Californias
Advanced Clean Cars
Midterm Review

Appendix J:
Vehicle PM Emission Control Technology Assessment

January 18, 2017

California Environmental Protection Agency

Air Resources Board

TABLE OF CONTENTS

LIST OF FIGURES

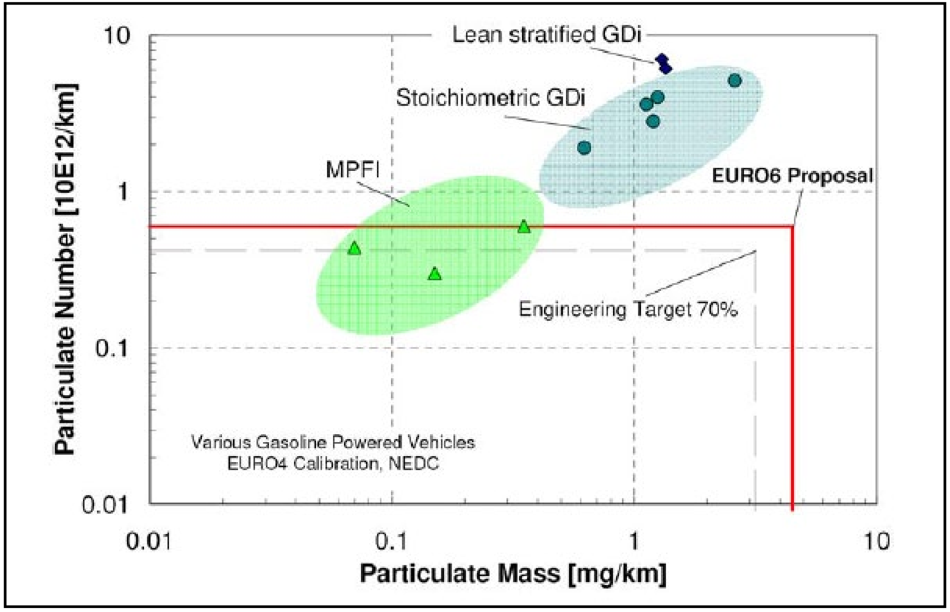
LIST OF TABLES

I. Introduction

PM emissions from light- and medium-duty vehicles are regulated as part of the Low-Emission Vehicle (LEV) program. Under LEV III, the PM standard for passenger cars, light-duty trucks, and medium-duty passenger vehicles was initially lowered from 10 mg/mi to 3 mg/mi over a phase-in period from 2017 through 2021 model year vehicles. Ultimately, with a phase-in spanning 2025 through 2028 model years, the 1 mg/mi PM standard will further reduce the health impacts of PM and will help ensure the continued development of low-PM engine technology. Both standards were phased in to provide flexibility.

The need to simultaneously lower GHG and criteria emissions, including PM, is driving significant innovation in gasoline engines with gasoline direct injection (GDI) likely to be a key technology. While GDI is a very important technology for reducing tailpipe CO2 emissions, it does come with the potential to increase PM emissions compared to conventional port fuel injection (PFI) systems. Data on PM emissions from production vehicles in the 2011 time frame using PFI and GDI technology from a study by Delphi Powertrain Systems suggests that, directionally, PM mass emissions from GDI systems are higher than PFI systems as shown in Figure 1 below.

Figure 1 - Vehicle emission measured on EURO 4 production vehicles[1]



Mitigation of the impact of PM emissions on public health is of paramount concern to ARB. Given the expected continued trend in increased GDI system usage and the potential for increased PM emissions as a result, the Board adopted the 3 and 1 mg/mi standards to ensure

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[1] Piock, 2011. Walter Piock, et. Al. "Strategies Towards Meeting Future Particulate Matter Emission Requirements in Homogeneous Gasoline Direct Injection Engines". April 2011 http://papers.sae.org/2011-01-1212/

continued progress towards reducing PM emissions from all sources in California. While the staff demonstrated the feasibility of meeting the 1 mg/mi standard at the time of adoption, the Board also recognized there is a significant technical challenge and manufacturer resource challenge to meet the 1 mg/mi standard while also reducing GHG emissions and fleet average emissions to a LEV III SULEV30 emission level. Consequently, the Board directed staff at the board hearing in 2012 to re-evaluate the measurement feasibility, the technical feasibility, and the timing of the 1 mg/mi PM standard.

In September 2015, ARB, in collaboration with the U.S. EPA, industry, and other stakeholders, presented the findings of an extensive study that evaluated the feasibility of measuring PM emissions at the levels required to comply with the LEV III 1 mg/mi standard.[2] Several of these studies were focused on investigating concerns regarding the limitation of the gravimetric measurement method that has been historically used in vehicle testing to determine PM mass. From the study, ARB staff concluded that the gravimetric method specified for vehicle emission testing in 40 Code of Federal Regulations (CFR) Part 1065/1066 is suitable for measuring PM mass emissions at the sub 1 mg/mi level. While the measurement review included evaluation of alternative measurement metrics including PMP based SPN and black carbon, the findings supported the gravimetric method as the most appropriate metric for controlling PM in California. This conclusion was based on evaluations of the potential sources of measurement variability, determination of the PM measurement precision, and a comparison of collocated measurements of selected sampling options described in 40 CFR Part 1066.

To assess the technical feasibility of the 1 mg/mi PM standard, ARB staff re-examined the status of PM emission control by testing current vehicles as well as updating staff's assessment of current and future PM control strategies and technologies. ARB conducted tests to determine PM emissions and composition from currently available vehicles using engine technologies most representative of future vehicles which is described in Appendix K. This appendix provides a review of PM formation, the effects of GDI technology on PM and a control technology evaluation based on literature review and meetings with OEMs, suppliers, and PM control experts.

Overall, test results and updated technology evaluation support staff's original assessment that the 1 mg/mi standards are technically challenging but achievable by 2025 at very low to no cost. Advances to in-cylinder PM control facilitated by improved engine and fuel injection systems have substantially reduced PM emissions on newly re-designed engines. Given the available lead time, manufacturers can use the knowledge they gain from in-use operation of the current generation of engines to redesign subsequent engines to meet the 1 mg/mi standard in the 2025 time period. In cases where more flexibility is needed for particularly challenging engines, the additional cost of a gasoline particulate filter (GPF) may be warranted to effectively control PM. To be most effective in-use, PM control technology needs to reduce PM emissions for all driving conditions including high speed transient operation and cold weather conditions.

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[2] ARB. 2015. Air Resources Board. "AN UPDATE ON THE MEASUREMENT OF PM EMISSIONS AT LEV III LEVELS". October 2015. https://www.arb.ca.gov/msprog/levprog/leviii/lev_iii_pm_measurement_feasibility_tsd_20151008.pdf

Accordingly, the need for additional PM standards and test procedures should be evaluated to ensure robust control strategies are utilized and in-use PM emissions are minimized.

I.A. General PM Formation

There are three general sources of light-duty vehicle exhaust PM emissions: lubrication oil, fuel composition, and rich combustion. Particles from these sources vary in composition and can be classified by physical state as volatile, semi-volatile, and solid or by their chemical composition as organic and inorganic. Inorganic particles include ash and oxides of sulfur that can only be controlled by eliminating precursors from the combustion chamber. Inorganic PM control is the same regardless of vehicle technology and so is not central to this GDI based PM control analysis. The increased PM typically associated with GDI vehicles is most commonly the result of a rich condition in the combustion chamber during a combustion event.

Organic PM includes elemental carbon particles that are in the solid phase and organic carbon which generally makes up the volatile and semi-volatile fraction of PM. The physical states of the volatile and semi-volatile compounds depend on a number of factors such as exhaust temperature, composition, vapor pressure, and concentration. Elemental carbon and organic carbon make up the majority of gravimetrically measured PM emissions and appropriately are the focus of this document.

Elemental carbon, also known as black carbon or soot, is comprised solely of carbon atoms and is the result of pyrolysis within the combustion chamber caused by a localized lack of oxygen and extreme heat and pressure. In this process, the hydrogen atoms dissociate from the carbon chain and the remaining carbon atoms form bonds with each other forming elemental carbon. Elemental carbon is the sooty, black material typically associated with older diesel car or truck exhaust, but it also often makes up between 50%-80% of PM emissions from modern GDI-equipped vehicles. The in-cylinder characteristics that affect the (Elemental Carbon/Organic Carbon) EC/OC ratio are specific to an engine's design and the control strategy, but some generalizations can be made. Elemental carbon is generally formed in areas where fuel exists without any oxygen and combustion occurs as a diffusion flame. One of the areas that can be a large source of elemental carbon is on the injector tip. Fuel that remains on the injector tip after an injection event can turn into elemental carbon before it can evaporate because the injector is often substantially hotter than the cylinder wall or piston.

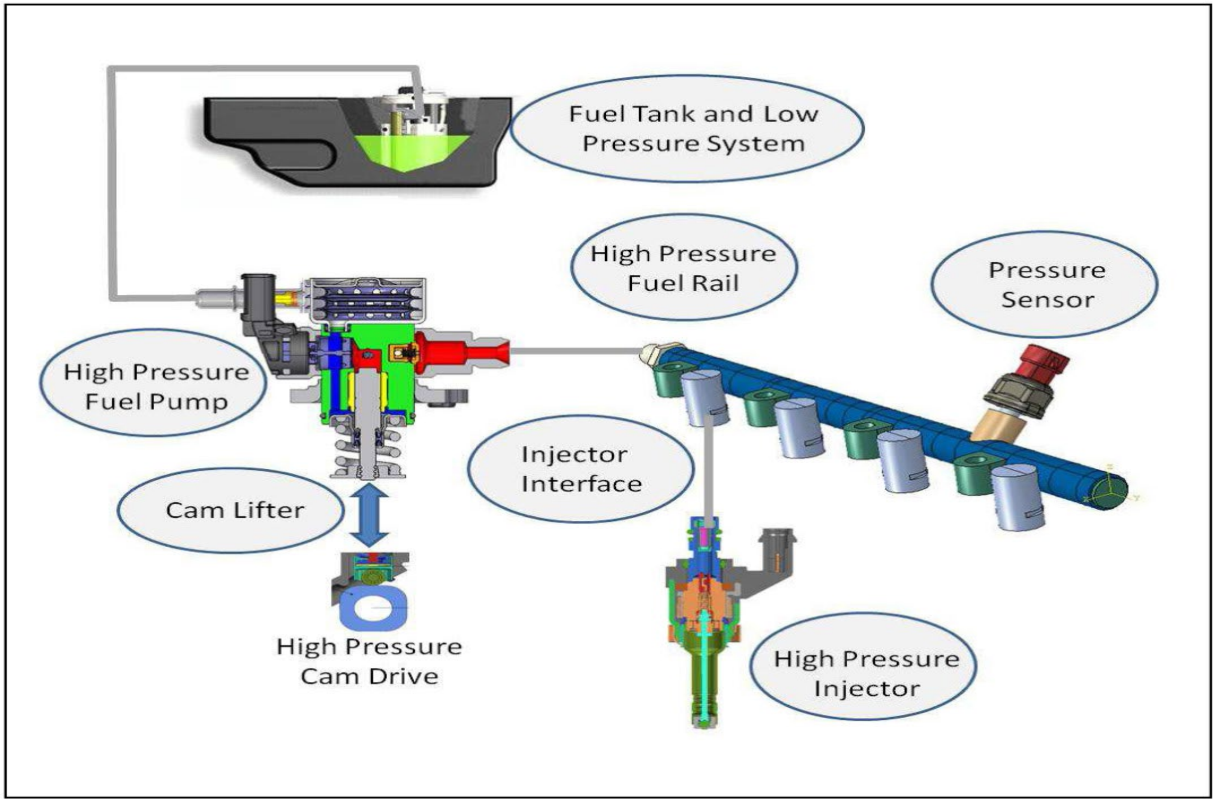
Organic carbon is formed in similar ways to elemental carbon, but it forms when there is insufficient oxygen to complete combustion. The result of incomplete combustion generally is that the most stable hydrocarbons, often aromatic rings, are not converted to CO_2 and H_2O. These hydrocarbons generally exit the combustion chamber in the gas phase and if they remain that way, are oxidized as they pass through the catalyst. However, some of these hydrocarbons condense onto solid particles or nucleate to form new particles before passing through the catalyst and result in organic carbon PM. Gasoline exhaust particles are often a heterogeneous particle containing both solid elemental carbon and liquid organic carbon within the same particle.

I.B. Gasoline Direct Injection - Technical Overview

A basic understanding of GDI systems is important to understand PM formation and control strategies. A more complete description of the GDI technology and technology trends can be found in the 2016 Draft Joint-Agency Technical Assessment Report (2016 TAR).[3] The increased PM typically associated with GDI vehicles is the result of a rich condition in the combustion chamber during a combustion event. The rich condition can be localized or homogeneous as discussed further in the PM Formation and Controls section.

GDI injection systems have two major components that relate to PM emissions. First, the high pressure fuel pump that determines the fuel pressure at the injector, typically between 150 and 400 bar. Second, the fuel injectors themselves, which inject the pressurized fuel into the combustion chamber. The fuel pressure, injector design, and integration can have a substantial effect on PM emission rates.

Figure 2 - GDI fuel system and components[4]



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[3] EPA 2016. United States Environmental Protection Agency, National Highway Traffic Safety Administration, California Air Resources Board. *Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025*. July 2016. https://www3.epa.gov/otaq/climate/documents/mte/420d16900.pdf

[4] Hoffmann, 2014. Hoffmann, G. et.al. SAE International. “Fuel System Pressure Increase for Enhanced Performance Hole Injection Systems” January 04, 2014. http://papers.sae.org/2014-01-1209/

II. PM Formation and Controls for GDI Vehicles

There are two paths for effective PM control from GDI equipped vehicles: in-cylinder control or the use of aftertreatment such as gasoline particulate filters (GPF). GPFs efficiently control PM for all operational modes but they do represent added hardware, at some expense, for manufacturers to integrate solely for PM control. GPFs are discussed in detail in the "Gasoline Particulate Filters (GPFs)" section, Section III. In-cylinder control is a balancing act between GHG, HC+NOX, and PM emissions. Reducing GDI PM emissions means controlling enrichment that can occur from one of three mechanisms. First, impingement and liquid droplets; this is where injected liquid fuel makes contact with the cylinder wall, piston, or injector tip, or fuel droplets do not evaporate and completely mix during an injection and combustion event. Second, areas of localized enrichment within the combustion chamber such as cases where a control strategy targets localized areas with the injection to achieve stable combustion. Third, homogenous rich combustion such as when a control strategy commands enrichment for component protection, catalyst conversion, or due to high speed transient operation. Additionally, some PM formation conditions are independent of GDI technology such as fuel and oil effects and measures to ensure those mechanisms are minimized are necessary for all vehicles to meet the 1 mg/mi future standard.

I.A. Impingement and Droplet Evaporation

Enrichment due to incomplete fuel evaporation in GDI engines occurs when fuel is impinged onto the walls of the combustion chamber, does not completely mix with the air charge, or remains on the injector tip due to coking. During the combustion event, any fuel that has not vaporized burns as a soot-forming diffusion flame that increases PM emissions.

Enrichment due to slow fuel evaporation is a function of temperature, droplet size, air speed, and time. Temperature, as it relates to fuel evaporation includes the air in the cylinder, the cylinder and piston surfaces, and the fuel. Time is affected by both injection timing, usually measured in degrees before top-dead-center, and overall engine speed. Droplet size is affected by injector design and fuel pressure. Finally, air speed is determined by intake shape, valve location, and the velocity of the fuel injected into the cylinder. Temperature, time, droplet size, and air speed are all important parameter for PM control strategies and vary under different engine operational conditions.

High torque operation generates PM emissions because the mass of fuel that must be injected into the cylinder is large, thereby increasing the chance of impingement on cylinder walls or the piston. High torque at low engine speed can generate additional PM because the piston isn't moving away from the fuel spray as quickly as it does at high speed; however this is offset by the increased residence time the charge has to completely mix before combustion. High torque at high engine speed, resulting in high power, tends to result in increased PM emissions because the large amount of fuel that is injected does not have enough time to completely evaporate and mix resulting in localized rich areas that form PM. A subset of high torque operation is spray collapse. This is a condition where the higher pressure in the cylinder causes the injected fuel cloud to collapse onto its self after being injected and results in reduced mixing and localized rich areas within the cylinder.

High torque impingement and injection spray collapse can be exacerbated by highly boosted downsized engines because a large amount of fuel has to be injected into a relatively small, highly compressed combustion chamber.

Finally, cold starts generate more PM emissions because of slower evaporation of fuel and because of some catalyst heating strategies used to reduce light off time. Cold engine and ambient conditions inherently generate PM because of slower vaporization[5] on cold components with colder intake air.[6] The effects of slower evaporation are exacerbated on GDI systems that more routinely have impingement such as spray guided systems that rely on injected fuel making contact with wall or piston surfaces.

II.B. Impingement and Droplet Evaporation Control

Engineering a low PM emitting engine by eliminating rich combustion requires that PM control be simultaneously considered as manufacturers design the engine to comply with future GHG and criteria emission standards. By implementing appropriate design measures during an engine redesign, the cost to achieve good PM control can be very low. In-cylinder PM control strategies can be broken down into three main categories: fuel injection component and control improvements, and engine hardware improvements.

II.B.1. Fuel Injection System

Improvements to fuel injection hardware are central to controlling in-cylinder PM formation. Improvements can include increased fuel pressure, improved injector spray patterns, and reduced injector tip wetting. The fuel injectors on a GDI system are the heart of the injection system. The injector must accurately meter fuel as it is injected into the combustion chamber at extreme pressures. Injectors can be grouped by actuation type; solenoid vs. piezo, and injector tip type; inwardly opening vs. outwardly opening.

In a conventional solenoid configuration, the pintle is pulled away from the injector tip holes to allow fuel to spray into the combustion chamber as shown in Figure 3. Solenoid GDI injectors are less expensive, but accurately controlling fuel metering over multiple injections for PM control can be challenging.

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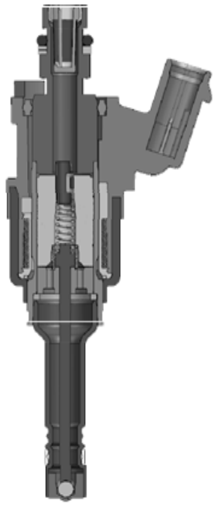
[5] Zhang, 2013. Gaomimg Zhang, et.al. Macroscopic Characterization of Flash-Boiling Multihole Sprays Using Planar Laser-Induced Exciplex Fluorescence. Part II: Cross-Sectional Spray Structure. July 2013. https://www.researchgate.net/publication/273223742_Macroscopic_characterization_of_flash-boiling_multihole_sprays_using_planar_laser-induced_exciplex_fluorescence_Part_II_Cross-sectional_spray_structure

[6] Chan, 2013. Tak W. Chan, et. Al. “Impact of Ambient Temperature on Gaseous and Particle Emissions from a Direct Injection Gasoline Vehicle and its Implications on Particle Filtration”. April 2014. http://papers.sae.org/2013-01-0527/

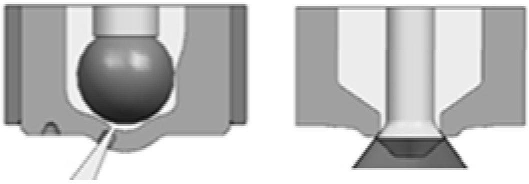
Figure 3 - GDI Solenoid Injector – Delphi-Piock-eng 2015 Vienna	**Figure 4 - Piezo Injector[1] tips: inwardly opening vs. outwardly opening**
	

A piezoelectric, or piezo, actuated system as shown in Figure 4, applies a current to a stack of piezos that respond by opening the conical tip of an outwardly opening injector. Piezo injectors are often used in diesel applications and are generally more expensive than solenoid injectors, but they can meter fuel very accurately over very short injection durations.

Injector tips come in two general types, inwardly opening and outwardly opening, as shown in Figure 5. Most solenoid injectors use an inwardly opening design. The first burst of fuel that sprays through the holes is not steady state and is known as the ballistic portion of the injection. This portion tends to atomize very well but because the fuel flow rate is non-linear, quantity control is challenging.

The pintle in an outwardly opening injector, as the name implies, opens outward into the combustion chamber. The conical shape of the pintle tip results in a hollow cone of fuel being injected into the combustion chamber that maximizes surface area and reduces evaporation times. Outwardly opening injector tips are often used in conjunction with piezo actuators.

Figure 5 - Inwardly and outwardly opening injector tips - Delphi-Piock-eng 2015 Vienna



II.B.1.i. Software Improvements

Manufacturers use a variety of software improvements to control PM emissions. Engine management strategies include: optimized injection timing, improved accuracy in fuel metering, and multiple injections per combustion event. These strategies reduce impingement during all operational modes, which is especially valuable during cold start when the combustion chamber is cold. Optimizing fuel evaporation time and charge mixing can be accomplished using early injection timing which increases the dwell timing in the cylinder and multiple short injections, which result in smaller droplets and more complete mixing. Multiple injections per combustion event historically decreased accuracy in fuel metering which led to some rich combustion events. However, recent improvements in injector control and feedback allow more accurate metering even with multiple injections. Multiple injections are an especially effective strategy to control impingement during high torque operation at low engine speeds.

II.B.1.ii. Fuel System Pressure

The simplest way to reduce droplet size and directionally reduce PM emissions is to increase the fuel rail pressure. Systems in production today typically run at pressures between 100 and 200 bar, with a majority of the newer systems operating in the upper portion of that range. Recent improvements to injectors and pumps have allowed fuel pressures to increase to between 300 and 400 bar. Increases in fuel pressure reduce PM emissions because the droplets are smaller, the penetration distance into the combustion chamber is similar or decreased[7] as shown in Figure 6, and mixing is increased. Smaller droplet size increases surface to volume ratio which leads to faster evaporation. The smaller droplets also experience higher aerodynamic drag on a mass basis which makes each droplet slow down much faster and limits penetration distance to avoid impingent on cylinder or piston surfaces. The energy that is given up to the air also results in increased charge mixing. Increased fuel system pressure does come at an overall energy cost to the engine as the parasitic pump loads reduce overall engine efficiency. However, the effect is small and, in a fully optimized design, most or all of that additional load can be offset by an increased combustion rate in the engine during the combustion event, which is a result of improved air/fuel mixing and increased charge motion.[8] In addition, increased fuel pressure and multiple injections can greatly reduce the effect of injector coking.[9]

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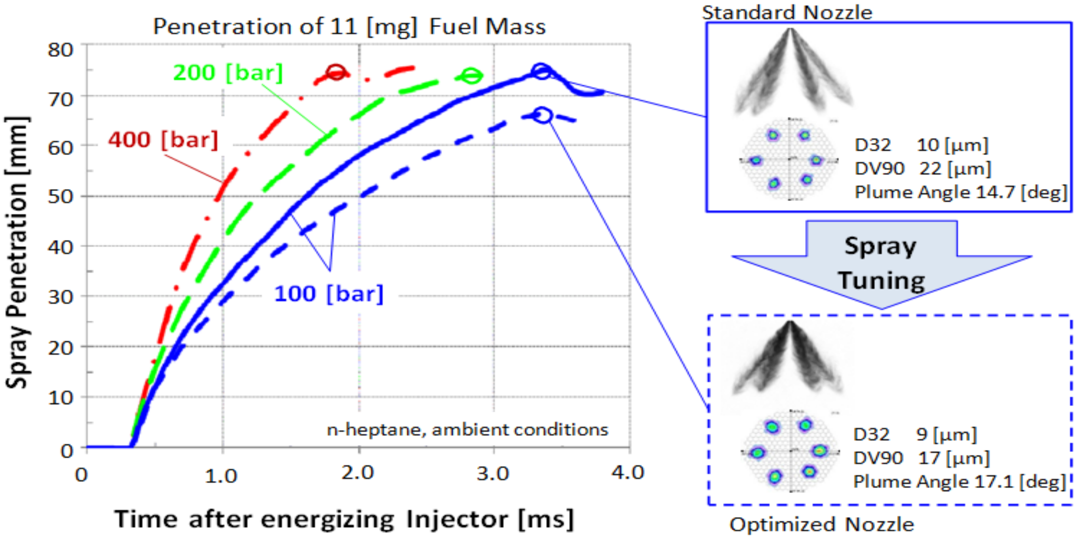
[7] Hoffmann, 2014.

[8] Piock, 2015. Walter F. Piock, et. Al. Fuel Pressure and Charge Motion Effects on GDi Engine Particulate Emissions. April 2015. http://papers.sae.org/2015-01-0746

[9] Berndorfer, 2013. Axel Berndorfer et. Al. Diffusion Combustion Phenomena in GDi Engines caused by Injection Process. April 2013. http://papers.sae.org/2013-01-0261/

Figure 6 - Fuel Spray Penetration as a Function of Pressure and Nozzle Design
- From “Delphi’s Fuel Injection Systems for Efficient and Clean Gasoline Engines with Direct Injection”

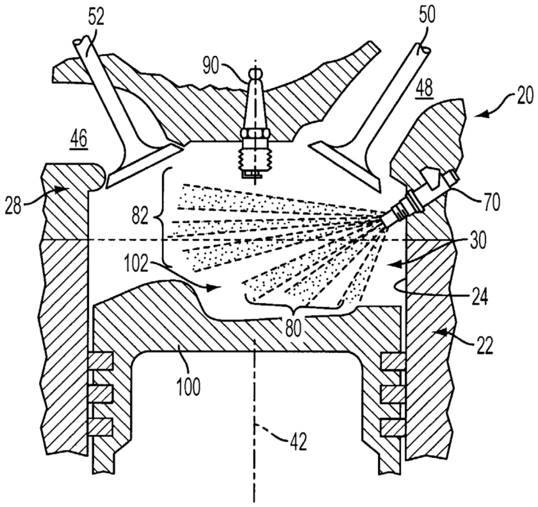


II.B.1.iii. Injector Tip Forming

It is essential that the injected fuel spray pattern matches the combustion chamber shape to reduce impingement. Injector tip manufacturing is continually improving to achieve more control on spray shape and distance to reduce impingement and improve mixing. Given the recent emphasis on PM control caused by the near term 3 mg/mi and future 1 mg/mi standards, many promising designs are still being developed and not yet commercially available but are expected to be available for mass production in the next few years and wide-scale deployment shortly thereafter.

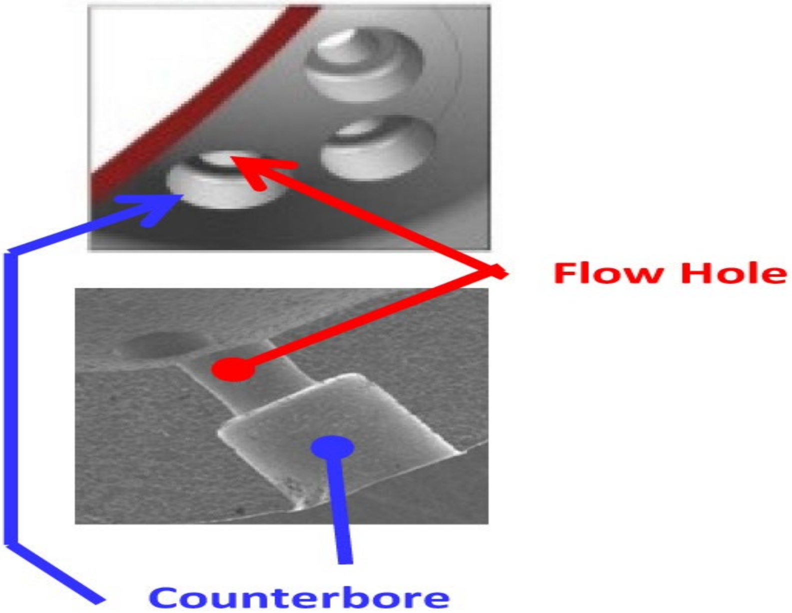
In a side mounted injection system, manufacturers and suppliers have learned that the spray pattern needs to be asymmetrical to minimize impingement. The best way to accomplish this is with precisely made holes at exact angles. The design of the holes in the tip of an injector can have a great effect on the spray of the fuel injected into the cylinder. The use of lasers to drill the holes allows optimized geometry including hole angle, diameter, and taper. A properly designed injector tip can result in side mounted injectors with asymmetric spray patterns as shown in Figure 7 that greatly reduce fuel impingement and improve atomization.

Figure 7 - Asymmetric spray pattern[10]



A second advancement is the use of counter bored holes as shown in Figure 8, which allow more accurate control of hole diameter to length ratio and fuel penetration distance.

Figure 8 - Counter bored injector tip[11]



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[10] Yi, 2008. Jianwen James Yi, et.al, Fuel injector spray pattern for direct injection spark ignition engines. September 2, 2008. https://www.google.com/patents/US7418940

[11] Kazour, 2014. Joseph Kazour, et. al. "Innovative Sprays and Particulate Reduction with GDI Injectors." April 2014. http://papers.sae.org/2014-01-1441/

II.B.1.iv. Outwardly Opening Injectors

The advantage of outwardly opening injectors is reduction of injector tip coking, very good fuel mixing because the sheet of injected fuel is very thin, and lower fuel pressures, often in the 150 bar range. At this time, however, asymmetric injection is not possible with such a design so the injectors must be center mounted to maximize the benefits. Second, outwardly opening injectors are often piezo driven, which allows for very fast response times, but can significantly increase the cost for the injector and the injector control system. Some research is being conducted to drive outwardly opening injectors with conventional injector solenoids. Solenoid driven outwardly opening injectors, along with engines designed for center mount injectors, greatly reduce impingement and droplet based PM but they are not yet commercially available.

II.B.1.v. Combination PFI/GDI

A fuel injection system that uses both port and direct fuel injection can effectively control PM by behaving like a PFI vehicle for all conditions except those that require the GDI's knock resistance characteristics. There are a variety of vehicles using this technology today including many Toyota vehicles for sale in California. Generally, the technology is added to maintain accurate fuel control for all fuel flow demands and to reduce parasitic losses from the high pressure pump, but an added benefit is PM emission characteristics similar to PFI vehicles.

II.B.1.vi. Durability of Fuel Injection Components

Degradation of fuel injection system components can lead to increased PM emissions over the useful life of vehicles. However, improvements to control strategies and improvements to injector technology including injector holes, system pressures, and harder injector tips can reduce the rate of deterioration from hole erosion or deposit formation and ensure PM control for the useful life.

II.B.2. Engine Improvements

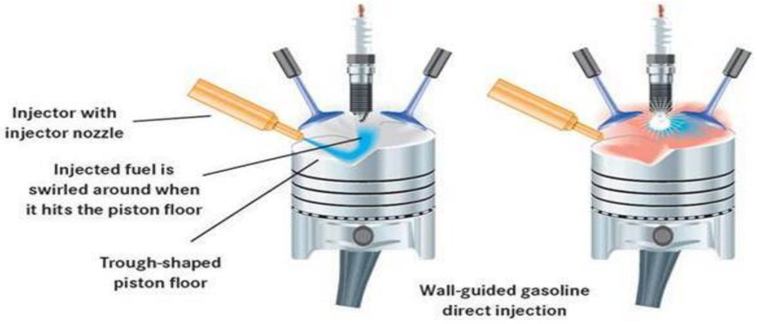
Changes to the engine hardware can optimize injector location, improve intake air tumble, and match the combustion chamber shape to injector spray pattern to ensure a homogeneous combustion charge. These types of improvements are best done in conjunction with engine redesigns where all effects can be simultaneously evaluated. With appropriate lead time, such changes can be integrated into normally scheduled redesigns or new engine introductions and the associated design features necessary for good PM control can be incorporated for little or no cost.

II.B.2.i. Matching Spray Pattern to Combustion Chamber Shape

The combustion chamber shape must match the injector spray shape. This can be done through changes to the spray pattern as discussed above or combustion chamber shape. The piston top is the simplest and most effective way to control combustion chamber shape. Designs that allow the injection event to occur earlier while reducing liquid fuel contact will effectively reduce PM emissions.

The fuel spray pattern can be affected by injector location and injector tip design as previously discussed in the Fuel Injection System section. There are two primary fuel injector location options for GDI technology: side mounted and center mounted. In a side mounted configuration, as shown in Figure 9, the spray pattern needs to be asymmetric and the injected fuel may use the piston bowl, the top of the piston, and the cylinder wall to help define the shape of the fuel spray. Any fuel contact with the combustion chamber walls can result in impingement and higher PM emissions. However, improved injector designs, especially with regard to modified spray patterns and multiple injections per firing event, combined with improved air flow control into the cylinder, are being utilized to reduce impingement and improve mixing. Side mounted injectors have the advantage of not interfering with the spark plug location and provide manufacturers increased flexibility in manufacturing and under hood packaging.

Figure 9 - Side Mounted GDI Injector[12]



In a center mount configuration, as shown in Figure 10, the injector is centrally mounted and located above the piston, which is similar to a diesel engine design. This allows the use of a symmetric spray pattern, including outwardly opening injectors, which helps avoids contact with the cylinder walls and results in lower PM emissions. Center mounted systems can be more challenging to integrate and are often only able to be implemented when a whole-head redesign is being done and engine/vehicle packaging allows for it.

Figure 10 - Center Mounted GDI Injector[13]

II.B.2.ii. Increased Tumble

Tumble is the term used to describe the air motion in the cylinder caused by the intake runner and valve geometry as shown in Figure 11. Tumble generally improves charge mixing which

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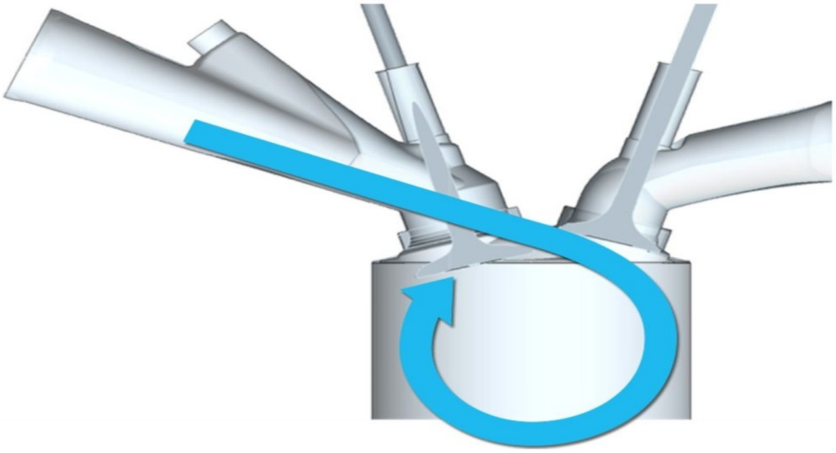
[12] GCC, 2006. Green Car Congress. Mercedes-Benz Premiers New Gasoline Direct Injection System for More Power and Lower Fuel Consumption. February 24, 2006. http://www.greencarcongress.com/2006/02/mercedesbenz_pr.html

[13] GCC, 2006.

leads to quicker and more complete combustion thus reducing PM emissions as well as criteria and GHG emissions. Increased tumble also helps control injector tip temperatures and reduces evaporation time of any impinged fuel.[14] In some cases, manufacturers have resorted to variable position tumble or swirl control valves on in the intake to alter the tumble in different operating conditions but most designs rely solely on intake manifold, runner, and intake valve designs and strategies to achieve the desired flow characteristics.

Figure 11 - Intake Air Tumble[15]



II.B.2.iii. Thermal Management

Thermal management is important inside the combustion chamber to ensure complete evaporation of fuel, and outside the combustion chamber to ensure that enrichment for component protection is not needed. Inside the engine, the two primary areas that need careful temperature control are the injector tip and the top of the piston. Ideally both are kept at a temperature that ensures quick evaporation without risking fuel pyrolysis. Injector tip temperature is primarily controlled through heat conduction into the head and coolant. Piston temperature is best controlled with a combination of oil squirters below the piston and the material properties of the piston itself.

Thermal management is also important to reducing the need for enrichment for component protection. Components exposed to the exhaust gas such as the exhaust valves, turbocharger (where applicable), and catalyst can indirectly lead to PM emissions when the engine goes into enrichment to reduce or avoid exhaust gas temperatures that could damage these components. The need for good emission control over all operating conditions and the increasingly stringent criteria pollutant and GHG emission standards has greatly reduced the number and duration of enrichment events for component protection during conventional driving. Manufacturers are designing systems to be more robust and avoid the need for enrichment by utilizing components such as valves, turbochargers, and catalysts with improved materials that can withstand higher

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[14] Piock, 2015b. Dr. techn. W. Piock, et. Al. Delphi's Fuel Injection Systems for Efficient and Clean Gasoline Engines with Direct Injection. May 2015

[15] Toyota, 2014. The official blog of Toyota GB. April 15, 2014. "New Toyota Aygo engine technology revealed" http://blog.toyota.co.uk/new-aygo-engine-technology-revealed

temperatures without damage. Manufacturers are also using redesigned systems such as integrated exhaust manifolds to provide additional thermal control of exhaust temperatures to minimize high temperature excursions.

II.B.2.iv. Durability of Engine Hardware to Control PM

Base engine hardware like combustion chamber shape and injector location do not change as the engine ages but items like spray pattern can deteriorate as deposits form on the injector tips or the holes in the nozzle of the injector erode. However, improvements in the control system provide significant feedback on the operation and allow the system to compensate for some of this change. Further, improvements in the materials and manufacturing processes used for the injector are being made to reduce erosion and deposit formation as the injector ages.

Additionally, increased oil consumption can theoretically occur as the system ages from oil getting by the rings or through the PCV system, into the combustion chamber, and forming PM during combustion events. However, since the advent of stringent NOx emissions with the LEV II and successor programs, manufacturers have already been implementing design improvements to cylinder walls and piston rings to minimize deterioration and virtually eliminate oil consumption. These changes were necessary to avoid catalyst poisoning from oil consumption that would jeopardize the ability to meet the LEV II or LEV III standards for the full useful life of the vehicle.

II.C. Localized Enrichment

Controlled localized enrichment, or stratified charge, is a phenomenon that is possible with GDI. In this mode a small amount of fuel is injected very late in the compression stroke and targeted to create a rich kernel around the spark plug that ensures stable combustion. However, the rich combustion around the spark plug results in increased PM emissions.

II.C.1. Cold Start Catalyst Light Off

Some catalyst light off strategies used to quickly heat the catalyst for HC+NOx emission control make use of very late combustion to maximize the temperature of the exhaust gas exiting the cylinder. The intent of the operation is to increase the temperature of the exhaust gases to facilitate rapid warm-up of the catalyst up to a temperature region where it has very high HC and NOx conversion efficiency. However, very late combustion (with late spark timing) is a more difficult condition to initiate combustion and combustion stability limits are often the limiting factor. With GDI systems, fuel can also be injected very late and result in a localized rich area near the spark plug so combustion can be robustly initiated at even later spark timing than a homogenous mixture in the cylinder would allow. While this is very effective at creating stable combustion with very late spark timing, the localized area of rich mixture around the spark plug results in increased PM emissions.

II.C.2. Cylinder Deactivation

Several vehicles now use engines employing a cylinder deactivation system whereby several of the engine's cylinders are not used during periods of operation like low or steady speed operation where total vehicle power demands are moderate. During cylinder re-activation, immediately following a period of cylinder deactivation, a late injection and late ignition is often used to temporarily reduce the cylinder specific power and promote a smooth transition in engine torque output while reducing noise, vibration, and harshness (NVH) impacts. The effect is similar to the catalyst light off strategy mentioned above, where the condition around the spark plug is slightly rich to ensure stable combustion and thus results in additional PM formation.

II.D. Localized Enrichment Control

II.D.1. Software Improvements

A variety of engine management strategies can be used to reduce PM emissions during catalyst light-off and cylinder deactivation. Reducing the mass of fuel injected around the spark plug during stratified combustion will help control PM but can cause increased hydrocarbon emissions so would likely need to be coupled with other strategy or hardware changes to control hydrocarbon emissions. Software improvements can be implemented quickly and likely account for some of the lower PM emission results from newer GDI systems tested by ARB and noted in Appendix K. Engine management is also an essential part of hardware improvements such as catalyst location and design but, OEMs must be careful when implementing new control strategies to maintain control of HC+NOx and GHG emissions.

Engine management changes can be quite durable against PM emissions degradation over the useful life of the vehicle. For many conditions, improved feedback control strategies allow a control strategy to adapt and continue to effectively control PM emissions as the hardware components age.

II.D.2. Catalytic Converter

Indirectly, improved three-way catalyst design, including location and composition, can reduce PM emissions by reducing light-off time, thereby decreasing the duration of operation in a mode that may generate higher PM while trying to warm-up the catalyst. The location of the catalyst generally represents a need to balance packaging, exposure to very high exhaust temperatures in more extreme operating conditions, and the need to achieve very quick light-off at start-up to mitigate cold start emissions. The further downstream, the cooler the catalyst will run but the harder it is to quickly achieve the high temperatures needed for light off. Substantial improvements for the last decades have resulted in catalysts that are much more thermally stable and capable of exposure to high temperatures without excess degradation allowing for closer location to the exhaust manifold. Additionally, the substrates have often become smaller and lighter to reduce the thermal mass and warm-up faster minimizing the length and severity of catalyst light-off strategies. And, as noted earlier, improved thermal management of the exhaust such as water-cooled integrated exhaust manifolds are being used to reduce peak exhaust temperatures, allowing for the catalyst to be located closer to the manifold itself. For turbocharged engines, where the turbo is located upstream of the catalyst, manufacturers are also considering exhaust bypass systems that would allow exhaust gas to bypass the turbo during cold start to facilitate early catalyst light-off. The durability of a catalytic converter is a function of time at elevated temperatures, so controlling catalyst temperature is essential for complete useful life catalyst operation.

II.D.3. Mild Hybrid

Mild hybrids, such as the 48-volt system described in the draft 2016 TAR[16] are projected to play an important role for vehicle to meet low GHG standards. The need for localized enrichment can be greatly reduced or eliminated by leveraging mild hybrid technology. For example, a 48-volt system with a belt-assisted starter-generator can be used to motor the engine during cold start, this can reduce the need for stable combustion and facilitates late ignition timing without the need for stratified combustion. Similarly a mild hybrid system can be used in conjunction with cylinder deactivation to smooth out the transition as cylinders are reactivated.

II.E. Homogeneous Enrichment

During limited modes of operation, it may be important to operate slightly rich of stoichiometric to promote stable combustion, cool exhaust gas temperature to protect components, maximize engine power, or for optimal catalyst conversion. Historically, homogeneous enrichment was more commonly used for component protection but increasingly stringent standards and newer technology such as improved high temperature alloys used in exhaust components, catalyst substrates and washcoats with improved high temperature stability, and other exhaust thermal management technologies like water-cooled integrated exhaust manifolds have allowed manufacturers to greatly reduce, if not eliminate, the conditions where such enrichment is needed in all but the most extreme conditions.

From an emissions perspective, homogeneous rich operation with a lambda less than one is rarely called for in any modern engine control strategy because the stringent LEV III emission standards require very high catalyst conversion efficiencies and conversion is optimal when the exhaust gas remains very close to stoichiometric operation. Short, slightly rich excursions can be tolerated given today’s catalysts can continue to effectively convert HC and CO emissions in such conditions but control systems are generally biased to avoid any similar lean excursions as the resulting increase in NOx emissions is significant. These rich excursions can, however, cause increased PM.

II.E.1. Stop/Start

A vehicle equipped with a stop/start system needs to start smoothly and dependably for user satisfaction and safety. One way this can be accomplished is with a slightly rich charge during the restart with the consequence being increased PM emissions.

II.E.2. Deceleration Fuel Cut

During a deceleration fuel cut, the exhaust flow through the catalyst is essentially ambient air, resulting in the catalyst being temporarily saturated with stored oxygen. While stored oxygen is critical for HC and CO conversion in the catalyst, efficient reduction of NOx emissions requires minimal stored oxygen to ensure a sufficient number of sites available to promote the necessary chemical reactions. In normal operation, fuel control systems effectively dither around stoichiometric exhaust concentrations to provide opportunity for storage and release of oxygen in sufficient quantities to satisfy the needs for both HC/CO conversion and NOx conversion. However, following a prolonged deceleration fuel cut event, the saturated oxygen status of the

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[16] EPA, 2016.

catalyst necessitates temporary rich operation to remove the stored oxygen on the catalyst and the rich operation can result in increased PM emissions.

II.E.3. Transient Engine Operation

Good fuel control during transient engine speed and load operation is critical for all pollutant emissions and is not unique to PM emissions. Reliably controlling PM emissions requires that each combustion event avoid areas of rich combustion and properly meter fuel and air with good mixing for complete combustion.

II.F. Homogeneous Enrichment Control

A variety of engine management strategies can be used to reduce PM emissions during situations where enrichment may have historically been used. The most direct way is to eliminate the need for the enrichment. And, as noted above, for enrichment used for component protection, manufacturers have increasingly been moving in the direction of higher temperature components and better exhaust thermal management to eliminate the need to use enrichment as a high exhaust temperature countermeasure.

For other situations, alternate control and hardware solutions may be necessary. For example, for additional GHG reductions, manufacturers are exploring many stop/start systems that are coupled with an electrical assist (e.g., belt-assisted starter-generator, ‘mild’ hybrid system) that uses electrical power to help initially propel the vehicle and reduce the dependence on as quick of a restart of the engine that many 12 volt stop/start systems have. Improved technologies for cylinder deactivation like the Tula skip-fire system have significantly more dynamic control of the system and can eliminate the need for rich operation when re-activating cylinders as well as reduce or eliminate the amount of ambient air that flows through the catalyst during a deceleration fuel cut event by disabling cylinders rather than simply cutting off injected fuel. Reducing or eliminating enrichment for transient operation is consistent with continual improvements manufacturers have been making to the engine management system to more precisely calculate and inject the correct amount of fuel during very dynamic changes in air flow. Such improvements lead to reduced fuel consumption, reduced HC+NOx emissions, and reduced PM emissions.

II.G. PM formation - Oil Control

Oil consumption can lead to organic and inorganic PM emissions. Engine lubrication oil contains metal-based additives such as zinc and sulfur and when oil gets into the combustion chamber during a combustion event, those additives either oxidize into solid particles such as SOx, or the metals turn to ash and are emitted as solid particles in the sub-23 nm size range. Additionally, the long chain and ring hydrocarbons that help keep engine oil viscous at high temperature and reduce its decomposition rate, do not combust completely. Lubrication oil based PM is not a significant source of PM on modern cars because oil control has steadily improved as the LEV programs have implemented emissions standards that require longer catalyst durability.

III. Gasoline Particulate Filters (GPFs)

Post-combustion control in the form of the gasoline particle filter (GPF) is another option available to reduce PM. A GPF can be used to filter and oxidize particles that are emitted from the engine during all modes of operation as shown in Figure 12. Conceptually, a GPF is a wall-flow filter placed in the exhaust stream that traps PM as it exits the engine and can periodically or continuously be cleaned through a process called regeneration.[17] GPFs are similar in concept to their diesel counter parts, diesel particulate filters (DPFs) which have been used predominantly on all new diesel engines since 2007, however there are some differences between a diesel and gasoline application of a particulate filter. Unlike DPFs that require periodic intrusive operation to regenerate the accumulated PM, GPFs tend to continuously regenerate because gasoline exhaust is significantly hotter and normal operation includes enough variance in temperature and oxygen content from events like deceleration fuel cut to promote regeneration of the stored PM.[18] A continuously or near-continuously regenerating PM filter never builds up a soot layer which has the advantage of keeping back pressure to a minimum but the disadvantage of a slightly lower filtration efficiency because the presence of a soot layer actually increases the filter efficiency. Recent advances in filter porosity design have reduced filter backpressure to help avoid any increase in CO_2 emissions that would result from a more restrictive exhaust system.[19,20] Relative to total GHG emissions, any increase in tailpipe CO_2 emissions from the use of a GPF can also be partially offset by an associated further decrease in black carbon, a powerful short lived climate pollutant.[21] The GPF can be manufactured with or without a catalyst washcoat to serve the role of either a dedicated GPF or integrated as part of the three way catalyst system.

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[17] Richter, 2012. Joerg Michael Richter, et. Al. “Application of Catalyzed Gasoline Particulate Filters to GDI Vehicles”. April 2012. http://papers.sae.org/2012-01-1244/

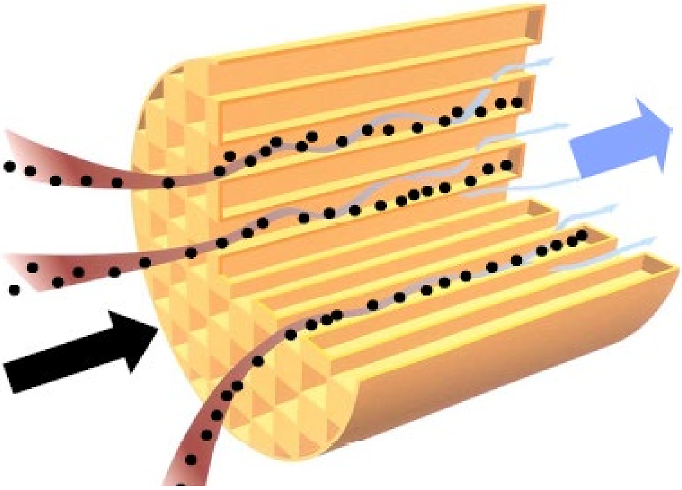
[18] Chan, 2016. Tak W. Chan, et. al. “Characterization of Real-Time Particle Emissions from a Gasoline Direct Injection Vehicle Equipped with a Catalyzed Gasoline Particulate Filter During Filter Regeneration.” Jan 2016, http://link.springer.com/article/10.1007/s40825-016-0033-3

[19] Kattouah, 2014. P. Kattouah, et.al. “Advanced Gasoline Particulate Filter for Effective Gasoline Emission Control Beyond Euro 6”. May, 2014. https://www.researchgate.net/publication/267335874_Advanced_Gasoline_Particulate_Filter_for_Effective_Gasoline_Emission_Control_Beyond_Euro_6

[20] Kattouah, 2013. P. Kattouah, et. al. “Ceramic Wall Flow Filter for Particulate Emission Reduction of Petrol Engines”. May 2013. http://www.cambridgeparticlemeeting.org/sites/default/files/Presentations/2013/PKattouah(NGK)_2013_Wall%20flow%20filter%20for%20particulate%20emission%20reduction%20of%20petrol%20engines.pdf

[21] Chan, 2014. Tak W. Chan, et. al. “Black Carbon Emissions in Gasoline Exhaust and a Reduction Alternative with a Gasoline Particulate Filter”. April 2014. http://pubs.acs.org/doi/abs/10.1021/es501791b

Figure 12 - Wall flow GPF[22]



While only a subset of one production vehicle built for the European market currently is equipped with a GPF, the upcoming European particle number standards may result in increased usage of GPFs on GDI vehicles and several manufacturers have announced their intent to equip some of their vehicles with GPFs for the European market. However, it is not yet clear if GPFs will be used as a long term control technology or if they will primarily be used as a bridge technology until manufacturers can sufficiently refine in-cylinder control strategies during scheduled engine redesigns. While not yet in mass production, GPF technology is rapidly evolving and will be a viable technology for manufacturers to use in the near future. Additional work is still needed to ready the technology for wide-scale deployment, especially for California or the U.S. markets where durability and onboard diagnostic (OBD) requirements are more rigorous than in other global markets but staff expects these hurdles can and will be met in upcoming years. GPFs do represent added cost to a manufacturer and based on today's knowledge and meetings with GPF manufacturers, staff estimates the costs to equip a vehicle with a GPF system meeting US requirements to likely to have a direct manufacturing cost between $70 and $100[23] for a catalyzed GPF (which, with mark-up to retail price, would be approximately an $84 to $150 increase in the price of the vehicle to the consumer). However, given the early state of development for GPFs and the history of catalyst suppliers (who are also the primary GPF suppliers), staff expects continued improvements in design, materials, and manufacturing as well as cost reductions as a result of high volume production would likely lead to even lower costs by the time GPFs are ready for wide-scale deployment.

III.A. Durability

During the useful life of a vehicle, the GPF porosity decreases due to ash loading with the result being increased filtration efficiency. While this directionally reduces PM emissions by increasing

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[22] Kattouah, 2013 a

[23] Posada, 2016. Francisco Posada, PhD. "Estimated Costs of Emission Control Technologies for Gasoline and Diesel Vehicles". July 2016.

the filter efficiency, it can also increase backpressure which could adversely affect tailpipe CO2 emissions. Mechanical failure due to high temperature exposure is likely the primary failure mode[24] that could result in increased PM emissions. Such failures could allow engine out PM to go unfiltered and the impact would depend on the degree of failure and engine out PM emission rate. A robust OBD system would be needed to ensure timely detection and repair of such failures and would likely require added sensors to effectively determine the proper function of the GPF.

IV. Fuel Effect on PM Emissions

Gasoline is a complex mixture of hundreds of hydrocarbons with molecular carbon numbers ranging from C4 to C15. Depending on the sources of the crude oil, refining processes, and blending practices, the profiles of chemical compounds in the gasoline can vary widely. For decades, U.S. EPA and ARB have regulated many gasoline bulk properties, such as Reid Vapor Pressure (RVP), distillation temperature (T50 and T90), and benzene, olefins, aromatics, oxygenates, and sulfur content, in order to reduce harmful air pollutants from vehicle exhaust.

Many studies have shown that gasoline fuel's physical and chemical properties, such as T50, T90, ethanol content, and aromatic contents, play an important role in vehicle PM emissions. Incomplete combustion leads to vehicle PM emissions. Gasoline components with low vapor pressures require more time to evaporate than high vapor pressure compounds. One study has demonstrated that a substantial reduction in PM emissions could be achieved by eliminating fuel components with lower vapor pressures, specifically any hydrocarbon with a carbon number of 10 to 12.[25] In addition, gasoline aromatic components can have a strong impact on the PM emissions due to their stable conjugated double bond structures that are relative difficult to combust completely.[26] A test that evaluated an increased content of higher carbon number aromatics in various test cycle from a lean-burn 2003 MY GDI vehicle concluded that the aromatic fuel content had greater impact on PM emissions than distillation characteristics.[27] Several studies have shown the impact on PM emissions of ethanol content in the fuel varies depending on the vehicle hardware especially the type of fuel injection system. Vehicles equipped with GDI systems were more likely to have a PM emission reduction as ethanol

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[24] Lambert, 2016. Christine K. Lambert, et. Al. "Analysis of High Mileage Gasoline Exhaust Particle Filters". April 2016, http://papers.sae.org/2016-01-0941/

[25] Khalek, 2010. Khaleh I. A., Bougher, T. and Jetter, J. J., "Particle Emission from a 2009 Gasoline Direct Injection Engine Using Different Commercially Available Fuels," SAE Technical Paper 2010-01-2117. 2010, doi: 10.4271/2010-01-2117.

[26] Aikawa 2010, Aikawa, K., Sakurai, T., and Jetter, J. J., "Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions," SAE Technical Paper 2010-01- 2115, 2010, doi: 10.4271/2010-01-2115.

[27] Lizuka, M., Kirii, A., Takeda, H., Watanabe, H., "Effect of Fuel Properties on Particulate Matter Emissions from a Direct Injection Gasoline Vehicle," *JSAE Review*, 28(3).

content increased, while vehicles with PFI systems tended to increase or showed no effects on PM emissions.[28,29,30,31,32]

For both California and U.S. EPA standards, vehicle certification is conducted using official certification fuel while operating on a specific test driving cycle. The California LEV III certification fuel (LEV III cert. fuel) specifications are based on average commercially available fuel sold in California, including 10v% ethanol. The specifications of both the LEV III and previous LEV II certification fuels and the federal Tier 3 certification fuel are shown in Table 1 and Table 2. Use of Tier 3 certification gasoline is also allowed as an alternative to California certification gasoline for both LEVII and LEV III passenger cars, light-duty trucks, and medium-duty vehicles.

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[28] Butler 2015, Butler A.,Sobotowski, R. A., Hoffman, G. J., and Machiele, P., “Influence of Fuel PM index and Ethanol content on Particulate Emissions from Light-duty Gasoline vehicles,” SAE Technical Paper 2015-01-1072, 2015, doi: 10.4271/2015-01-1072.

[29] Maricq 2012, Maricq, M. M., Szente, J. J., and Jahr, K., “The Impact of Ethanol Blends on PM Emissions from a Light-Duty GDI Vehicle,” Aerosol Science and Technology, 46, 576-583, 2012, doi: 10.1080/02786826.2011.648780.

[30] Chen 2010, Chen, L., Braisher, M., Crossley, A., Stone, R. et al., "The Influence of Ethanol Blends on Particulate Matter Emissions from Gasoline Direct Injection Engines," SAE Technical Paper 2010-01-0793, 2010, doi: 10.4271/2010-01-0793

[31] Vuk 2013, Vuk, C. and Vander Griend, S., “Fuel Property Effects on Particulates in Spark Ignition Engines,” SAE Technical Paper 2013-01-1124, 2013, doi: 10.4271/2013-01-1124.

[32] Storey 2012, Storey, J., Barone, T., Thomas, J., and Huff, S., “Exhaust Particle Characterization for Lean and Stoichiometric DI Vehicles Operating on Ethanol-Gasoline Blends,” SAE Technical Paper 2012-01-0437, 2012, doi: 10.4271/2012/01-0437.

Table 1 - California Certification Gasoline Specifications for LEV II and LEV III Light-Duty Vehicles and Medium-Duty Vehicles

	CA Cert. Gasoline Specifications for LEVII	**CA Cert. Gasoline Specifications for LEVIII**
Fuel Property	**Limit**	**Limit**
Octane (R+M)/2	91 (min)	87-88.4; 91 (min)
Sensitivity	7.5 (min)	7.5 (min)
Lead	0-0.01 g/gal (max); no lead added	0-0.01 g/gal (max); no lead added
Distillation Range:		
10% point	130-150 °F	130-150 °F
50% point	200-210 °F	205-215 °F
90% point	290-300 °F	310-320 °F
EP, maximum	390 °F	390 °F
Residue	2.0 vol.%	2.0 vol.%
Sulfur	30-40 ppm by wt.	8-11 ppm by wt.
Phosphorous	0.005 g/gal (max)	0.005 g/gal (max)
RVP	6.7-7.0 psi	6.9-7.2 psi
Olefines	4.0-6.0 vol. %	4.0-6.0 vol. %
Total aromatic Hydrocarbons	22-25 vol.%	19.5-22.5 vol.%
Benzene	0.8-1.0 vol.%	0.6-0.8 vol.%
Fuel Property	**Limit**	**Limit**
Multi-substituted Alkyl Aromatic Hydrocarbons	12-14 vol.%	13-15 vol.%
Oxygenate	10.8-11.2 vol.% (MTBE)	9.8-10.2 vol.% (Ethanol)
Additives	Sufficient	Sufficient
Copper Corrosion	No. 1	No. 1
Gum, washed	3.0 mg/100mL (max)	3.0 mg/100mL (max)
Oxidation Stability	1000 minutes (min)	1000 minutes (min)
Specific Gravity	Report	Report
Heat of combustion	Report	Report
Carbon	Report wt.%	Report wt.%
Hydrogen	Report wt.%	Report wt.%

Table 2 - Federal Gasoline Emission Test Fuel Specifications

Fuel Property	**Units**	**Specifications**		
		General Testing	**Low-Temperature Testing**	**High altitude Testing**
Antiknock Index (R+M)/2	-	87.0-88.4		87.0 minimum
Sensitivity (R-M)	-	7.5 minimum		
Dry Vapor Pressure Equivalent (DVPE)	kPa (psi)	60.0-63.4 (8.7-9.2)	77.2-81.4 (11.2-11.8)	52.2-55.2 (7.6-8.0)
Distillation 10% evaporated	°C (°F)	49-60 (120-140)	43-54 (110-130)	49-60 (120-140)
50% evaporated	°C (°F)	88-99 (190-210)		
90% evaporated	°C (°F)	157-168 (315-335)		
Evaporated final boiling point	°C (°F)	193-216 (380-420)		
Residue	milliliter	2.0 maximum		
Total aromatic Hydrocarbons	volume%	21.0-25.0		
C6 Aromatics (benzene)	volume %	0.5-0.7		
C7 Aromatics (toluene)	volume %	5.2-6.4		
C8 Aromatics	volume %	5.2-6.4		
C9 Aromatics	volume %	5.2-6.4		
C10+ Aromatics	volume %	4.4-5.6		
Olefins	mass %	4.0-10.0		
Ethanol Blended	volume %	9.6-10.0		
Ethanol confirmatory	volume %	9.4-10.2		
Total Content of Oxygenates Other Than Ethanol	volume %	0.1 maximum		
sulfur	mg/kg	8.0-11.0		
Lead	g/liter	0.0026 maximum		
Phosphorus	g/liter	0.0013 maximum		
Copper Corrosion	-	No.1 maximum		
Solvent-Washed Gum content	mg/100mL	3.0 maximum		
Oxidation Stability	minute(min)	1000 minimum		

IV.A. PM Index- PMI

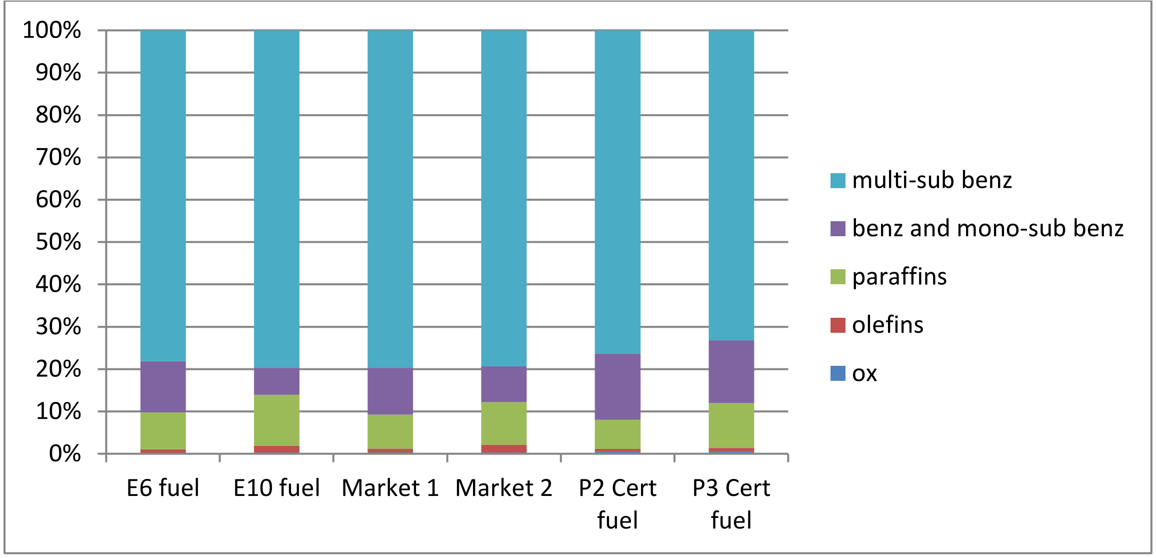
Researchers from Honda R&D have proposed a predictive model, termed PM index (PMI), to quantify the relationship between gasoline properties and PM emissions based on fuel composition (Aikawa, 2010). PMI is defined as follows:

$$PM\ Index = \sum_{i=1}^{n} \left(\frac{DBE_i + 1}{V.P(443K)_i} \times Wt_i \right)$$

Whereas DBE_i is the double bond equivalent, based on the total numbers of hydrogen, carbon, nitrogen, and oxygen atoms in the gasoline component "*i*"; $V.P\ (443K)_i$ is the vapor pressure of component (*i*), at 443 K; and Wt_i is the weight percentage of the component "*i*".

The double bond equivalent and vapor pressure reflects individual component's chemical and physical properties which is related to PM forming potential; and the weight percentage reflects that the component's concentration is proportional to the effect on PM emissions. Gasoline fuel consists of at least 300 components and the PMI sums each component's contributing value. With the structure of the model, the greater the resulting sum, the more PM the fuel would be expected to cause a vehicle to emit. The PMI suggests that low-volatility aromatics in gasoline are responsible for a large share of PM emissions. ARB used six different fuels to assess PMI values and the results show that the aromatic components contribute to approximately 90% of the PMI value as shown in Figure 13. Within the aromatics components, naphthalenes in particular, which are high in DBE value (7) and low in vapor pressure, contribute ~15% to the total PMI and yet only represent ~0.5 v% of gasoline fuel. On the other hand, paraffins make up greater than 60 v% of gasoline fuel, but contribute only ~7% to total PMI. The contribution from oxygenates and olefins is insignificant to the PMI value.

Figure 13 - Chemical group contribution to PMI value from different fuels.



Note: Fuels include E6, E10 vehicle testing fuels, two commercially available fuels (Market 1 and 2), LEV II, and LEV III California certification fuels.

Several, but not all, studies have reported a strong correlation between PMI and vehicle emissions. Typically, this was done by using a laboratory modified test fuel where individual or specific groups of hydrocarbons are added to the base fuel to investigate the emission impacts associated with the specific fuel parameters or to vary PMI values[33,34] (Aikawa, 2010; Butler, 2015). The correlation studies between PMI and vehicle emissions are summarized chronologically in Table 3.

Table 3 - Studies showing correlation between PM emissions and PMI values

	PMI range	Vehicles	Fuel injection system	correlation
Aikawa et al., 2010	~0.9-2.3 (3 commercial fuels)	2009 MY	2 L turbocharged wall-guided GDI, equipped with TWC	R^2 = 0.9826 (PM vs. PMI)
Aikawa et al., 2010	~1.0-4.0 (special blends)	Engine	2.4 L PFI naturally aspirated.	R^2 = 0.9774 (Soot vs. PMI)
ARB, 2012	1.44-1.58 (3 commercial fuels)	2010 MY	Wall-guided GDI	No clear correlation
Karavalakis et al., 2015	1.10-1.87	2012 MY	5 GDIs and 2PFIs	R^2:0.80-0.96, except for one PFI no sensitivity
Sobotowski et al., 2015	0.9-2.7 (special blends)	4 vehicles (2007-2009 MYs)	3 PFI and 1 GDI	2 PFI and the GDI showed high sensitivity to PMI
Butler et al., 2015	0.85-2.10 (special blends)	15 vehicles (2008 MY)	PFI	5 of the 15 showed little or no sensitivity to PMI

Very high correlation was demonstrated by Aikawa et al., for a single GDI vehicle and a naturally aspirated engine. U.S. EPA conducted a comprehensive evaluation which was performed for the EPAct/V2/E-89 gasoline fuel effects program[35] (Sobotowski 2015; Butler 2015). Emission data were collected for a fleet of 15 high-sales cars and light trucks with PFI systems from the MY2008 using 27 test fuels over the LA92 or Unified Cycle Driving Schedule. The study found a significant interaction between ethanol and fuel components and a wide variation in sensitivity to PMI across the 15 vehicles. Five of the 15 test vehicles showed little or no PM emissions sensitivity to ethanol or PMI, indicating the interaction of fuel properties with vehicle engine technology is important when modeling the effects of fuel properties. Overall, a positive correlation between PMI and PM emissions indicates that low volatility compounds, particularly heavy aromatics, have a strong influence on PM emissions from LD vehicles.

Sixteen California market fuels (12 obtained in the period of 2013 to 2014 and 4 from 2010), along with LEV II and LEV III cert. fuels, were analyzed (by detailed hydrocarbon analysis

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[33] Soborowsk 2015, Soborowski, R. A., Butler, A. D., and Guerra, Z., “A Pilot Study of Fuel Impacts on PM Emissions from Light-Duty Gasoline Vehicles,” SAE Technical Paper 2015-01-9071, doi: 10.4271/2015-01-9071.

[34] Karavalakis 2015, Karavalakis, G., Short, D., Vu, D., Russell, R., Hajbabaei, M., Asa-Awuku, A., and Durbin, T. D., “Evaluating the Effects of aromatics Content in Gasoline on Gasoline and Particulate Matter Emissions from SI-PFI and SIDI Vehicles,” Environmental Science and Technology 49, 7021-7031, 2015, doi: 10.1021/es50611726

[35] EPA, 2013. U.S. Environmental Protection Agency, “Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Analysis of Data from EPAct Phase 3” (EPAct/V2/E89). Document number EPA-420-R-13-002.

conducted by SWRI) and their PMIs were calculated. These fuels' PMI values ranged from 1.2 to 1.7. Emission testing conducted in ARB's laboratory was on a very narrow span of the PMI range, more consistent with what is expected in the range of commercial fuels, and no clear correlation was observed.[36] The lack of correlation could be due to the narrow range of the PMI as well as large vehicle test-to-test variability.

Certification fuel does not specify the exact concentration of individual fuel components; therefore the PMI values of a cert. fuel can also vary. However, ARB's cert. fuel specifications reflect an average of California market fuels. The LEV III cert. fuel used for ARB's evaluation of PM emissions from low GHG engine technology vehicles[37] has a PMI value of 1.41. The potential range for PMI for LEV III cert. fuel is most likely in a narrow span since the formula of the PMI calculation is only based on the fuel composition and the specifications essentially allow a limited range of components.

Data was also received from the U.S. EPA on testing of recent model year vehicles tested on two different fuels. The testing included vehicles with technology that is likely to be found in the future low GHG emission fleet, including a number of GDI vehicles. The test fuels used represented typical certification fuels for Tier 2 fuel (90 octane, 0% ethanol) and Tier 3 fuel (87-88 octane, 10% ethanol) with PMI values of 1.86 and 1.52, respectively, as shown in Table 4.

Table 4 - EPA Cert Fuel PMI

Tier 2 Fuel PMI	Tier 3 Fuel PMI	Percent Change
1.86	1.52	-0.18

According to the PMI, the percent difference shown would predict that the PM emissions from the Tier 3 fuel blend would be 18% lower than the PM emissions on the Tier 2 fuel blend. The PM emission test results shown in Table 5 confirm that advanced low GHG technology vehicles follow the same trend as previous studies found; PM emission projections based on PMI are highly depend on vehicle technology. Not only is the average impact of the vehicles below a 6% increase, rather than the predicted 18% decrease, the individual impact varies widely from a 45% decrease to a 60% increase.

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[36] ARB, 2011. Air Resources Board. "LEV III PM Technical Support Document Appendix P (December 7, 2011)". Development of Particulate Matter Mass Standards for Future Light-Duty Vehicles. http://www.arb.ca.gov/regact/2012/leviiighg2012/leviiighg2012.htm

[37] See Appendix K

Table 5 - EPA PM Test Results for Tier 2 and Tier 3 Fuel

MY	Model	Engine	Tier 2 fuel PM Emissions (mg/mi)	Tire 3 Fuel PM Emissions (mg/mi)	Emissions Rate Percent Change
2014	Ram 1500	3.6L V6 PFI	0.11	0.06	-45%
2016	Acura ILX	2.4L I4 GDI	0.18	0.27	50%
2013	Nissan Altima	2.5L I4 PFI	0.60	0.34	-43%
2016	Honda Civic	1.5L I4 GDI	0.67	0.55	-18%
2015	Ford F150 Eco-Boost	2.7L V6 GDI	3.34	4.12	23%
2013	Chevrolet Malibu	2.4L I4 GDI	2.59	3.06	18%
2016	Chevrolet Malibu	1.5L I4 GDI	2.66	2.63	-1%
2014	Mazda 3	2.0L I4 GDI	1.26	2.02	60%
2016	Chevrolet Silverado 1500	4.3L V6 GDI	1.47	1.59	8%
2015	Volvo S60 T5	2.0L I4 GDI	0.84	0.89	6%

From the studies and testing done to date, staff finds the scientific underpinnings of the PMI model are sound but the effects of vehicle technology on PM emissions can dwarf any impacts from fuel properties especially in the expected range of PMI from actual commercial fuels in California. Currently, most of the PMI data has been generated using PFI and some early GDI engines and primarily using laboratory modified fuel that may not be representative of the types of variation expected in commercial fuel. The correlation between PM emissions and PMI were highly variable according to the most recent U.S. EPA results. The results from early GDI systems also may not be representative of future GDI vehicles as total PM emissions from newer GDI systems are already substantially lower. As discussed in Appendix J, GDI systems are still undergoing significant improvements in avoiding in-cylinder PM formation which may dramatically change any previously observed relationship to fuel properties. Accordingly, staff finds the current PMI model is not a good indicator of the PM tailpipe emissions especially in the range of expected PMI for certification or commercial fuel.

V. Conclusion

To answer the Board's question regarding feasibility of meeting the 1 mg/mi standard from a technology perspective, the new test results and updated technology evaluation support staff's original assessment that the 1 mg/mi standards are technically challenging but achievable by 2025 at very low to no cost. Staff expects this will predominantly be done with in-cylinder control as engine and fuel injections systems are refined over the next engine design cycles. Given the substantial PM reductions down to 1.2 to 1.5 mg/mi already observed in testing (Appendix K) on newer designed engines in anticipation of the 3 mg/mi standard, manufacturers are well on track to understanding and effectively controlling PM emissions on the FTP cycle. With the additional lead time, manufacturers should be able to incorporate the knowledge they gain from in-use operation of these vehicles and improved injection system controls into future engine redesigns. GPFs could also be used to effectively control PM and provide manufacturers additional flexibility especially for particularly challenging engines. While there are additional per vehicle part costs associated with a GPF solution, there may be cases where a manufacturer finds such costs are offset by savings in design, manufacturing, calibration, testing resources, or other trade-offs associated with ensuring good in-cylinder PM control on engine redesigns.

Regarding the Board's question of earlier implementation than 2025 model year for the 1 mg/mi standard, from a technology standpoint, earlier implementation would likely necessitate that GPFs play a larger role. This is because the shorter lead time may not be sufficient to update all engine designs during a normal redesign cycle or to incorporate the newest injection control system components. As noted earlier, this would also result in increased cost to comply with the standards and may result in a temporary solution as manufacturers eventually are able to redesign the engine and eliminate the need for the GPF.

The technology exists to control PM for all driving conditions, but changes to the current standards are needed to ensure manufacturers effectively implement it. Comprehensive PM control technology will ensure Californian's exposure to PM emissions is reduced regardless of where they live or what time of year it is.

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