reducing PM and PN emissions from GDI engine vehicle has become the priority mission for all engine manufactures and related research institutions. Essentially there are three ways to reduce vehicle emissions: engine design, fuel formulation and exhaust after-treatment system. Manufacturers are testing new stoichiometric and homogeneous injection systems such as adjust the engine injection parameters (e.g., position and number of nozzle and piston, injection pressure) to achieve better mixture of intake air and fuel to reduce PM emissions, Academic research indicates gasoline combined with ethanol will have a grateful on PM reduction aspect; further studies are required to investigate the best gasoline/ethanol ratio under different driving conditions that benefits fuel economy and emission. As for an exhaust after-treatment system, the gasoline particulate filter (GPF) is a reliable strategy to control the PM mass and the number of ultrafine particles under a range of real driving conditions and still meet California's PM mass emission standards. GPF is developed based on diesel particulate filter (DPF). Ceramic wall flow gasoline particulate filter has been rapidly developed. One important concern about GPF is pressure drop while many materials have been tried for GPF such as silicon carbide and aluminum titanate, the currently most common material used is cordierite because of its excellent thermodynamic parameters, low coefficient of thermal expansion and high quality filtration performance. Currently, studies indicate some high performance GPF can reduce tailpipe PM emissions up to 99% eventually even for the new model GDI vehicles, which have certified by California LEVIII and U.S. Tier 3 regulations. Therefore, GPF has been suggested as an effective strategy for emission reduction. [13-16]

Dynamometer based measurements of vehicles following standard driving cycles have been the standard method to verify vehicle emissions are meeting meet current federal regulations. These same emissions measurements and driving cycles have been used as the basis to estimate emission inventories or the total pollutant emissions in a particular area based on population and vehicles acting at a defined time and set of conditions. However, average driving cycles do not necessarily give an accurate estimate of everyday vehicle use or typical power demands on the vehicle's engine despite being the standard for verifying that the vehicle meets current regulations. Additionally the average cycles designed more than 20 years ago do not give a complete picture of typical power demands. These differences between conditions for chassis or engine test cycles defined by vehicle emission regulations and real-world driving can contribute to the differences between expected and actual pollution levels.[17]

Recent air quality studies show significant exceedances for NOx and PM emissions worldwide, mainly in urban areas with high populations where emissions are mainly contributed by transportation sources despite tightening of emissions standards. There is additional concern that emissions under real world driving conditions exceed regulating standards for vehicles. Therefore portable emission measurement systems (PEMS) were introduced and have been used for the purpose of investigating and regulating real driving emissions (RDE) of vehicles with PEMS becoming an increasingly important regulatory tool. Need of such RDE testing was highlighted as the Volkswagen (VW) Scandal disclosed in 2015. Therefore PEMS measurements of PM, PN and gaseous emissions level difference between regulating dyno based and real world ambient driving conditions based by independent testing institutes is needed.

With recent developments in the US and the European Union (EU), PEMS is becoming an important regulatory device, as evidenced by recent developments in the US and EU. With improvements in PEMS measurement accurate, the Environmental

Protection Agency (EPA) and the California Air Resources Board (CARB) have increased the use of PEMS in the US to evaluate heavy duty on-road and light-duty vehicles emissions during on-road test. This is in addition to the normal Federal Test Procedure (FTP-75), Highway Fuel Economy Test (HWFET), and US06 Supplemental Federal Test Procedures (SFTP) chassis dynamometer testing. Similar regulations have been formulated by RDE legislation for automotive vehicles to use PEMS for on road emission testing under real world driving conditions. [2-4]

PEMS technology has developed significantly to accurately measure vehicle emissions with increasingly stricter emissions regulations. State-of-the-art PEMS units can simultaneously measure CO_2, CO, PM soot, total PM, total hydrocarbons (THC), Non-methane hydrocarbons (NMHC) and with additional components PN measurement is also attainable. Despite limitation in size, weight along with vibration during on road test, automotive testing equipment manufacturers have made significant improvements to the accuracy and stability of PEMS, with AVL, HORIBA and SEMTECH making tremendous progress on their testing equipment over the last decade. Although PEMS instruments varies by companies, the fundamental measuring theory is similar. Flame ionization detector (FID) is used to measure THC concentration, NO / NO2 is measured by ultra-violet (UV) absorption, and CO / CO2 measurement is based on non-dispersive infra-red (NDIR) absorption. Exhaust flow is measured by an exhaust flow meter based on differential pressure. The technology applied for reduction of vehicles emissions such as engine technology and after-treatment systems, is developing rapidly to meet increasingly stringent emission standards. This demands higher equipment measurement accuracy, certification regulations have been applied by regulating agencies to guarantee PEMS remain a reliable measure strategy for vehicle exhaust. [14]

The purpose of this study is to investigate the PM mass and particle number emissions from a current technology GDI vehicle retrofitted with a gasoline particle filter (GPF) during on-road testing using state-of-the-art PM and PN-PEMS units. Dyno based FTP-75 and US06 tests were performed by CE-CERT to provide guidance for on road vehicle emission testing. Emissions were measured over different driving conditions mimicking urban, rural, and highway driving patterns in southern California area. For the original OEM (original equipment manufacturer) and GPF-retrofitted vehicle and for each test route, on-road testing were performed three times to validate tailpipe emissions.

2. Experimental procedures

2.1 Test Vehicles & Fuels

For this study, emissions testing with real world driving routes was conducted on a light duty GDI vehicle. Testing was originally performed on the vehicle with the original aftertreatment system to serve as a baseline, and then retrofitted with a GPF provided in kind by the Manufactures of Emissions Controls Association (MECA). The GDI vehicle was selected to be compliant with the 2017 PM mass emissions standards of 3 mg/mile. The test vehicle was equipped with a centrally-mounted injection system and a turbocharged stoichiometric engine. A 2017 Ford Fusion which conformed to regulations as a MY 2017 Low-Emission Moto Vehicle with an original three-wat catalyst (TWC) after treatment system met the requirements and was selected as the test vehicle for this study. Table 3 describes the vehicle parameters of the selected Ford Fusion.

Table 3 Test vehicle parameter

Make and Model	2017 Ford Fusion
Cylinder number	4, Inline
Displacement	1.5 L
Horsepower	181 at 6000 rpm
Torque	185 lb-ft at 4320 rpm
Compression ratio	10.0:1
Fuel Delivery	Direct Injection, Centrally-Mounted
Emissions Standards	USEPA:T3B30, CA: SULEV 30 PZEV

This study used a typical E10 (10% ethanol, 90% gasoline, Splash blended gasoline with 10% ethanol) market fuel with 87 AKI (Anti-Knock Index). The E10 fuel was tested for the main ASTM D4814 properties. Fuel analyses results included distillation parameters, oxygen content, heating value, aromatics content, RON and MON.

The California market sale pipeline fuel was used for this study which represents typical fuel available in Southern California. Gasoline is not a pure chemical compound and it contains hydrocarbon substances form C_4 to C_{12}, The stoichiometric ratio H/C or hydrogen to carbon atom ratio in the hydrocarbon portion of the gas blend is about 14.9. The composition and properties of gasoline that comes from crude oil is complex and the regulation certification is carried out by EPA and California Air Recourses Board (CARB), Fuel samples were collected from the market prior to testing and the fuel properties were measured and are presented in Table 1. The chemical composition of fuel is reported on a volume percent basis.

Table 4 E10 fuel parameter

Property	% weight
Carbon	83.05
Hydrogen	13.58
Oxygen	3.04
Nitrogen	<0.15
Sulfur (mg/kg)	29.19
Density(kg/m^3)	748
Specific gravity (60/60F)	0.749

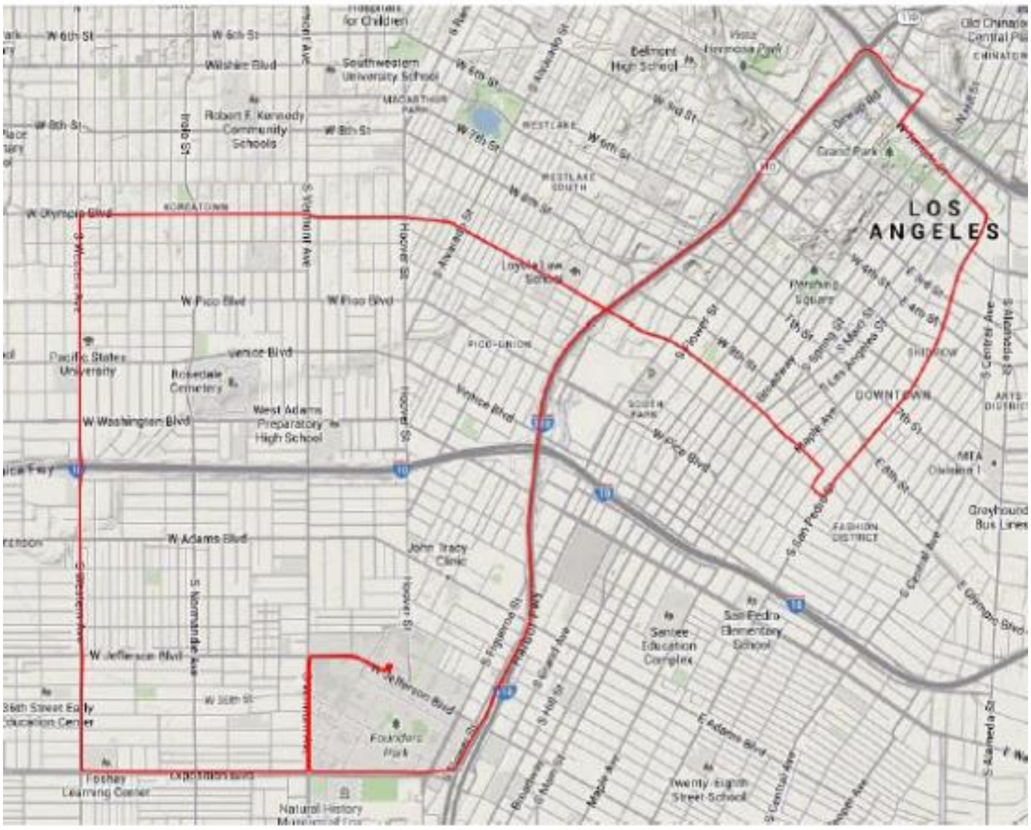
Vehicle manufacturer recommended lubricants were used for this study. Fresh lubricant oil was added to the crankcase when the vehicle was received and was not be changed for the duration of the test.

2.2 Real-World Driving Test Routes

Emissions testing was performed by CE-CERT on the GDI vehicle with and without a retrofitted GPF to compare differences during different routes in Southern California using ~~a~~ Portable Emissions Measurement Systems (PEMS). The test routes used were defined by three major areas of Southern California, 1) Los Angeles, 2) the Inland Empire, Mt. baldy (Ontario area) and 3) San Diego and were designed to reflect a relatively rich variety of topological features including altitude, driving patterns, and environmental conditions, to represent typical vehicle operation in a variety of areas. As mentioned earlier, these routes were divided into three aspects; 1) urban driving, characterized by low speeds and frequent stops; 2) highway driving, characterized by high-speed driving, frequent stop and go operation during rush hour; 3) uphill/downhill driving, characterized by steeper slopes than usual roads and medium to higher vehicle operating speeds. Tests were separated into two phases. The first phase consisted of emissions testing with the original equipment manufacturer (OEM) after treatment system. Immediately following the first phase, the second phases consisted of emissions testing with the retrofitted catalyzed GPF installed. On-road testing was performed three times for each route to validate vehicle exhaust. Only one same experienced driver is was chosen for the duration of both phases in order to maintain same driving behavior. A pretest for test driver was performed in order to get familiarized with the test routes. A chase vehicle was used as back up fuel carrier and for on road driving protection.

All testing routes started from CE-CERT in Riverside CA. A cold start phase is defined as the drive from CE-CERT to the route start point. The tests conducted on the routes were all considered hot driving phases, meaning the engine was warmed up for a significant amount of time. After testing has concluded for the day, the vehicle was driven back to CE-CERT where the test vehicle would soak overnight for next day testing. Tests were separated into two phases with and without GPF as described earlier. For each phase, testing followed a sequence of, first conducting the LA downtown route, followed by the highway route, and finishing with the Mt.Baldy route in one day. The vehicle would then soak overnight and the sequence would be repeated for a total of 3 runs. After finishing the LA sequence, the next day was followed by triplicated SD downtown test in same one day. The GPF was installed by a professional exhaust modification shop before the campaign started and was taken off and replaced with the original TWC after treatment system once the emission testing with GPF on is completed.

Figure 1 Topographic map of downtown Los Angles test route

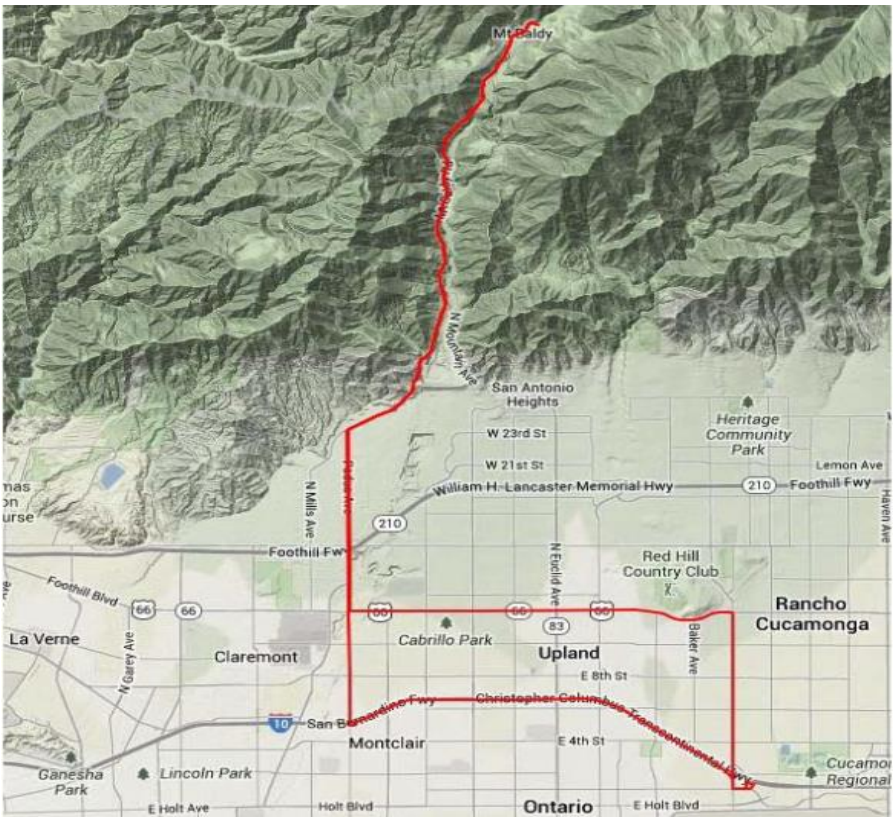


The first route (Downtown LA route) is a 16-mile round trip in downtown Los Angeles (LA). The route in downtown LA will be representative of urban driving affected by dense traffic and can also incorporate the route used to develop the Los Angeles Route Four (i.e., LA4) as part of the original FTP cycle. Downtown LA route start and ends at USC's main campus, it imitates normal day urban driving with low vehicle speed and frequent stop and go operation. The route is about 16 miles and average test duration is about one hour with an average speed of 16 mph.

Figure 2 Topographic map of highway route from LA to Ontario

The second route (Highway routes) will start from Downtown LA and end in Ontario, CA. This route is around 43 miles in distance and is comprised of approximately 95% highway driving between the main campus of the University of Southern California (USC) and the convention center in Ontario. This route will utilize Interstate 110N and Interstate I-10E. This route is characterized by more highway driving conditions, and some urban driving in Ontario. This route will also include high temperatures and low humidity conditions in the Ontario area, and possible congestion on several parts of the I-110 and I-10 freeways. Route 2 contains high speed driving also including stop and go patterns during rush hour. The travel distance is about 43 miles with an average vehicle speed of 48.3 mph.

Figure 3 Topographic map of Mt. Baldy route



The third route (Mt.Baldy route) will start from Ontario Convention Center and terminate at same point. This route is characterized by more rural and uphill/downhill driving conditions. This route includes large altitude variations with the highest elevation of 6200 feet above sea level and a low of 1000 feet above sea level at the base of Mount Baldy. High temperatures and low humidity conditions are expected for Mt.Baldy area. This route consists of steep road grades and medium to higher speeds operation. The total travel distance is around 44.2 miles with an average speed of 25.1 mph.

Figure 4 Topographic map of Downtown San Diego test route

The fourth route (Downtown SD route) starts in downtown San Diego. The route imitates normal day urban driving with low vehicle speed and frequent stop and go operation in addition with a short period of highway speeds. Downtown San Diego routes were tested three times in one day to validate tailpipe emissions. The total distance is about 13 miles with an average test duration of one hour and average speed of 13 mph.

2.3 Emission Measurement Instruments

Table 5 Items used for emission measurement

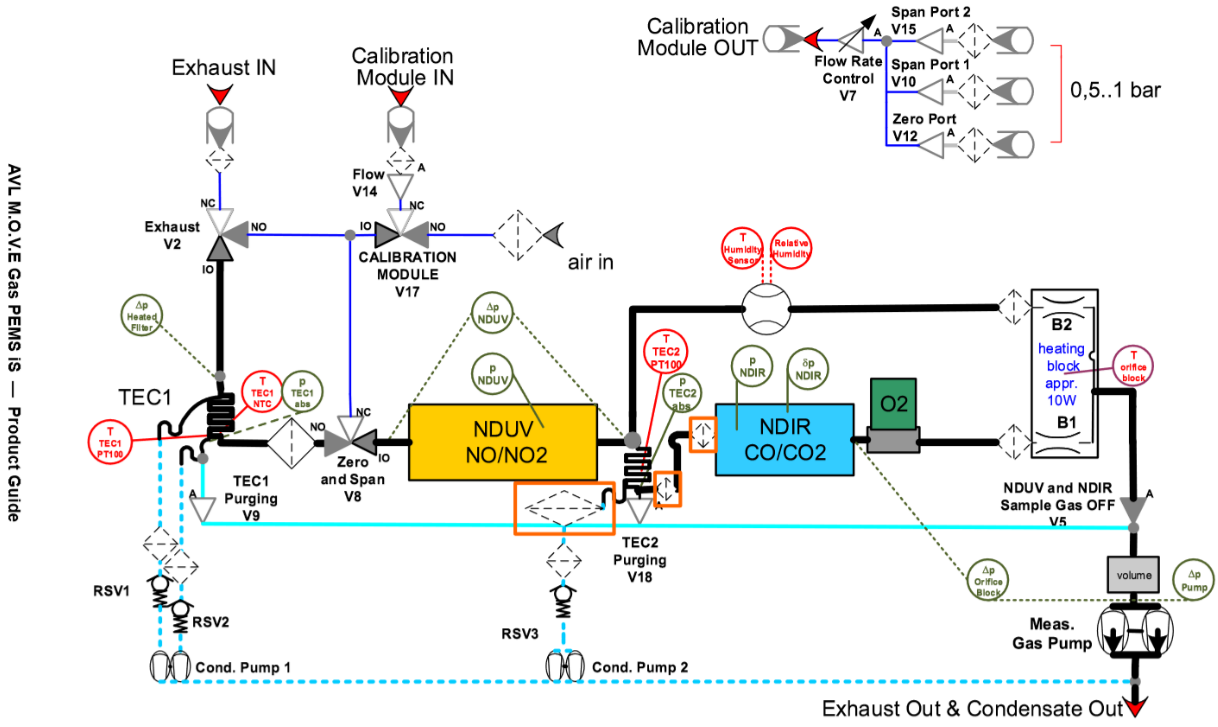
Emission test instrument
AVL Gas PEMS
AVL GAS PEMS Sample Line
AVL PEMS PC
Inverter
Fan
Laptop
EFM
AVL MSS
UCR Grav Box and Filter Holder
PM PEMS Sample Line
PM PEMS Pump
Charge Master
Lithium Battery
NTK
FID and Zero Bottle
Generator and Hitch

The instruments were installed following the manufacturer's recommendations, which typically include some type of vibration isolation, an isolated power source (generator or batteries), and ambient enclosure. Based on our previous PEMS evaluation it is believed that thermal impacts may represent the most significant drift in the measurement comparison.

For this study, AVL's M.O.V.E (Mobile Onboard Vehicle Evaluation) PEMS unit was utilized. Real-time PM was measured with a photoacoustic based AVL Micro Soot Sensor (MSS), Gravimetric teflon filter was used for total PM measurement. A portable

NTK Compact Emissions Measurement System (NCEM) unit, designed for real world driving emission test was also installed to measure PN, NO_x, Air flow ratio, in addition with engine RPM, vehicle speed and other parameters from the Engine Control Unit (ECU). Although the focus of this study is the measurement of PM and PN emissions, CE-CERT has the capability of measuring gaseous emissions with AVL's M.O.V.E GAS PEMS 493 system. The GAS PEMS measures NO/NO2, CO/CO2, THC and includes direct sampling from the exhaust flow, ambient dew point (temperature, pressure and relative humidity), and internal performance on the thermal electric coolers (TECs). An Exhaust Flow Meter based on differential pressure was used to measure total exhaust flow and tailpipe exhaust temperature. All the electric power required by instruments was supplied by a gasoline Honda generator mounted on the backside hitch plate that powered an inverter placed inside the test vehicle. Laptops were used for data logging and a monitor ~~is~~ was fixed on the front passenger seat to allow the test driver to monitor the instruments. A fan was installed in front of PEMS unit to avoid overheating. He/H_2 bottle and zero bottle are carried in a security cage with the test vehicle as FID fuel and calibration gas respectively. A Jeep was selected as the chase vehicle to carry back up fuel and necessary tools as a protection of the test vehicle.

Figure 5 AVL GAS PEMS Principle



1. AVL Move 493 Gas PEMS

- NDIR for CO/CO2

Non-dispersive infrared (NDIR) detectors are industry standard methods for measuring carbon oxide concentrations (CO and CO_2). Different molecule absorbs different infrared rays at a specific frequency and transform to vibrational energy. The NDIR detector measures the volume concentration of CO or CO_2 by irradiating the infrared beam through the sample and measuring the amount of infrared light absorbed by the sample at the necessary wavelengths. NDIR detector can measure two different gas concentrations with a chopper wheel installed before the detector correcting the offsets of the analyzers.

- Ultra-Violet (UV) Analyzer for NO/NO2

UV gas analyzer is based on the Lambert-Beer law: $I1(\lambda) = I0(\lambda)\exp[-\sigma(\lambda)cL]$

NO and NO_2 absorptions spectra is different in UV wavelength range from 200 nm to 500 nm. UV analyzer can measure NO and NO_2 directly at the same time.

- FID for THC

The flame ionization detector (FID) is the standard strategy for measuring hydrocarbon (HC). FID has a hydrogen flame inside the FID supporting by He/H_2 bottle. Sample gas goes through the flame and HC burning will provide ions to a metal collector, which can be detected by electric current with a high DC voltage. The current across indicates the concentration of HC of the inlet sample gas. The ionization process is very rapid and have millisecond response times

2. AVL MSS 483

The AVL Micro soot sensor (MSS) is based on photoacoustic measurement theory. A modulated laser beam provides periodic heating and cooling conditions for black carbon containing sample diluted exhaust gas resulting to periodic pressure pulsation which can be treated as acoustic waves and detected by the microphone and converted to real time ~~PM~~ soot data. Micro soot sensor has the capacity to measure real time ~~PM~~ soot concentration dilution corrected with accuracy up to 0.001 mg/m3

3. Semtech 2.5 EFM

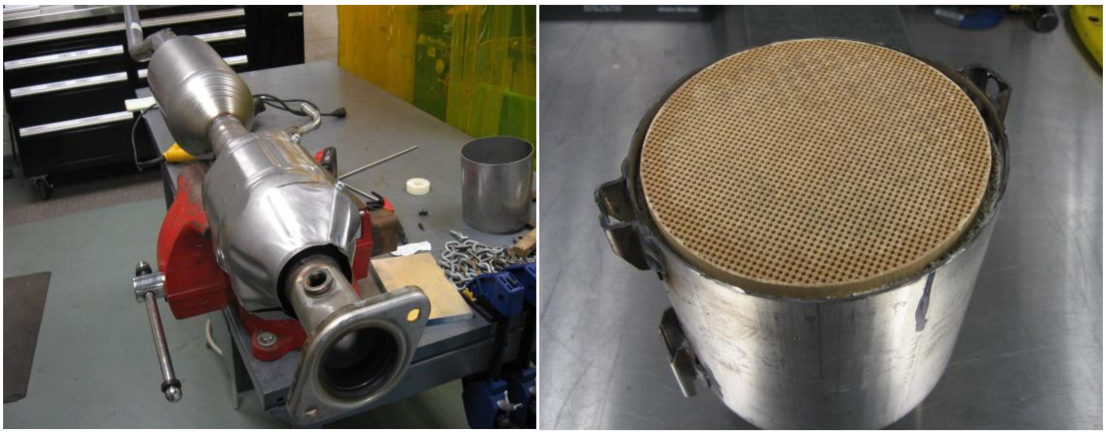
Exhaust Flow Meter is designed based on differential pressure theory. It can measure total exhaust flow ratio and tailpipe exhaust temperature.

4. UCR Filter Box and pump

Teflon Filter was used to collect PM with each test route using one filter. Total PM mass is measured by gravimetric analysis, humidity and temperature modified accurate balance was used to weigh the filter.

2.4 Catalyzed GPF

Figure 6 Appearance and internal structure diagram



The original underfloor three-way catalyst is installed on the test vehicle to control emission level and test vehicle is approved by LEV III regulations. The state of art retrofitted three-way catalyst coated GPF provided by Manufacturers of Emissions Controls Association (MECA) is installed in place of the original underfloor TWC after original testing is completed. The coated GPF has approximately 1.0 g/L loading of palladium (Pd) and rhodium (Rh) which is typical to TWC catalysts with matching certification level. The design parameters of the catalyzed GPF are listed below.

Table 6 Catalyzed GPF parameter

Parameter	
Diameter, in	4.66
Length, in	4.5
Cell wall thickness, mil	8
Cell density, cells per square inch (cpsi)	300
Loading, g/L	1.0
Pd:Rh	4:1

CE-CERT has previously done a series of dyno based FTP75 and US06 tests to compare the performance of this retrofitted GPF with an original underfloor three-way catalyst after treatment system. The GPF showed a significant reduction of PM, PN, and black carbon soot, with a filtration efficiency up to 99%. It also has remarkable reduction efficiency of THC, CO and NO_x emissions. This reduction is seen due to the fact that the catalyzed GPF has more active specific surface area when compared to the original TWC. Furthermore, the GPF did not significantly affect the back pressure so no effect on fuel economy and CO_2 generation was noticed. This study will act as an extension of the former study done by CE-CERT to test catalyst GPF emission control performance in real world driving conditions. Typical stoichiometric chemical reaction equations of TWC emission conversion are presented in table below. More reactions will occur depends on chemical compounds, temperature and humidity. Under stoichiometric conditions and when warmed up to catalytic characteristic temperature, the conversion efficiency can reach up nearly 100%.

Table 7 Reaction of TWC

$2\ CO + 2\ NO = 2\ CO_2 + N_2$
$2\ CO + O_2 = 2\ CO_2$
$Hydrocarbon + NO = CO_2 + H_2O + N_2$

3. Results and discussion

3.1 Gaseous emissions and fuel economy

Statistic data for gaseous emission for all test routes is shown below. All actual data analysis routes are hot start phase, the results of cold start starting from CE-CERT to real start point will be used as reference.

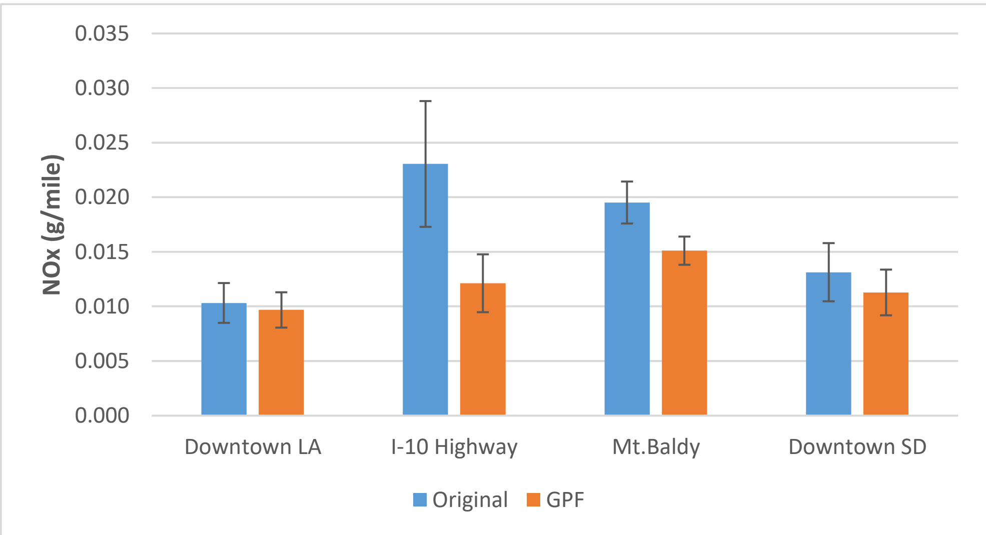
Table 8 AVL GAS PEMS and NTK emission results

	NTK (g/mi)	AVL GAS PEMS (g/mi)							
Original	NO_x	NO_x	NO	NO_2	THC	NMHC	CO	CO_2	O_2
LA	0.0141	0.0103	0.0085	0.0025	0.0008	0.0007	0.0306	501.4094	38.8052
Highway	0.0592	0.0230	0.0211	0.0022	0.0020	0.0020	0.6738	368.6953	19.3067
Mt.Baldy	0.1198	0.0195	0.0165	0.0032	0.0072	0.0071	2.5072	566.1640	31.6581
SD	0.0190	0.0131	0.0097	0.0038	0.0015	0.0014	0.1800	592.1643	51.9015
GPF									
LA	0.0146	0.0097	0.0078	0.0022	0.0005	0.0005	0.0381	508.7220	30.3134
Highway	0.0817	0.0121	0.0106	0.0016	0.0021	0.0021	0.5713	331.7853	10.4992
Mt.Baldy	0.1535	0.0151	0.0119	0.0034	0.0096	0.0095	3.3879	588.3191	27.9947
SD	0.0529	0.0113	0.0081	0.0036	0.0014	0.0014	0.1566	789.2873	30.1774

The average gaseous emissions from triplicated tests of all test routes are presented in the table above. Test vehicle (2017 Ford fusion) is certified as both Super Ultra Low-emission motor vehicle and Partial Zero Emission Vehicle by California LEV III emission standard SULEV 30 category, which means NMOG+NO_x under 0.030 g/mi, CO less than 1.0 g/mi, HCHO standard is 4 mg/mi and PM emission less than 0.01 g/mi. NMOG represents non-methane organic gases and HCHO is the chemical composition of formaldehyde. In general the test vehicle performed great with and without GPF during emission testing for all test cycles. AVL gas PEMS results showed the vehicle met all emission standards for NO_x, NMOG and CO, except for Mt.Baldy tests, for mountain test CO exceed limits is acceptable as mountain routes is steep and requires high loading of engine during all course. Statistically significant reduction of emissions can be found with GPF installed. Further detailed discussion for each gaseous emission and GPF performance are presented below.

3.1.1 NO_x emissions

Figure 7 NO_x emissions (g/mile)

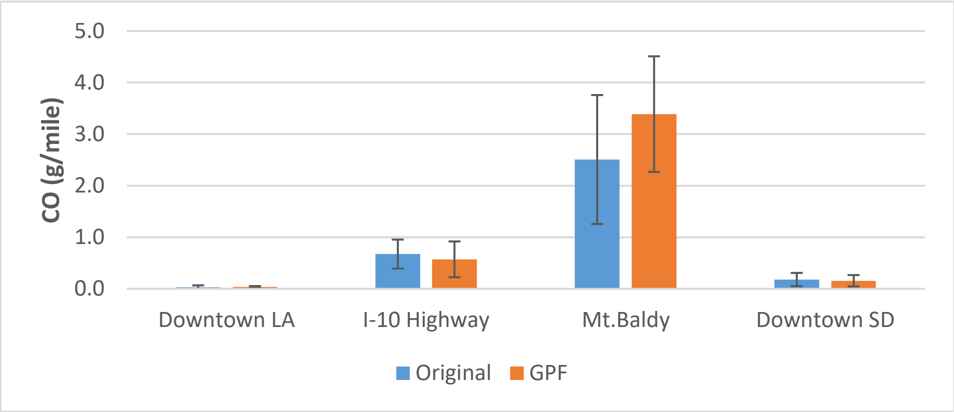


NO_x (g/mile)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	-6.2%	-47.4%	-22.6%	-14.1%
P Value	0.67	0.04	0.03	0.40

2 CO + 2 NO = 2 CO2 + N2 and Hydrocarbon + NO = CO2 + H2O + N2 are key reaction happened in catalyst to reduce NO. Statistical data indicates decreasing trend in NOx emission for downtown LA and Downtown SD routes with no statistically significant differences, and statistically significant reductions for highway and mountain routes. catalyzed GPF shows more reduction efficiency for higher NO_x emission level (over 0.02 g/mile) and can control NO_x emission to the range from 0.01-0.015 g/mile. As discussed previously, the retrofitted catalyst GPF has more active surface comparing to original TWC. It is worth noting that 0.02 g/mile of NO_x emission level is already relative low, but catalyst still shows capacity to convert NO_x. Richter et al [18] and Demuynck et al [19] tested their catalyst GPF in 2012 and 2017 and no reduction of NO_x was observed. Jiacheng et al [21] tested the same GPF under FTP75 and US06 dyno based test at CE-CERT with different vehicles. A reduction efficiency of 17% and 88% for NOx is observed depending on the vehicle model. The MECA built catalyzed GPF shows significant reduction potential for high NO_x vehicle.

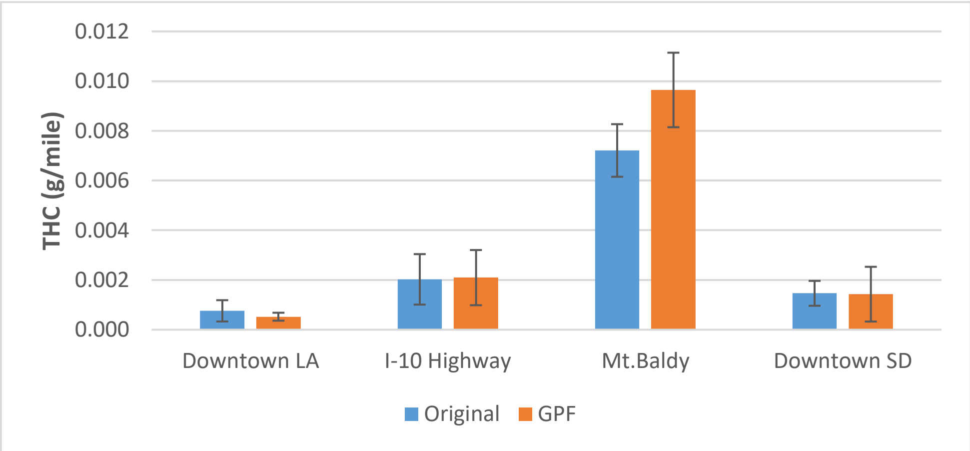
3.1.2 CO, THC, NMHC emissions

Figure 8 CO emissions (g/mile)



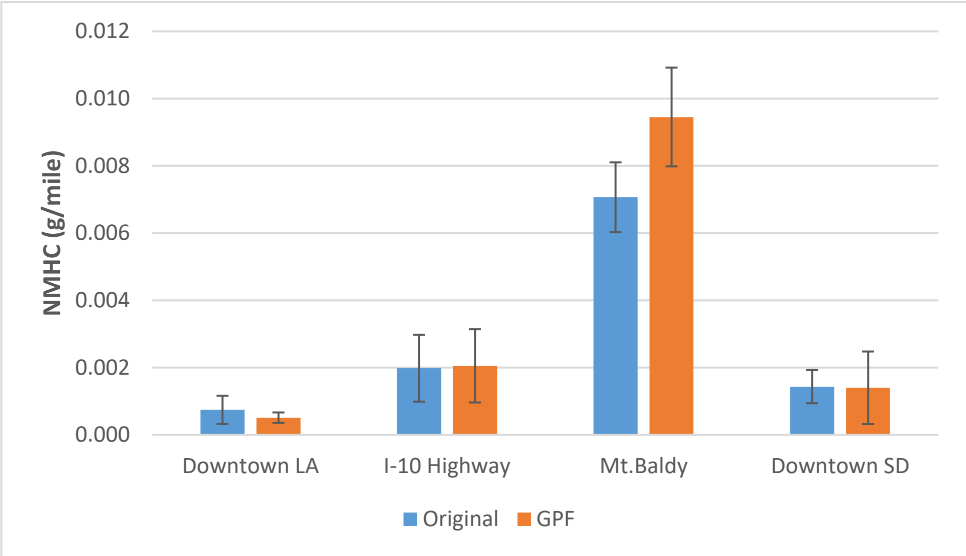
CO (g/mile)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	24.5%	-15.2%	35.1%	-13.0%
P Value	0.76	0.71	0.42	0.82

Figure 9 THC emissions (g/mile)



THC (g/mile)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	-31.2%	3.5%	33.8%	-2.4%
P Value	0.42	0.94	0.08	0.96

Figure 10 NMHC emissions (g/mile)



NMHC (g/mile)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	-31.2%	3.4%	33.8%	-2.3%
P Value	0.42	0.94	0.08	0.96

CO, THC, NMHC emissions coordinate relatively well with each other and similar trend is observed. A majority of these three species should be converted to CO_2 and H_2O. For ultra-low level of CO under 0.2 g/mile for urban driving test, catalyst GPF doesn't demonstrate the variability shown by the error bar, catalyst GPF has reached its conversion limits. For downtown LA, SD, and highway routes, CO emission is acceptable as 0.2 mg/mile which is already 5 times lower than current CO level of 1.0 mg/mile. The same reasoning can be applied for THC and NMHC emission under 0.002 g/mile. High loading and more fuel consumption leads to higher CO and THC emissions.

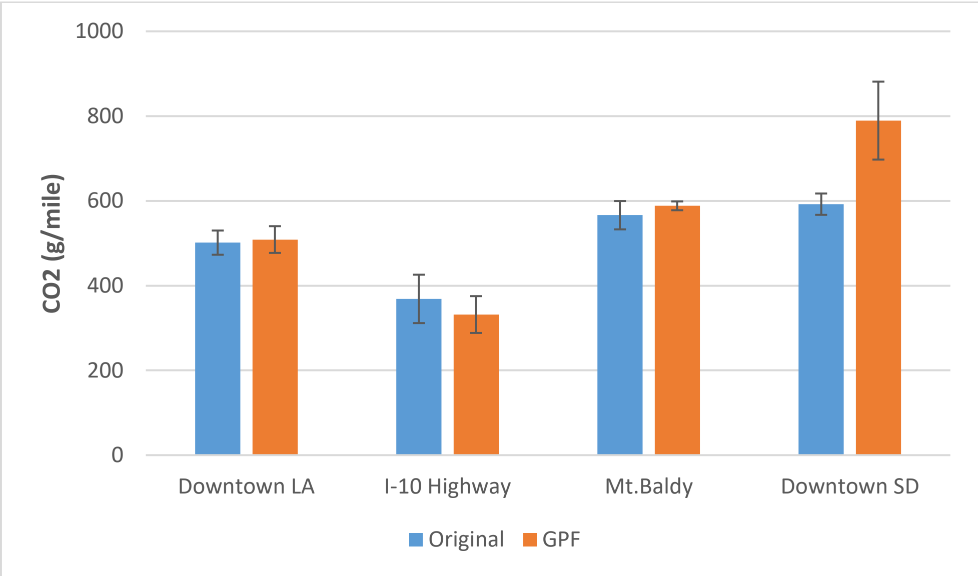
A 33% increase for THC, and NMHC emissions with GPF installed is observed for Mt.Baldy route is present in figure with marginally statistically significant different.

There is 35% increase for CO emissions with GPF installed for Mt.Baldy but the P value which is larger than 0.1 indicates that the difference is not statistically significant different and basically the same. The error bars in the graphs represent a single standard deviation of the average. The relatively large magnitude of the error bars are due to the low emission levels measured for several species. And the P value larger than 0.1 indicates that there is no statistically significant differences for CO, THC, and NMHC during downtown LA, Highway and downtown SD routes, the P value for mountain routes is between 0.05 and 0.1 which indicates that marginally statistically significant increase for mountain routes. We expect that with the use of catalyzed GPF the THC, NMHC, and CO emissions will reduce but the results showed no statistically significant differences. The marginally statistically significant increase coincides with uphill climbing phase which requires increased engine loading and increased fuel consumption resulting in higher gaseous emission. The amount of CO, THC, NMHC emissions is likely reaching the conversion upper limit therefore the reduction efficiency become lower. In addition, lower ambient pressure and lack of air may also contribute to this phenomenon.

Comparing to NO_x emissions conversions, there is no statistically significant differences for THC, NMHC, and CO emissions. There are two possible reasons, the first reason can be the catalysts inside the GPF has better conversion efficiency for NO_x than for THC, NMHC, and CO emissions compared to the original TWC. The other reason could be the catalyst area for NO_x is larger than the catalyst area for THC, NMHC and CO. These results match with previous dyno tests done for this GPF: nearly no influence on backpressure and fuel economy for normal test and slight effect for high loading phase. [21] Similarly, a small backpressure issue and CO_2 emission increase with GPF installed were observed by Saito et al. [24] and Ogata et al. [25].

3.1.3 CO_2 Emission

Figure 11 CO_2 emissions (g/mile)



CO_2 (g/mile)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	1.5%	-10.%	3.9%	33.3%
P Value	0.78	0.42	0.33	0.02

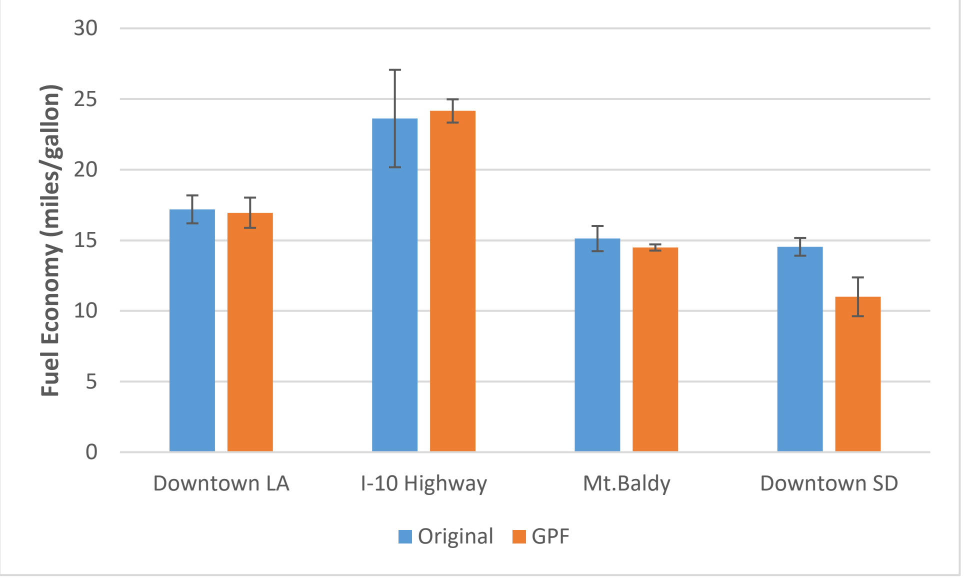
CO_2 emission results are plotted in the figure above. Similar results indicates no measurable impact was made by GPF for downtown LA with acceptable error bar within measurement spread. A slight reduction is observed for highway test. For mountain routes, CO_2 emission increase nearly 4% while CO and THC emissions increase about 34%. Only 4% increase in CO_2 emissions indicated that GPF has reached the limit for CO-CO_2 conversion. With the P values larger than 0.1, we can draw the conclusion that the differences for downtown LA, highway and mountain routes are not statistically significant and basically the same. It's worth noting that statistically significant increase penalty ($P < 0.05$) on CO_2 emissions for SD route for GPF installed configuration compared with traditional TWC can be found. This phenomenon can be separate to two aspects.

The first possible hypothesis is a humidity effect. Condensation of water affected on NDIR sensor resulting in noise levels at relative high humidity level. Real time data showed that there is much more noise for SD routes than LA routes. Secondly, because of traffic condition, the triplicate GPF test average duration is 67.72 minutes and the triplicate original test average duration is 61.08minutes, there is 6 minutes 37 seconds (10.87%) increase between the average duration of triplet GPF tests and original tests, longer duration means more idling (4 minutes 39 seconds longer) and more stop and go operations, this will lead to more CO_2 emissions and total amount of emission. The results became much higher after dividing by similar mileage presented by the unit of g/mile. Furthermore, on the GPF testing day the weather was overcast, causing more humidity than original testing. This could be another reason for the GPF producing higher CO_2 results.

Table 9 Weather parameter

	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
Humidity (%)	68.5	60	53	78
Temperature (°F)	75	79	70.5	76

Figure 12 Fuel Economy (miles/gallon)



Fuel Economy (miles/gallon)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	-1.4%	2.8%	-4.2%	-24.3%
P Value	0.79	0.81	0.30	0.02

Fuel economy is calculated based on the fuel properties and carbon mass balance:

$$\text{Fuel economy (miles/US gal)} = \frac{CWF_{fuel}*3781.8*SG}{CWF_{exh}*EF_{NMHC}+0.749*EF_{CH4}+0.429*EF_{CO}+0.273*EF_{CO2}}$$

CWF_{fuel} is the carbon weight fraction of the fuel, SG is the specific gravity, EF_{NMHC}, EF_{CH4}, EF_{CO}, and EF_{CO2} are the Non-methane hydrocarbons, CH_4, CO, and CO_2 emissions in grams per mile. CWF_{exh} is the carbon weight fraction of the exhaust, the carbon weight fraction (CWF) of exhaust was assumed to be the same as that of the fuel, consistent with current certification practices. Exact values are listed in the Table 10. [18]

Table 10 E10 fuel parameter

Fuel	CWF_{fuel}	SG	CWF_{exh}
E10 Low Aromatics	0.8277	0.7501	0.8277

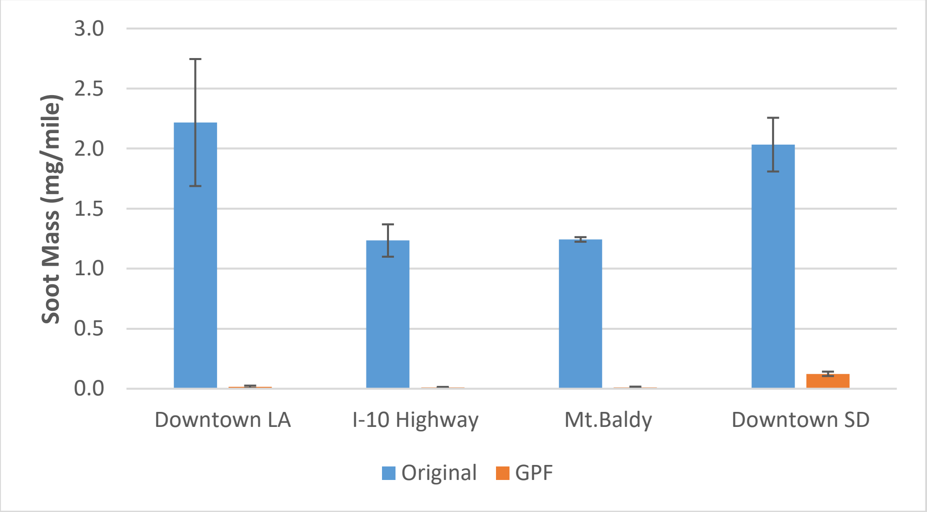
The test vehicle averaged 24 miles per gallon fuel economy for highway routes. The large P value showed there are no statistically significant different for downtown LA, highway, and mountain routes. The only concern was for SD downtown routes, there is a statistically significant decrease for fuel economy and the fuel economy is below 15 miles per gallon based a calculation. The CO_2 growth mentioned earlier is the dominating cause for the deterioration of fuel economy. No statistically significant differences indicates that there is no measurable back pressure issue.

3.2 Particulate emissions (PM, BC and PN)

Table 11 MSS and NTK particle emission results

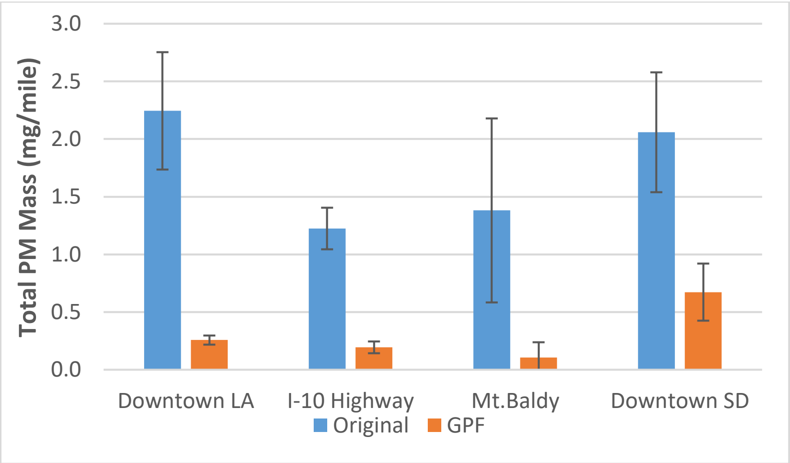
	MSS PMsoot (mg/mi)	MSS tPM (mg/mi)	NTK PM (mg/mi)	NTK PN (#/mi)	BC/PM
Original					
LA	2.2170	2.2444	0.4012	3.72E+12	0.9878
Highway	1.2343	1.2242	0.3707	3.43E+12	1.0083
Mt.Baldy	1.2434	1.3811	1.7167	1.59E+13	0.9003
SD	2.0330	2.0588	0.3611	3.35E+12	0.9875
GPF					
LA	0.0155	0.2570	0.0331	3.07E+11	0.0603
Highway	0.0107	0.1940	0.1085	1.01E+12	0.0552
Mt.Baldy	0.0101	0.1068	1.4030	1.30E+13	0.0946
SD	0.1240	0.6728	0.0573	5.31E+11	0.1843

Figure 13 MSS PMsoot (mg/mile)



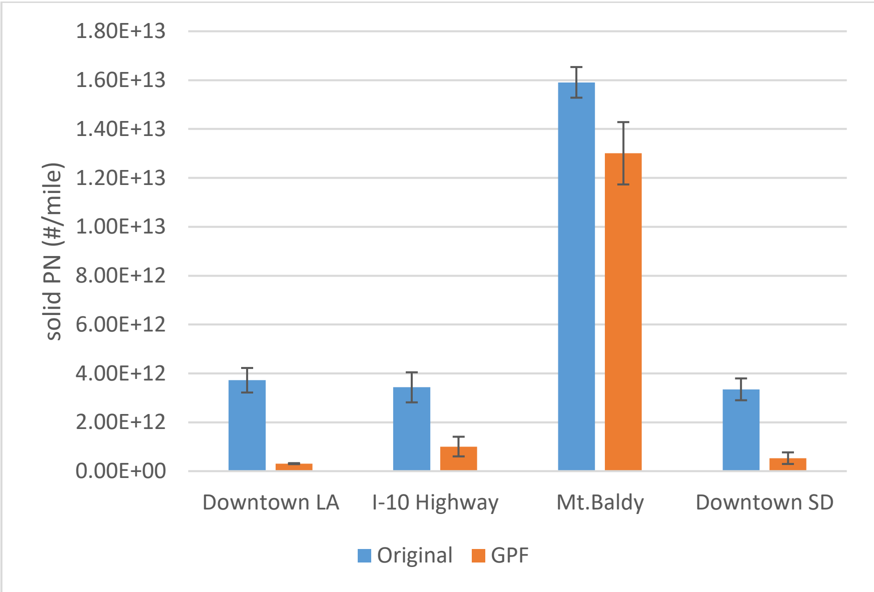
Soot Mass (mg/mi)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	-99.3%	-99.1%	-99.2%	-93.9%
P Value	0.0020	0.0001	0.0000	0.0001

Figure 14 MSS tPM (mg/mile)



Total PM (mg/mi)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	-88.6%	-84.2%	-92.3%	-67.3%
P Value	0.30	0.0007	0.34	0.01

Figure 15 NTK PN (#/mile)



NTK PN #/mi)	Downtown LA	I-10 Highway	Mt.Baldy	Downtown SD
% Difference	-91.8%	-70.7%	-18.2%	-84.1%
P Value	0.0003	0.0046	0.02	0.0006

As shown in the figure, total PM mass and PM soot emissions with and without the GPF are all under current standards of 3 mg/mile. A statistically significant reduction between the traditional TWC and catalyst GPF data is observed. The variability shown by the large error bars was investigated further by evaluating the real-time data. The real-time analysis suggests the variability is not from measurement issues, but appears to be due to variability in the operation of the vehicle itself between different iterations of the same test cycle. For LA downtown, highway, Mt.Baldy routes, the PMsoot filtration efficiency reaches up to 99% level and P value lower than 0.01 indicate that the reductions are statistically significant. As mentioned before, humidity for SD is much higher than the others, the humidity will have significant impact on MSS photoacoustic measurements and much more noise reading is shown by real-time reading which will increase low level PM emissions data. Therefore, the PM soot reduction efficiency for SD downtown routes is 93% level not as efficient as the others.

Total PM reduction is analyzed by gravimetric calculation. The reductions for highway and mountain routes are statistically significant but for downtown LA and Downtown SD there is no statistically significant difference. For LA downtown, highway, Mt.Baldy routes is around 88% level and for SD downtown is 67% level. Condensed water droplet on filter was observed for SD downtown test, which effected the results.

The average Black Carbon/ PM stable ratio is 0.971 indicates that the majority of particle emission is black carbon soot. The differences between PM mass and PM soot mass is because the difference of measurement equipment. PM soot is measured by MSS and total PM is measured by the Teflon filter, researchers have shown that there are more impurities on the filter, including some gases that are absorbed onto the filter. The zero detection level of filter analysis is not as accurate as micro soot sensor so the data for PM soot is more reliable than the total PM mass.

NTK results are used as references which showed GPF performed well for LA downtown, SD downtown, and highway routes. Original PN conforms to current $6*10^{12}$ #/mile regulation, catalyst GPF after treatment system made it possible to meet stricter $*10^{11}$ #/mile standard enforced lately without any reformative updates from engine aspect which can save abundant budget. For mountain routes the reduction is not as significant as others but is acceptable. P value analysis showed that there are statistically significant reduction with the use of catalyzed GPF for all routes.

4. Conclusion

This study focused on the real world driving emissions from a GDI vehicle equipped with and without catalyzed GPF. The results showed statistically significant filtration rate of black carbon soot emissions up to 99% level under all driving conditions, statistically significant decrease in PM emission in most routes. A decreasing trend for NOx emissions under most driving conditions, no statistically significant differences for CO and THC emissions under all driving conditions and no measurable impact on fuel economy and CO_2. The catalyzed GPF improved the reduction efficiency for total PM and PM soot compared to old models, combined the function of TWC and GPF, it also solved the back pressure issue. This study is one of the first in this field that simultaneously measured a catalyzed GPF's impact on both gaseous and particulate emissions during real world driving tests. With this study the Manufacturers of Emissions Controls Association can optimize the catalyzed GPF to reach maximum efficiency and create stronger regulations for gasoline vehicle emissions. Further detailed conclusions are summarized as below.

1. As for particle emissions, black carbon soot demonstrated the total PM emission, Statistically Significant reduction with average filtration rate of catalyst GPF for black carbon soot reaches up to 99%. Total PM is reduced around 88% ~~level which~~ indicating great potential for further application in the vehicle market for reducing

particle emissions. The original results meet the current regulation of 3 mg/ mile, after catalyst GPF 99% PM emissions is converted which will satisfy the further configuration for a long period and great market application perspective.

2. Catalyzed GPF showed decrease trend for NO_x emissions under most driving conditions with statistically significant difference; for CO, CO_2, THC, and NMHC emissions there are no statistically significant improvement compared to traditional TWC; for fuel economy there is no statistically significant difference with the use of catalyzed GPF.
3. Humidity may cause noise which will increase the results of measured gaseous emissions. Condensed water on Teflon filter will affect the total PM mass. Further dehydration process like desiccant should be applied to ensure the accuracy of the experiments.
4. Generally speaking the catalyzed GPF can significantly reduce particle emissions, enhance the conversion rate of gaseous without causing much backpressure. The results are consistent with our expectations. With more improvement coat design and cost reduction the GPF can become an important and reliable strategy to reduce vehicle tailpipe emissions and contribute to social pollution control.

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6. Appendix

No GPF - LA	NTK	AVL Gas PEMs								AVL MSS	Filter PM	NTK PM	NTK PN
12-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to USC	0.036	0.011	0.0098	0.0012	0.0026	0.0025	0.201	306.0	9.1	1.325	1.716	0.225	2.09E+12
Downtown LA Route	0.011	0.008	0.0067	0.0023	0.0005	0.0004	0.014	528.6	37.1	2.824	2.793	0.432	4.01E+12
I-10 Highway Route	0.080	0.030	0.0274	0.0025	0.0032	0.0031	0.996	432.9	20.6	1.355	1.294	0.444	4.12E+12
Lunch Break (Idle)	0.756	0.084	0.0328	0.0530	0.0197	0.0193	0.124	8033.1	656.8	8.570	16.036	2.441	2.26E+13
Mt Baldy Route	0.117	0.019	0.0153	0.0041	0.0083	0.0082	3.478	601.4	38.8	1.221	0.626	1.765	1.64E+13
Ontario to Riverside	0.018	0.012	0.0089	0.0032	0.0004	0.0004	0.159	408.3	30.4	1.287	1.482	5.853	2.67E+12
13-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to USC	0.028	0.009	0.0086	0.0010	0.0023	0.0023	0.167	304.2	5.5	1.006	1.300	0.197	1.83 E+12
Downtown LA Route	0.020	0.012	0.0101	0.0025	0.0006	0.0006	0.005	471.6	37.5	1.967	2.154	0.433	4.01 E+12
I-10 Highway Route	0.051	0.019	0.0171	0.0021	0.0013	0.0013	0.537	323.8	16.3	1.089	1.019	0.316	2.93 E+12
Lunch Break (Idle)	0.072	0.018	0.0056	0.0155	0.0117	0.0115	0.024	3336.6	291.1	3.559	4.043	0.912	8.46 E+12
Mt Baldy Route	0.129	0.018	0.0165	0.0016	0.0062	0.0061	2.947	535.0	40.9	1.256	2.215	1.641	1.52 E+13
Ontario to Riverside	0.019	0.010	0.0081	0.0019	0.0004	0.0004	0.264	353.8	30.2	21.669	24.414	4.995	2.28 E+12

14-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to Ontario	0.050	0.018	0.0160	0.0021	0.0256	0.0251	0.376	445.1	11.6	2.232	3.592	0.430	3.99 E+12
Mt Baldy Route	0.113	0.022	0.0178	0.0039	0.0071	0.0069	1.097	562.1	15.2	1.252	1.302	1.744	1.62 E+13
Ontario to Riverside	0.012	0.013	0.0091	0.0037	0.0007	0.0007	0.135	385.6	10.8	1.268	0.927	0.265	2.46 E+12
17-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to USC	0.024	0.011	0.0102	0.0012	0.0015	0.0014	0.083	350.9	12.0	1.634	1.823	0.319	2.96 E+12
Downtown LA Route	0.012	0.011	0.0086	0.0026	0.0012	0.0012	0.073	504.1	41.9	1.860	1.787	0.339	3.14 E+12
I-10 Highway Route	0.047	0.021	0.0187	0.0022	0.0015	0.0015	0.488	349.4	21.0	1.258	1.356	0.352	3.24 E+12
Ontario to Riverside	0.014	0.013	0.0109	0.0024	0.0004	0.0004	0.155	357.0	29.2	1.225	1.190	0.229	2.13 E+12
GPF - LA	**NTK**	**AVL Gas PEMs**								**AVL MSS**	**Filter PM**	**NTK PM**	**NTK PN**
5-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to USC	0.032	0.007	0.0063	0.0006	0.0014	0.0013	0.169	299.9	7.8	0.007	0.000	0.025	2.36 E+11
Downtown LA Route	0.017	0.010	0.0087	0.0020	0.0005	0.0005	0.030	537.0	31.8	0.016	0.229	0.032	2.95 E+11
I-10 Highway Route	0.066	0.014	0.0118	0.0024	0.0015	0.0014	0.380	368.4	12.6	0.010	0.135	0.111	1.03 E+12
Lunch Break (Idle)	0.126	0.052	0.0252	0.0283	0.0045	0.0044	0.014	3226.3	194.1	0.085	5.346	0.112	1.04 E+12
Mt Baldy Route	0.198	0.015	0.0093	0.0063	0.0113	0.0110	2.476	600.3	24.4	0.010	0.014	1.417	1.31 E+13
Ontario to Riverside	0.041	0.014	0.0083	0.0055	0.0004	0.0004	0.333	467.8	17.2	0.015	0.477	0.064	5.96 E+11

6-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to USC	0.037	0.005	0.0047	0.0005	0.0013	0.0013	0.192	302.9	7.2	0.003	0.297	0.033	3.07 E+11
Downtown LA Route	0.016	0.008	0.0065	0.0016	0.0004	0.0004	0.028	474.7	30.9	0.005	0.285	0.032	2.95 E+11
I-10 Highway Route	0.115	0.013	0.0120	0.0012	0.0034	0.0033	0.973	343.2	11.3	0.007	0.219	0.151	1.4E +12
Lunch Break (Idle)	0.068	0.037	0.0232	0.0151	0.0065	0.0064	0.018	3996.7	272.0	0.042	4.238	0.163	1.51 E+12
Mt Baldy Route	0.205	0.016	0.0143	0.0021	0.0083	0.0081	3.048	583.3	30.2	0.003	0.090	1.533	1.42 E+13
Ontario to Riverside	0.022	0.009	0.0069	0.0025	0.0001	0.0001	0.156	372.9	18.0	0.005	0.221	0.037	3.47 E+11

7-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to USC	0.031	0.009	0.0078	0.0011	0.0015	0.0014	0.149	327.7	9.2	0.011	0.000	0.027	2.47 E+11
Downtown LA Route	0.011	0.011	0.0081	0.0030	0.0007	0.0007	0.056	514.4	28.2	0.026	2.901	0.036	3.31 E+11
I-10 Highway Route	0.065	0.009	0.0080	0.0013	0.0014	0.0014	0.361	283.8	7.6	0.015	0.228	0.064	5.94 E+11
Lunch Break (Idle)	0.083	0.017	0.0112	0.0074	0.0047	0.0046	0.000	2275.9	148.3	0.127	4.411	0.070	6.49 E+11
Mt Baldy Route	0.057	0.014	0.0121	0.0017	0.0093	0.0092	4.640	581.4	29.4	0.017	1.673	1.259	1.17 E+13
Ontario to Riverside	0.014	0.010	0.0073	0.0028	0.0001	0.0001	0.131	381.3	19.3	0.019	0.393	0.028	2.58 E+11

No GPF - SD	NTK	AVL Gas PEMs								AVL MSS	Filter PM	NTK PM	NTK PN
10-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to San Diego	0.039	0.012	0.0114	0.0010	0.0089	0.0087	0.319	290.4	26.0	0.946	1.350	0.211	1.95 E+12
Downtown SD (1) - CW	0.028	0.015	0.0134	0.0022	0.0012	0.0012	0.149	485.4	32.3	2.231	1.792	0.425	3.94 E+12
Downtown SD (2) - CW	0.024	0.010	0.0067	0.0040	0.0013	0.0013	0.323	563.1	45.4	2.011	2.131	0.364	3.38 E+12
Downtown SD (3) - CW	0.016	0.016	0.0118	0.0041	0.0020	0.0020	0.075	608.2	55.9	1.569	1.170	0.279	2.59 E+12
San Diego to Riverside	0.062	0.018	0.0157	0.0028	0.0021	0.0021	0.868	409.5	24.6	0.341	0.426	0.060	5.52 E+11
15-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to San Diego	0.032	0.013	0.0118	0.0012	0.0018	0.0017	0.322	334.3	7.3	1.200	1.433	0.278	2.58 E+12
Downtown SD (1) - CCW	0.052	0.015	0.0129	0.0030	0.0042	0.0041	0.631	550.2	45.2	2.107	1.533	0.438	4.06 E+12
Downtown SD (2) - CCW	0.056	0.023	0.0194	0.0035	0.0019	0.0018	0.305	520.2	52.0	1.945	1.634	0.423	3.92 E+12
Downtown SD (3) - CCW	0.034	0.012	0.0081	0.0039	0.0015	0.0015	0.198	549.8	62.3	2.211	0.000	0.345	3.2E +12
San Diego to Riverside	0.115	0.033	0.0283	0.0052	0.0041	0.0040	2.013	739.2	55.7	62.195	55.229	13.812	2.81 E+12

GPF - SD	NTK	AVL Gas PEMs								AVL MSS	Filter PM	NTK PM	NTK PN
3-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to San Diego	0.073	0.009	0.0081	0.0006	0.0028	0.0028	0.556	317.3	9.7	0.055	0.214	0.140	1.3E+12
Downtown SD (1) - CW	0.041	0.010	0.0078	0.0028	0.0011	0.0011	0.109	683.2	33.6	0.120	0.543	0.043	3.98E+11
Downtown SD (2) - CW	0.081	0.014	0.0098	0.0042	0.0026	0.0026	0.282	846.8	31.5	0.144	0.958	0.087	8.05E+11
Downtown SD (3) - CW	0.037	0.010	0.0066	0.0037	0.0005	0.0005	0.078	837.8	25.4	0.108	0.517	0.042	3.9E+11
San Diego to Riverside	0.105	0.013	0.0109	0.0023	0.0045	0.0044	0.968	422.2	11.6	0.063	0.054	0.143	1.33E+12
4-Aug	NO_x (g/mi)	NO_x (g/mi)	NO (g/mi)	NO_2 (g/mi)	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	O_2 (g/mi)	Soot (mg/mi)	PM (mg/mi)	PM (mg/mi)	PN (#/mi)
Riverside to San Diego	0.056	0.006	0.0052	0.0008	0.0013	0.0013	0.392	317.1	6.4	0.031	0.147	0.112	1.04E+12
Downtown SD (1) - CCW	0.049	0.006	0.0045	0.0020	0.0037	0.0037	1.216	611.5	32.7	0.104	0.468	0.056	5.2E+11
Downtown SD (2) - CCW	0.064	0.011	0.0087	0.0029	0.0028	0.0027	0.437	713.6	38.1	0.111	0.541	0.077	7.16E+11
Downtown SD (3) - CCW	0.114	0.015	0.0118	0.0041	0.0084	0.0083	1.640	742.1	42.6	0.110	0.000	0.087	8.08E+11
San Diego to Riverside	0.066	0.009	0.0071	0.0022	0.0011	0.0011	0.532	416.6	12.3	0.053	0.000	0.187	1.74E+12

*All Values are averages of the trip

*SD route was repeated Clockwise 3 times and Counter Clockwise 3 times

*CW – Clockwise

*CCW - Counter Clockwise

20170803 GPF Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to SD)	T170813	0.0124
Trip 2 (downtown SD)	T170846	0.0076
Trip 3 (downtown SD)	T170816	0.0110
Trip 4 (Downtown SD)	T170845	0.0071
Trip 5 (SD to Riverside)	T170822	0.0036

20170805 GPF Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to USC)	T170753	0.0000
Trip 2 (downtown LA4 route)	T170820	0.0061
Trip 3 (USC to Ontario)	T170848	0.0053
Trip 4(lunch break idle)	T170720	0.0158
Trip 5 (Mt.Baldy)	T170849	0.0009
Trip 6 (Ontario to Riverside)	T170819	0.0080

20170806 GPF Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to USC)	T170745	0.0099
Trip 2 (downtown LA4 route)	T170827	0.0042
Trip 3 (USC to Ontario)	T170823	0.0045
Trip 4(lunch break idle)	T170727	0.0050
Trip 5 (Mt.Baldy)	T170723	0.0052
Trip 6 (Ontario to Riverside)	T170801	0.0021

20170807 GPF Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to USC)	T170739	0.0000
Trip 2 (downtown LA4 route)	T170740	0.0489
Trip 3 (USC to Ontario)	T170767	0.0072
Trip 4(lunch break idle)	T170738	0.0112
Trip 5 (Mt.Baldy)	T170762	0.0166
Trip 6 (Ontario to Riverside)	T170768	0.0069

20170810 Original Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to SD)	T170850	0.1316
Trip 2 (downtown SD)	T170863	0.0395
Trip 3 (downtown SD	T170862	0.0218
Trip 4 (downtown SD)	T170839	0.0356
Trip 5 (SD to Riverside)	T170854	0.0948

20170812 Original Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to USC)	T170858	0.0710
Trip 2 (downtown LA route)	T170829	0.0512
Trip 3 (USC to Ontario)	T170836	0.0424
Trip 4(lunch break idle)	T170825	0.0131
Trip 5 (Mt.Baldy)	T170856	0.0163
Trip 6 (Ontario to Riverside)	T170828	0.0212

20170813 Original Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to USC)	T170831	0.0482
Trip 2 (downtown LA4 route)	T170832	0.0348
Trip 3 (USC to Ontario)	T170867	0.0744
Trip 4(lunch break idle)	T170855	0.0073
Trip 5 (Mt.Baldy)	T170780	0.0568
Trip 6 (Ontario to Riverside)	T170782	0.0168

20170814 Original Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to Ontario)	T170786	0.0552
Trip 2 (Mt Baldy)	T170796	0.0340
Trip 3 (Ontario to Riverside)	T170797	0.0140

20170817 Original Test	Filter ID	Filter Net (mg)
Trip 1 (Riverside to USC)	T170887	0.1093
Trip 2 (downtown LA4 route)	T170884	0.0391
Trip 3 (USC to Ontario)	T170881	0.0388
Trip 4 (Ontario to Riverside)	T170880	0.0182