American Chemistry Council

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Petroleum Additives Panel

Fuel Additives Task Group

A Review of Recent Research Related to High Gasoline Additive Treat Rates

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The American Chemistry Council's (ACC) Fuel Additive Task Group (FATG), a task group of the Petroleum Additives Panel, is comprised of fuel additive manufacturers[1]. Gasoline deposit control additives play a significant role in engine cleanliness and performance. They help to control the formation of deposits in the fuel system e.g., fuel injectors and/or intake valves.

In doing so, they help maintain optimum fuel delivery to minimize exhaust emissions and limit fuel economy degradation.

Summary

Studies published by General Motors in 2021 raised concerns related to the use of gasoline deposit control additives (DCA) in direct-injection gasoline engines [1] [2]. Testing was conducted for four levels of additive treat rates. The parameters of interest were particulate emissions and Stochastic Pre-Ignition (SPI). Increases in particulates were observed at both the lowest and highest deposit control additive treat rates evaluated, and SPI events increased for some high additive treat rates.

This paper reviews other contemporary research to help understand the impact of gasoline deposit control additives on particulate matter (PM) emissions or performance concerns in gasoline direct injection (GDI) engines and help address concerns about higher additive treat rates.

FATG's survey of the existing literature supports that proper application of a gasoline deposit control additive can help avoid deposits which lead to injector fouling and elevated levels of PM emissions. For any regulatory program in which additives are certified, the FATG has always supported requirements based on performance limits, not chemical or treat rate limits. In North America, this would mean no upper limit on treat rates and no unwashed gum limits.

[1] Members of the FATG include Afton Chemical, BASF, Chevron Oronite, Infineum, Innospec, and The Lubrizol Corporation.

Background

In recent years, there has been increased concern about greenhouse gas emissions, primarily CO_2 from the combustion of fossil fuels [3]. There are several options to reduce greenhouse gas emissions from the transportation sector using different available technologies. Electrifying vehicles is one way to reduce CO_2 emissions, which are measured at the tailpipe of a vehicle. A second option is to lower the carbon intensity of fuels used in internal combustion engines. The use of low carbon fuels is not the only way to lower the carbon emissions of the existing vehicle fleet. A third way to minimize CO_2 emissions is to design more efficient internal combustion engines that have improved fuel economy and reduced carbon emissions as a result. In the last several years, OEMs have introduced new gasoline direct injection (GDI) fuel systems, where fuel is delivered directly into the engine, to meet increasingly stringent fuel economy and emission targets and to lower greenhouse gas emissions [4].

The United States Environmental Protection Agency (EPA) has recently proposed rules to lower criteria pollutants – primarily NO_x and particulates from new motor vehicles [5]. The proposed PM limit for 2027 and beyond is 0.5 mg per mile. Limits this low may result in gradual adoption of gasoline particulate filters, and they are bringing more attention to PM emissions in general.

One unintended consequence of GDI is an increased tendency for particulate formation. The potential for particulates and small liquid droplets in the combustion process can lead to Stochastic Pre-Ignition (SPI) – rare but high intensity pre-ignition events that can result in engine hardware failures. This phenomenon is primarily seen in small GDI engines running at low speeds and high loads.

Engine cleanliness plays a significant role in maintaining emissions and fuel economy. TOP TIER™, a consortium of vehicle manufacturers, has established a voluntary program to register gasolines with higher levels of deposit control under the TOP TIER™ trademark [6]. TOP TIER™ fuels are typically treated with detergent at higher concentrations than required by the EPA. The treat rate that passes the required performance testing is often referred to as 1X TOP TIER™, and additives certified with TOP TIER™ can be used up to 3X that treat rate.

Initial investigations of fuel and additive effects

Given the growing concerns with particulates, there was a desire to investigate the effect of fuels and additives on the performance of GDI engines. General Motors (GM) published findings in 2021 of work conducted to understand these effects. They wanted to evaluate the tendency of fuels to form particulates during combustion in a GDI engine. They also wanted to understand if gasoline additives might have any effect of particulates or issues related to them.

One area of investigation was a market survey of fuels and their tendency for particulate formation. There are a couple of commonly used models that look at fuel composition to predict their propensity for particulate formation. [7]. The Particulate Evaluation Index (PEI), developed by GM, focuses on fuel aromatics content to estimate particulate forming tendencies. GM used PEI to assess trends in fuel particulate forming tendencies. Encouragingly, the survey found a general improvement in fuel particulate tendencies over the last five years.

In another study, GM ran engine testing to look at instantaneous PM emissions [1] as a function of DCA treat rate. Three additive classes were evaluated at four treat rates – the EPA minimum, lowest additive concentration (LAC), and 1X, 3X and 5X TOP TIER treat rates. Testing was prompted by a concern that high treat rates might add sufficient heavier materials to the fuel to contribute to particulate emissions. Results showed that unadditized fuels had the higher particulate emissions, supporting the need for DCA to control deposits in GDI engines. Interestingly, there was a tendency for higher particulate generation from fuel treated at the lowest (LAC) and highest (5X TOP TIER™) treat rates in their study, suggesting some optimum level of treat rate within that range.

In a third study, GM [2] evaluated the same additives and treat rates to determine any additive effect on SPI. To allow a significant response, this work was conducted using fuel of high particulate forming tendency (as reflected by the high PMI value of 3.98), and a test oil known to produce a high rate of SPI events. While this allows good discrimination among test cases, it is an artificially severe set of conditions that is likely to generate a higher rate of SPI events than most real-world fuels and lubricants. Results for 5X TOP TIER treat rates, and one of the 3x tests resulted in SPI rates above the upper level of the baseline's confidence interval.

Related research

Several companies have investigated the effect of additives on GDI fuel systems.

A 2022 paper by BASF [8] evaluated the impact of DCA on injection time and particulate number (PN) emissions in a VW EA 111 engine, finding no negative instantaneous impact in European E0 and E10 fuels (compliant with the European fuel standard EN228). Furthermore, no increase in emissions was observed at high DCA dosages [3 or 5 to 7 times TOP TIER™ range, based on the DCA technology used] during the duration of a 48-hour steady state engine test. Figures 1 and 2 below demonstrate the change of injection time (TI) and particulate emissions (Particulate number, PN) with unadditized and additized (at 7X TOP TIER) E0 fuel.

The inset SEM image of the injector tip provide visual evidence of the additive effect.

Figure 1 - base fuel additive dose

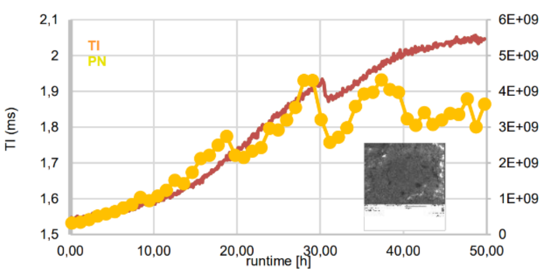
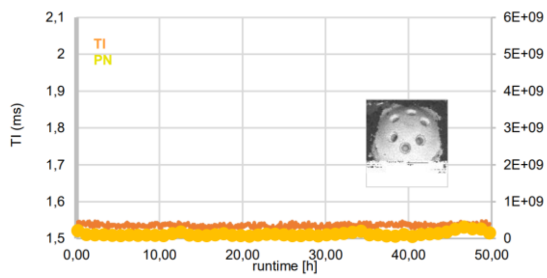


Figure 2 – base plus 7x TOP TIR



Figures 1 and 2 reprinted with author’s permission.

Chevron Oronite and collaborators published a study in 2022 [9], evaluating the impact of several aftermarket fuel additives at 1-tank clean-up concentrations (more than five times TOP TIER™ treat rates) [9]. In each test, PM emissions were recorded. First, the engine was run on base fuel for a 50-hour dirty up period. During dirty up, PM emissions doubled. At hour fifty, additized fuel was substituted and the test continued for an additional 50 hours. The first class of additives, which did not contain a DCA, did not reduce or control PM emissions, and may have contributed to an increase (Fig 1). A second class of additives, formulated with a DCA, reversed the PM trend, resulting in an overall decrease in PM emission of 30% by the end of the test (Fig 2). The final class of additives studied were experimental additive packages developed specifically for GDI engines. Additives in this class sharply reversed the PM trend and resulted in a 65% reduction in PM emissions at test completion (Fig 3). Even at treat rates of more than five times TOP TIER™, none of the formulations that included DCA resulted in a spike in PM emissions, and all the DCA-containing additives resulted in significant PM reductions.

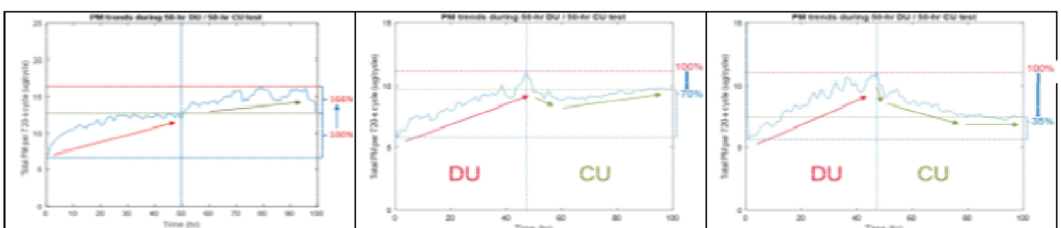


Fig 1: Measured PM emissions trend for an aftermarket fuel additive without deposit control additives.	*Fig 2: Measured PM emissions trend for an aftermarket fuel additive with polymeric PEA deposit control additives (more than 5 times Top Tier treat rates).*	*Fig 3: Measured PM emissions trend for an aftermarket fuel additive with deposit control additive components specifically developed for GDI engines (more than 5 times Top Tier treat rates).*

Figures 1, 2, and 3 reprinted with author’s permission.

A 2022 publication by Shell [10] provides a critical overview of the GM papers. The authors go on to review the literature linking injector cleanliness to particulate matter and emissions and SPI. They also review studies addressing the impact of higher treat rates of additives and the role of DCA's in mitigating PM emissions from injector fouling. In various testing programs from 1997 to 2005, while different DCA chemistry may have differed in the degree of performance observed, all DCAs evaluated were effective to some degree at controlling GDI injector deposits.

The development of PMI models showed that the heavier end of the gasoline boiling range can have a disproportionate effect on particulate emissions, but heavy aromatics are the most deleterious compounds. In joint testing by Shell and Bosch [11], unwashed gum levels of 100 mg/100 ml did not cause PM or PN increases. They attributed this to the nature of the heavy materials in question. Results show that heavy aromatics can cause increases in PM or PN, but heavy paraffins had no impact unless there were alterations in injection timing. A heavy aromatics fuel was used to dirty up injectors and generate particulates. The same fuel was then additized with a high treat rate of DCA and particulate numbers were reduced by 50% due to the cleaning effect of the additive on injector deposits. The testing reported in this paper supports our belief that limits based on unwashed gums don't take the differences in heavy components into account. That is the main reason unwashed gums are not a reliable measure for estimating particulate forming tendencies.

In a study between Shell, IAV, and the Imperial College London [12], particulate generation was tracked in a VW EA211 GDI engine. Four fuels were evaluated, a high aromatics fuel run as a base and with two different DCA levels plus a second lower aromatic fuel without additive. The only fuels that saw an increase in particulates over time were the untreated fuels. Fuel with the highest DCA treat rate was also used to clean deposits from the untreated fuels and resulted in significant reductions in particulates over eight hours of operation.

The Shell paper also describes that higher treat rates of additives were also shown to be beneficial in three other demonstrations – a high mileage Nissan Juke, a Mini Cooper, and a VW engine on a test stand. There was no evidence of increased particulate emission in these evaluations.

Conclusion

Gasoline deposit control additives play a significant role in engine cleanliness and performance. The performance standards in the voluntary TOP TIER^{TM} Detergent Gasoline program result in deposit control additive treat rates that are at least as high - and typically higher - than those needed to meet EPA's Lowest Additive Concentration (LAC) standards. High doses of gasoline performance packages are needed to meet the performance standards of premium branded fuels, particularly in Europe and Asia.

Our review of the literature supports that properly formulated deposit control additives will not cause significant increases in PM emissions or resulting SPI events. In fact, results of the papers reviewed here suggest that the worst case for particulate emissions is injector fouling from fuels without deposit control additives. Chemical and treat rate limits alone are insufficient to determine the impact of deposit control additives on engine performance. The FATG recommends requirements based on performance limits, not chemical or treat rate limits.

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