

Analysis of DPF Incombustible Materials from Volvo Trucks Using DPF-SCR-Urea With API CJ-4 and API CI-4 PLUS Oils

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ABSTRACT

This paper reports on a field test with 23 Volvo D12C non-exhaust gas recirculation diesel engines using the Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR), and urea system with Ultra-Low-Sulfur-Diesel (ULSD). This combination will be used to meet the on-highway emission standards for U.S. 2010, Japan 2010, and Europe 2013.

Because of future widespread use of DPF-SCR, this study reports on our field experience with this system, and focuses on enhancing our understanding of the incombustible materials which are collected in the DPF with API CJ-4 and API CI-4 PLUS oils.

The average weight of incombustibles was lower in the trucks using API CJ-4 oils at 1.0% sulfated ash, than in those using API CI-4 PLUS oils at 1.4% sulfated ash. The difference in weight between the two groups was highly significant. Further, the weight of the incombustibles per kilometer substantially decreased with each subsequent cleaning within a truck.

The gray powder of incombustible materials recovered from the DPF is dominated by inorganic lubricant additives—Ca, Mg, P, S, Zn, and Mo. Calcium sulfate, zinc magnesium phosphate and zinc pyrophosphate were identified. These materials accounted for more than 90% of the materials from the DPF. Wear metals and a small amount of carbon were also identified, and made up the material unaccounted for by the lube oil inorganics.

The particle size distribution of the incombustibles is bimodal, with a large number of particles at 0.4 microns and the remaining at 10 microns. Particles at 0.4 microns present inhalation and irritation health risk, and so exposure to incombustible trap ash should be minimized.

The DPF-SCR system provided excellent durability and reliability during this five year field test. Both API CJ-4 and API CI-4 PLUS oils demonstrated equal wear, viscosity control, and oil drain capability based on used oil analysis.

INTRODUCTION

Diesel engines have demonstrated fuel efficiency, durability and high torque for pulling power, making them the prime power-plant globally for both heavy and light duty trucks, as well as some passenger cars. Unfortunately, the diesel combustion system can produce particulate – small particles which are associated with health issues. It can also produce high levels of nitrogen oxides (NO_x) which result in smog and acid rain pollution of waterways and crops. (1)

Consequently, in Japan, Europe, and North America, there has been demand to reduce diesel emissions for on-highway, off-highway and passenger car vehicles to historic lows by 2010-2013. These step reductions in exhaust emissions focus on particulate, which is composed of soot, sulfate bound with water, and unburned oil and fuel. The NO_x is formed during combustion by oxidation of atmospheric nitrogen at high temperatures in the power-cylinder. (See Figure 1 and Figures A1-A5)

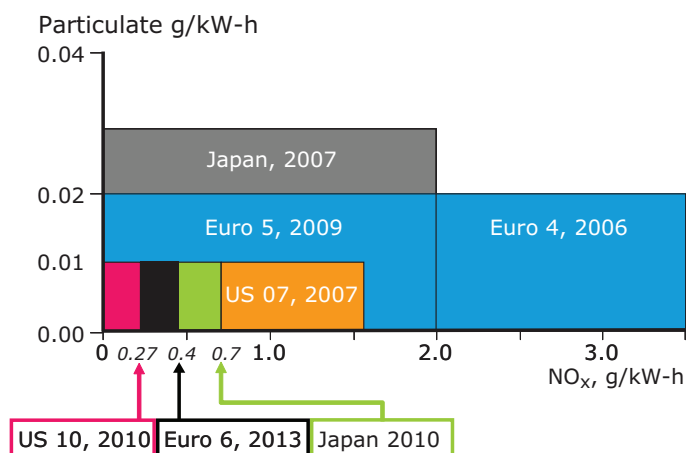


Figure 1. On-highway emission standards for E.U., U.S. and Japan.

Reductions in particulate and NO_x since 1988 have been achieved by a series of improvements to in-cylinder combustion:

- The use of turbo-charging and air-inter-cooling
- Changes in piston bowl design with high top ring positions
- The use of direct injection and very high injection pressures
- The use of retarded fuel injection timing to lower the peak flame combustion temperature, which reduces NO_x formation by displacing the combustion event until later in the expansion stroke
- The use of cooled Exhaust Gas Recirculation (EGR), which is a dilution of the intake charge with an inert gas which reduces peak flame temperature and NO_x formation (2)
- The use of common rail electronically controlled fuel systems which allow multiple fuel injections during the combustion to control in-cylinder temperatures.

Despite these recent improvements in regard to in-cylinder combustion, diesel engines cannot meet the U.S EPA 2007 on-highway, or the 2011 off-highway emission standards without DPFs. (See Figure 2) In addition, the California Air Resources Board voted that all on-highway diesel vehicles registered in the state must employ DPFs by 2014. (3-4)

In order to meet the U.S. 2010, Japan 2010, and Europe 2013 emission standards for on-highway vehicles, the majority of truck manufacturers have selected the DPF-SCR system combined with some use of EGR. In addition, it is expected that the off-highway U.S. EPA 2014 standards may also require this system. (See Figure A-2)

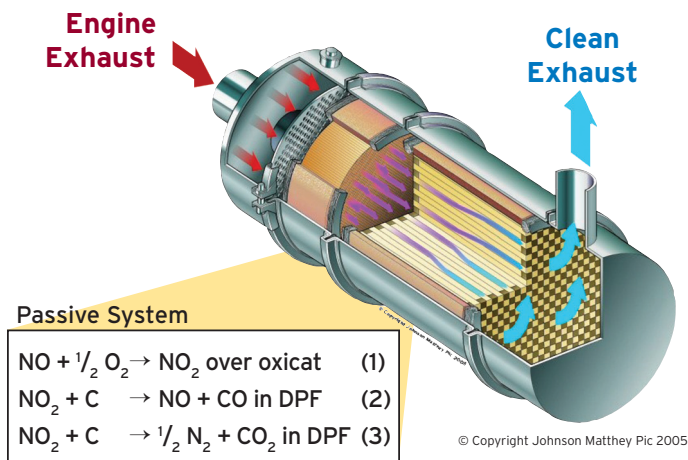


Figure 2. Passive diesel particulate filter (DPF) shown with wall-flow filter substrate.

The DPF-SCR-urea system provides the best approach to meeting emission standards and providing fuel economy. It allows the fuel injection timing to be optimized for best fuel economy while minimizing combustion soot in cylinder, and hence in the DPF. This allows the SCR-urea system to control the NO_x output to meet the emission targets.

The study of the DPF-SCR system which is reported in this paper is the second phase of a U.S. field test which was initiated in 2000 as part of the consent decree settlements between the United States/California's Air Resources Board and Volvo Truck Corporation. The results of the first phase were published in 2005. The total field test was comprised of 23 VN-trucks equipped with non-EGR, D12C engines rated at 465 bhp (350 kW) at 1300 rpm. They operated on ultra-low sulfur diesel fuel (ULSD). (See Figure 3)

The first phase of this study provided an opportunity to measure on-road exhaust emissions. On-road emissions



Figure 3. Twenty-three Volvo VN trucks equipped with DPF-SCR-urea systems.

measurements of each of the 23 trucks were performed with a portable FTIR analyzer which was mounted on the back of a cab and measured NO_x and NH_3 . The road test was an 18-mile (29 km) cycle consisting of 8 miles (13 km) on Interstate 79 and 10 miles (16 km) on smaller roads. This provided a wide range of road inclinations and speeds in a cycle which lasted approximately 25 minutes.

The NO_x emissions for the fleet averaged 0.96 g/bhp-hr (1.29 g/kW-h) or 1.06 g/bhp-hr (1.42 g/kW-h) when including the time the exhaust gas temperature was below 200°C. This meets the 2007 phase in emission level of 1.2 g/bhp-hr (1.61 g/kW-h). The NO_x average conversion efficiency for the fleet was 77% above 200°C. After 2 years in the field the 23 trucks are still providing a very high NO_x conversion of 75%. (5)

No particulate measurements were performed on-road; consequently, a chassis dynamometer test was conducted on a 24th truck equipped and fueled to match the road test vehicles. This was stationed at Volvo Powertrain Corp. and used the ESC cycle in which both particulate and NO_x were recorded. These tests demonstrated particulate levels of 0.008 g/bhp-hr (0.011 g/kW-h), meeting the 2007 and 2010 limits of 0.01 g/bhp (0.134 g/kW-h).

In this first phase of the program, the incombustible materials from DPFs were shared between Volvo and Chevron, and consequently, weight measurement of incombustibles was not documented. However, the incombustibles in the DPFs were characterized for API CI-4 oil at 1.4% ash, as well as an experimental oil meeting ACEA E6 chemical limits at 1.0% ash. Both were SAE 15W-40 oils. (6) (See Table A-1)

In the second phase of the program reported here, all the incombustibles were sent to Chevron, allowing both weight measurement and characterization of the incombustible material from the DPF. Also, two different oils were used – API CI-4 PLUS and API CJ-4 SAE 15W-40.

This paper combines key data from both phases of the field test, which after five years duration is now completed. It provides a more fundamental and comprehensive knowledge of DPF incombustibles.

The paper is organized into the following sections:

- Compact DPF-System in the Volvo Trucks
- Field experience of DPF-SCR and DPF Servicing
- Weight measurements of incombustible materials
- Characterization of incombustible DPF materials
- Used oil analysis of API CJ-4 and API CI-4 PLUS SAE 15W-40 oils.

Because of the projected use of DPFs on all future diesel vehicles in countries controlling emissions, a fundamental knowledge of the incombustible material collecting in the DPF would be valuable. This would help to minimize maintenance cost by extending the DPF cleaning interval, and maximizing fuel economy by reducing the exhaust back pressure as a result of lower ash in the DPF. In addition, understanding the incombustible material is essential for its safe handling and disposal.

REDUCTION OF NO_x AND PARTICULATE THROUGH USE OF THE COMPACT DPF-SCR-UREA SYSTEM

This field test uses a very compact DPF-SCR-urea installation which allows easy removal of the DPF for cleaning, and close installation to the engine for exhaust heat. The DPF-SCR is positioned below the cab, which requires that one of the two fuel tanks be placed on the other side. (See Figure 4)

The DPF traps the particulate matter and the oxidation catalyst oxidizes a portion of the engine's NO exhaust to generate NO_2 . This NO_2 results in thermal combustion of particulate matter at low temperatures in the range of 250-350°C. This is a passive operation with continuous particulate removal.

The exhaust gas first passes through the DPF system which prevents the particulate matter from fouling the SCR catalysts. Urea is injected into the particulate-free exhaust as it leaves the DPF. The exhaust gas is then turned 180 degrees, which allows effective mixing with the urea be-

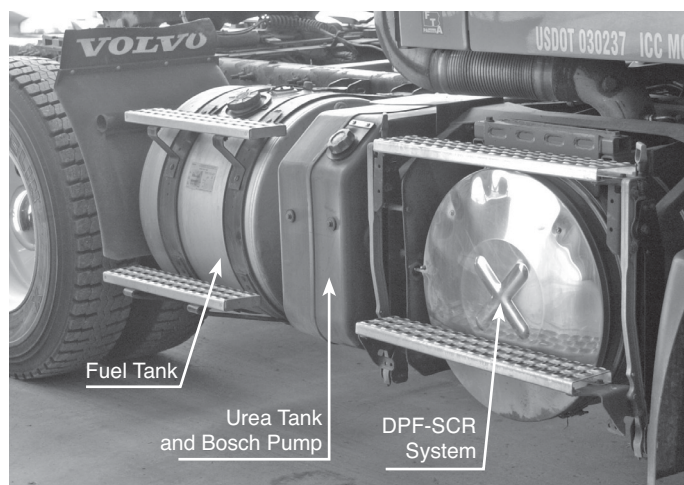


Figure 4. Vehicle installation of DPF-SCR system, urea and fuel tanks – Two tanks with a total of 150 gallons (568 liters) of diesel fuel and a 5 gallon (19 liters) tank of urea.

fore flowing through the SCR catalysts. (See Figure 5) In the U.S. urea is called “Diesel Exhaust Fluid”–DEF, and in Europe urea is called AdBlue™.

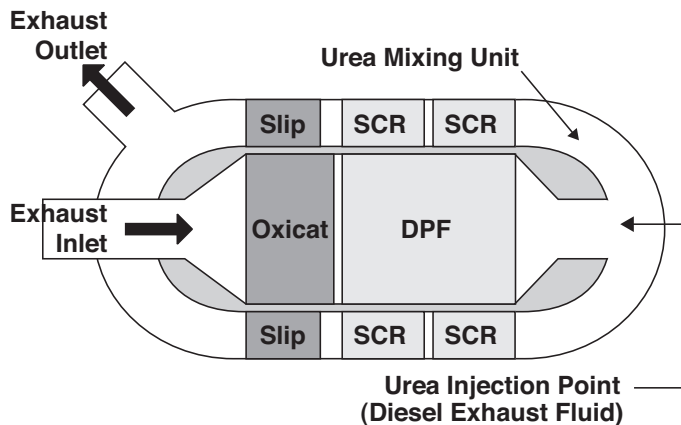


Figure 5. Schematic representation of compact DPF-SCR system. The DPF material was cordierite in this field test.

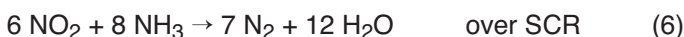
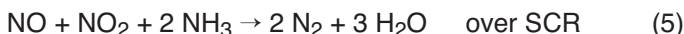
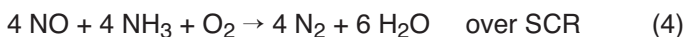
The SCR system reduces the NO_x via reaction with ammonia which is generated on board the vehicle through the rapid hydrolysis of urea. In regard to the possibility of excess urea in the exhaust, it is necessary to match the amount of urea injection to the amount of NO_x to be reduced. (7-8) Also, as an additional safety guard, a clean-up catalyst is installed downstream of the urea-SCR catalysts to prevent possible urea slip. The ratio of urea to diesel fuel was 3.5% in this field test.

The oxidation reactions in DPF-SCR are shown in equations 1-3 and the reduction reactions of SCR-urea are shown in equations 4-6.

DPF System:



Urea SCR System:



The above system is a “Passive Regeneration” in the DPF providing the exhaust temperatures are sufficiently high for combustion of the particulate. In other applied systems commonly used for DPF, fuel is injected into the exhaust system at the outlet of the turbo-charger when the delta pressure across the DPF is too high. This is in engines over 10 liters in which thermal combustion occurs in DPF

at temperatures of 600°C. In passenger car diesels, there is post-injection into the cylinder during the exhaust event. This increases the exhaust temperature to produce “thermal combustion” in DPF. In all cases DPFs are employed to reduce particulate.

FIELD TEST EXPERIENCE WITH DPF-SCR SYSTEM

All 23 trucks operated in the distribution of frozen food throughout the eastern U.S., traveling at night and returning to the same site each morning. This allowed for accurate and consistent servicing of the trucks in regard to ULSD, urea and DPF cleaning.

During the five year field test with the DPF-SCR system, the fleet maintained its normal operations without down time. The urea for the SCR system, supplied by Fleetguard, is diluted with de-mineralized water to a concentration of 32%, and has a freezing point of -11°C (12°F). As a precaution against freezing, it was stored in an indoor location.

This fleet travels as far north as Cleveland where temperatures can reach the freezing point of the urea; however, the urea tank is heated by the engine coolant which prevents freezing during operation. When the engine is turned off, some freezing did occur according to the mechanics, but it is quickly heated into a liquid on engine start-up. In addition, an air purge is used in the urea line during engine shut-downs.

The BP ultra low sulfur diesel fuel was in the range of 4-10 ppm, meeting the 15 ppm maximum fuel limit for 2007 on-highway vehicles. This was used until ULSD became widely available in the U.S. in 2003. Its cetane number was 45. There were no lubricity issues in regard to fuel pump or injector operations. Both the diesel pump and urea pump were located outdoors, close together for easy filling as shown in Figure 6.

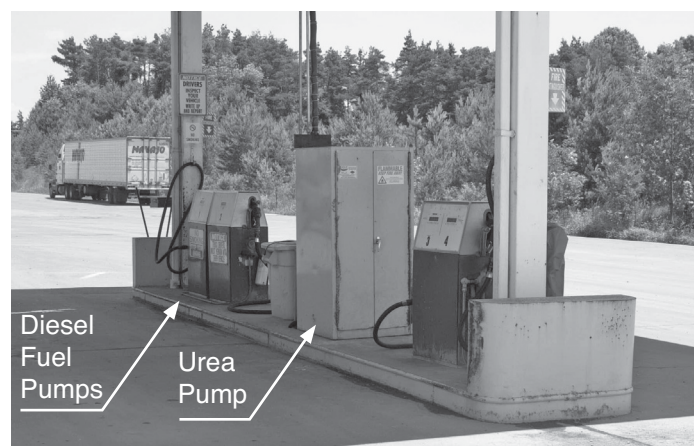


Figure 6. Pumps for diesel fuel and urea at the site.



Figure 7. DPFs waiting to be cleaned in front of the cleaning equipment. The DPF size was 12 inches (30 cm) in diameter by 15 inches (38 cm) long.

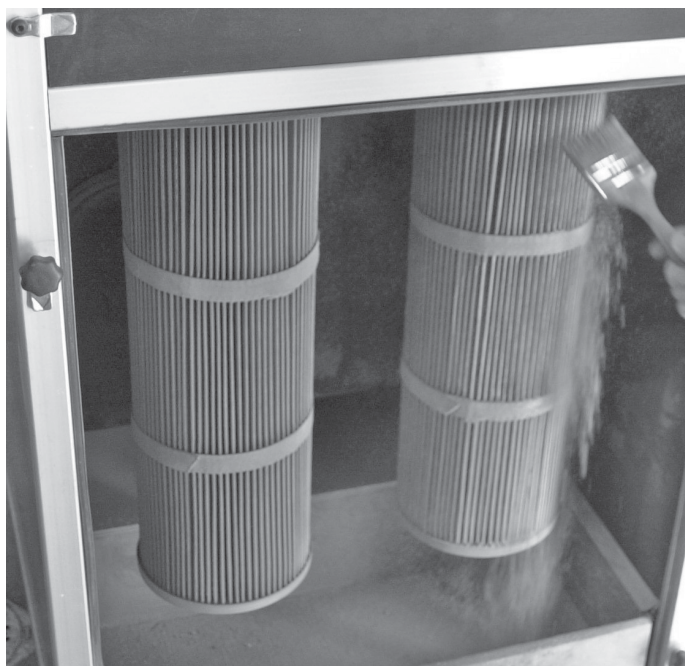


Figure 8. Back of the DPF cleaning machine. Image shows the fine incombustible material being brushed from the filter elements for collection.

DPF SERVICE FOR REMOVAL OF INCOMBUSTIBLE MATERIALS AT FIELD TEST SITE

The DPF-SCR system allows easy removal of the filter, with cleaning and reinstallation taking a total of about one hour. The DPF cleaning machine and the urea storage tank were on site. There was no filter delta pressure measurement to determine the appropriate removal time, so the filters were generally removed at about 160,000 km (100,000 miles). With the filter in position in the cleaning machine, shop compressed air – not-heated – is forced through the DPF, and the incombustibles are collected on two filters in the rear of the machine. (See Figure 7)

With the mechanic using a face mask and goggles, the incombustibles are brushed off the filters and collected in a box on the floor. The gray color of the incombustibles varied according to the level of soot still remaining in the sample. With less than 1.0 wt% carbon the samples were quite white, but if the level was 2-3 wt% the samples were darker. (Figures 8-9)



Figure 9. Typical bags of incombustibles received from test site after each DPF cleaning.

FIELD TEST OILS – API CJ-4 AND API CI-4 PLUS

To meet EPA 2007 particulate emission standards, all diesel engines employ DPFs in the exhaust system. Due to the collection of incombustible material in the DPF, EPA has mandated that for 2007 engines and beyond, the DPF must be capable of working without cleaning for at least 150,000 miles (241,350 km) or 4,500 hours in pick-up and delivery vehicles.

API CJ-4 oil category was introduced in October 2006 to minimize incombustibles in DPF and to increase oil quality level. The API CJ-4 oil category limited the fresh oil's sulfated ash to 1.0% as measured by ASTM D874. Sulfated ash is derived from the oil's detergents, zinc dithiophosphates (ZnDTP) and any metal-containing components, such as molybdenum (Mo) or boron.

In addition, the oil's phosphorus was limited to 0.12 wt% to minimize any possible catalyst deterioration, while providing adequate valve-train wear protection for all legacy diesels. The sulfur is limited to 0.4 wt% to minimize acid formation in after-treatment system, and volatility is limited to 13% to improve oil consumption control. This was the first time that chemical limits were imposed on the fresh oil in any diesel API category. (9) (See Figure 10)

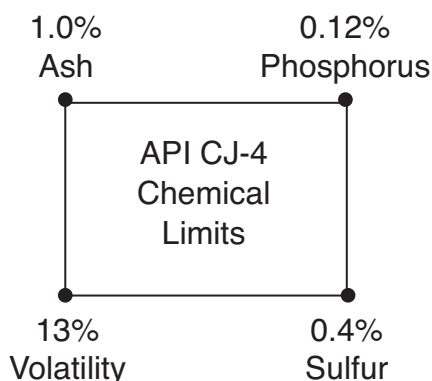


Fig. 10. API CJ-4 chemical limits: ash, phosphorus, sulfur and volatility.

The API CI-4 oil category had been launched in 2002 to provide engine durability for the more severe operating conditions of cooled exhaust gas recirculation (EGR). (10) One year after its introduction, this category was enhanced to improve viscosity control due to soot by the addition of the Mack T-11 test. This revised category, called API-CI-4 PLUS, was launched in 2003. It does not have chemical limits on ash, phosphorus, and sulfur, but limits volatility to 15%.

Each of the above oil categories has different Original Equipment Manufacturers (OEM) approvals. Both oils in this field test passed the 500 hour Caterpillar C13 test for oil consumption control and piston deposits. (9) The API CI-4 PLUS was approved for Caterpillar ECF-2, Volvo VDS-3, MB 228.3 and Cummins CES 20078. The API CJ-4 oil was approved for Caterpillar ECF-3, Volvo VDS-4, MB 228.31 and Cummins CES 20081. These were the two oils field tested, with 18 trucks on API CI-4 PLUS (site oil) and five trucks on API CJ-4.

The API CJ-4 formulation remained constant through this field test. The API CI-4 PLUS at 1.4% ash formulation was initially an all calcium detergent, but it was changed out very early in the field test to an optimized formulation in which the detergent contained mostly calcium, but also a small amount of magnesium. The sulfated ash remained the same at nominally 1.4%.

INCOMBUSTIBLE WEIGHTS FOR API CJ-4 AND API CI-4 PLUS ENGINE OILS

Incombustible materials were recorded for fourteen trucks only. Eleven of these trucks used API CI-4 PLUS oil and the other three used API CJ-4. Of the eleven API CI-4 PLUS trucks, four trucks had incombustible materials removed and weighed twice. One of the API CJ-4 trucks had incombustible materials weighed twice. These were the only samples returned to Chevron from the field which were accurately documented with mileages.

Average rate of incombustibles accumulation for the trucks using API CJ-4, 1.0% ash oil was 1.23 mg per km; and for the trucks filled with API CI-4, 1.4% ash oil it was 2.90 mg per km. The difference between the two groups was highly significant ($p=0.002$)—99% confidence level. (See Figures 11-13, Figures A-6 and A-7)

Incombustible materials per kilometer decreased consistently and substantially within a truck at the latter measurement. (See Figure 11) It is possible that the incombustibles from the DPF are more difficult to remove with repeated cleanings. Johnson Matthey have seen this effect before. The authors believe it is associated with the ash sintering a little and adhering to the walls of the filter channels, making it more difficult to remove.

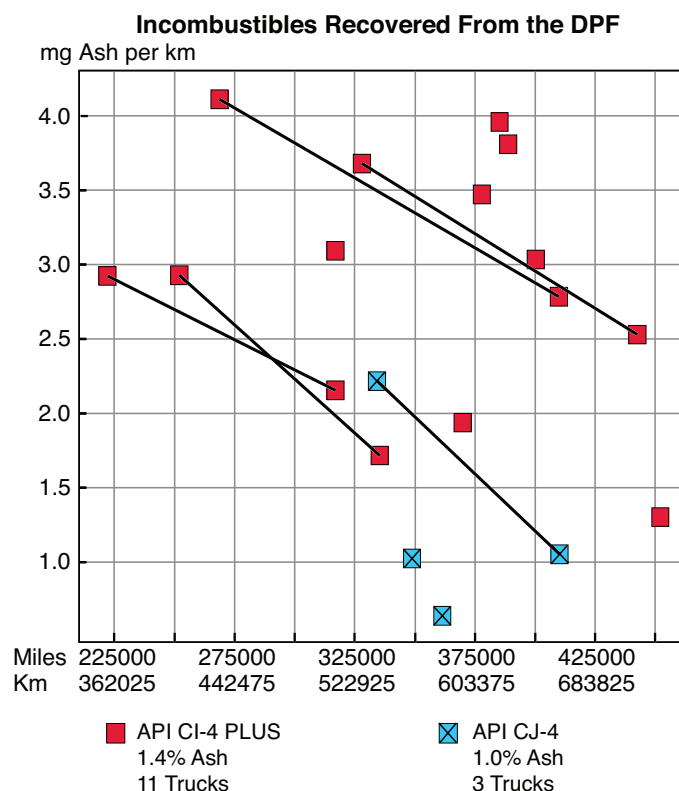


Figure 11. Within a truck, incombustible materials per km decreases with increasing mileage at DPF cleaning. The lines that are connected, represent the same truck. (See Figure A-6 for mg per mile.)