



## The Influences of Diesel Particulate Filter Installation on Air Pollutant Emissions for Used Vehicles

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### ABSTRACT

Three kinds of diesel particulate filters (DPFs) were installed on used diesel-powered vehicles to investigate their influences on air pollutant emissions. The air pollutant emissions were measured before, after and running for specific distances to assess the deterioration effect. The emission measurement was performed on a chassis dynamometer. The results show that emissions of smoke, CO and HC are all reduced after DPF installation. After 20000 km driving, the emission concentrations of the above 3 criteria air pollutants do not increase in comparison with that right after installation. When DPFs are installed, the emissions of PAHs (polycyclic aromatic hydrocarbons) are reduced by 85.6–89.4% and 69.0–89.2% for heavy-duty diesel vehicles (HDVs) and light-duty diesel vehicles (LDVs), respectively. After driving 20000 km for HDVs and 2500 km for LDVs, PAH emissions do not increase in comparison with that right after installation, indicating that the DPFs do not deteriorate after driving for the test mileages. The lower molecular weight PAHs predominates in the exhaust both before and after DPF installation. The results also show the reduction rate is higher for higher molecular weight PAHs due to their tendency to adsorb on particulate.

**Keywords:** Diesel vehicle; Smoke; Particulate matter; Diesel particulate filter; PAHs.

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### INTRODUCTION

The diesel-powered vehicles are popular because of their driving benefits including higher power output and greater fuel economy than gasoline-powered vehicles. In addition, diesel-powered vehicles emit lower traditional air pollutants including carbon monoxide (CO), hydrocarbons (HC) and carbon dioxide (CO<sub>2</sub>) than gasoline powered vehicles in term of its impact on air quality (Williams *et al.*, 1989; Schinder, 1992). Unfortunately, specific attention has been devoted to PM (particulate matter) emission from diesel exhaust. PM emitted from diesel vehicles are mainly less than 2.5 µm in diameter, which might traverse deep into lungs and inflict more death damage than that of larger particles

that are arrested in the upper respiratory tract removed by mucociliary action. In addition, air toxics such as polycyclic aromatic hydrocarbons (PAHs) from diesel exhaust have been proved to link with the mutagenic or carcinogenic activity of adverse public health (Dorie *et al.*, 1987; Collier *et al.*, 1995). Traffic vehicles are important sources of PAHs (Mi *et al.*, 2001; Yang *et al.*, 2005; Chien *et al.*, 2009; Shi *et al.*, 2009; Shi *et al.*, 2010). Some PAHs are strong carcinogens and can cause pulmonary inflammation and allergic asthma in human airway cells (Richter, 2000; Hays *et al.*, 2003).

In addition to the improvements of engine technology and fuel quality, diesel particulate filter (DPF) has been used to reduce PM emission from diesel-powered vehicles. The DPF allows diesel exhaust gas pass through the porous walls while at the same time separating particles from the flow. Many studies have shown that DPF can reduce the emissions of PM, HC, CO, NO<sub>x</sub> and PAHs.

The study by Heeb *et al.* (2005) show that THC, PM and PAHs are reduced by 25–49%, 95–96% and 28–91%,

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respectively with DPF. Heeb *et al.* (2007) assessed 2 kinds of DPFs installed on a heavy-duty diesel engine. Their results show THC emissions decreased by about 40% when deploying DPFs. Lev-On *et al.*'s (2002) study show that over 90% PAHs was removed by DPF. It is also observed that CNG (compressed natural gas) fueled vehicles emit the same or higher PAHs than the vehicles equipped with DPFs. The study by Wenger *et al.* (2008) shows DPF can reduce individual PAH emissions by 70–80%.

Previous studies have shown that DPF can effectively reduce most air pollutant emissions. However, the mechanisms of PM removal and regeneration processes differ. The performances of different types of DPFs installed on the vehicles with different driving conditions might vary. In this study, a partial flow DPF was installed on 2 heavy-duty vehicles (HDVs) and 3 different DPFs (1 partial flow and 2 wall-flow) were installed on 3 light duty vehicles (LDVs). The emissions of air pollutants (including gaseous pollutants, smoke and PAHs) were measured before and right after DPF installation. After long term driving, the emissions of the above air pollutants were measured to assess the deterioration effect.

## EXPERIMENTAL SECTION

### *DPFs and Vehicles*

Two HDVs and 3 LDVs were tested in this study. The displacement volume is 10640 cc for the test HDVs and is 6925–7625 cc for the test LDVs. The maximum horse powers are both 350 hp/2200 rpm for HDVs. The accumulated mileages before installation of DPF are 646268 and 86432 km for the HDVs and are 145238, 121885 and 72792 km for the 3 LDVs, respectively. The air pollutant emissions were measured before, right after and running for specific distances to assess the deterioration effect of the DPFs on air pollutant emission. Three kinds of DPFs (1 partial flow and 2 wall-flow) were tested in this study. The 2 HDVs was installed with partial flow DPF. One partial flow DPF and 2 wall-flow DPFs were installed on the 3 LDVs. The 3 DPFs are denoted as car P, Cw and Ew. The regeneration temperatures are 350–475°C, 400–600°C and 350–450°C for P, Cw and Ew, respectively. All the DPFs were spiked with oxidative catalysts (Pt and Pd). The partial flow DPF was installed on car P and the two wall-flow DPFs were installed on car Cw and Ew.

### *Dynamometer and Sampling*

The air pollutant emission measurement was performed on a chassis dynamometer (Mustang, MD-1000-DAC). The precision of driving speed is less than  $\pm 50$  rpm. The test vehicles were driven on the dynamometer following the test driving procedure Taiwan CNS 11644 free acceleration test and CNS 11645 full load test for the measurement of traditional air pollutants. For PAHs sampling, the driving mode is steady-state. The driving load is set at 60% of the maximum of the test engine and run for 10 mins for PAHs sampling.

The sampling probe was put inside the exhaust tail pipe and the gas was then measured for smoke, CO and HC. CO

and HC were measured by EGA-300 gas analyzer (Mastek) and smoke was measured by smoke meter (Zexel, Model DSM20A/307621-1200) following the rule of CNS 9845. The above traditional air pollutants were measured only for HDVs in this study. Particulate PAHs were collected by Pallflex filters. Before taking the samples, the filters were placed in an oven at 450°C for 8 h to burn up any organic compounds that might be present in the filters. The PAH sampling system was equipped with a sampling probe, a cooling device, a glass cartridge, a pump and a flow meter. A PAH sampling system with a tube-type glass fiber filter (cleaned by heating to 450°C) was used to collect particulate matter and particle-phase PAHs. A glass cartridge packed with XAD-16 resin and supported by a polyurethane foam (PUF) plug was used to collect the gas phase PAHs. After each sampling cycle the sampling train was rinsed with n-hexane. Breakthrough tests were conducted by two stages of XAD-16/PUF cartridge. Each stage of cartridge was analyzed individually and compared for the PAH mass collected. Breakthrough tests results showed that there was little PAH mass found in the cartridge of the second stage. After sampling, each PAH-containing sample was Soxhlet extracted with a mixed solvent (n-hexane and dichloromethane, 500 mL/L each) for 24 h. The extract was then concentrated by purging with ultra-pure nitrogen to 2 mL for the cleanup procedure and then reconcentrated to 0.5 mL with ultra-pure nitrogen. One glass cartridge containing polyurethane foam (PUF) plug and XAD-16 resin were used to collect the gaseous PAHs. An electronic cooling device (Model-1090, Universal Analyzers Inc.) with four stainless steel heat exchanger drainers was installed to cool the exhaust gas. The hot exhaust gas can be cooled to 4°C through this device. The samples were collected for approximately 10 min to reach the detection limit of GC/MS but without breakthrough. After each sampling cycle the sampling train was rinsed with n-hexane.

### *PAHs Analysis*

The concentrations of the following 16 USEAP priority PAHs were determined: naphthalene (Nap), acenaphthylene (AcPy), acenaphthene (AcP), fluorene (Flu), phenanthrene (PA), anthracene (Ant), fluoranthene (FL), pyrene (Pyr), cyclopenta[c,d]pyrene (CYC), benz[a]anthracene (BaA), chrysene (CHR), benzo[b]fluoranthene (BbF), benzo[k]-fluoranthene (BkF), benzo[e]pyrene (BeP), benzo[a]-pyrene (BaP), perylene (PER), indeno[1,2,3,-cd]-pyrene (IND), dibenz[a,h]anthracene (DBA), benzo[b]-chrysene (BbC), benzo[ghi]perylene (BghiP) and coronene (COR). A gas chromatography (GC) (Agilent 6890) with a mass selective detector (MSD) (Agilent 5973N) and a computer workstation was used for the PAH analysis. This GC/MS was equipped with an Agilent capillary column (Agilent Ultra 2–50 m  $\times$  0.32 mm  $\times$  0.17  $\mu$ m), an Agilent 7673A automatic sampler, injection volume 1 mL, splitless injection at 310°C, ion source temperature at 310°C, oven, from 50°C to 100°C at 20 °C/min, 100°C–290°C at 3 °C/min, hold at 290°C for 40 min. The masses of primary and secondary ions of PAHs were determined by using the scan

mode for pure PAH standards. Qualification of PAHs was performed by using the selected ion monitoring (SIM) mode. PAH recovery efficiencies were determined by processing a solution containing known PAH concentrations through the same experimental procedure used for the samples. This study showed that the recovery efficiency of PAHs varied between 75% and 94% and averaged 85%. Blank tests for PAHs were accomplished by performing the same procedure as the recovery-efficiency tests without adding the standard solution before extraction. Analyses of field blanks, including filters and PUF/XAD-16 cartridges, found no significant contamination (GC/MS integrated area < detection limit).

The laboratory analysis entailed separate extraction and analysis of the filters and the cartridges, but in summarizing the results the sum of the two is presented in this study. This is due to the fact that the apportionment between the particulate and gas phase PAHs is variable and highly dependent on the exhaust temperature. Therefore, providing data separately for the particulate and gas PAHs is not meaningful.

## RESULTS AND DISCUSSION

### Criteria Air Pollutants

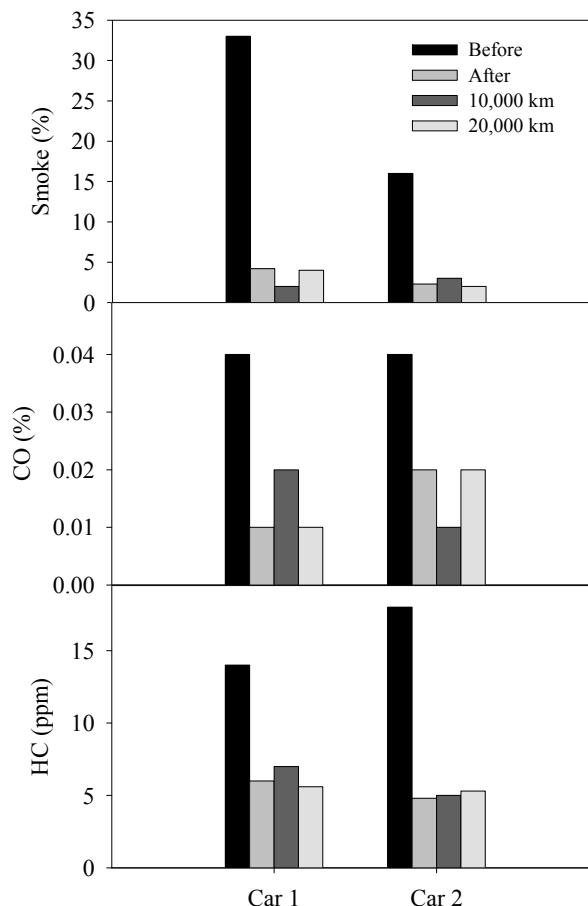
The criteria air pollutant emissions before and after installation of DPF on HDVs are listed in Table 1. The emissions of smoke, CO and HC for car 1 are 33%, 0.04% and 14 ppm, respectively. For car 2, the emissions of smoke, CO and HC are 16%, 0.04% and 18 ppm, respectively. All the emissions of the 3 criteria air pollutants are reduced after the installation of DPF. The reduction efficiencies are 90.3%, 75% and 57.1% for car 1 and 85.6%, 50.0% and 94.4% for car 2, respectively. The DPF is designed mainly to eliminate particulate and the results indicate that PM can be reduced very effectively. DPF can also reduce the emissions of CO and HC. It is explained that the DPFs used in this study are coated with oxidative catalysts which could help reduce the criteria air pollutants. The emissions of the criteria air pollutants after driving for 10000 and 20000 km are shown in Fig. 1. After 20000 km driving, the emission concentrations of smoke, CO and HC are 4.0%, 0.01% and 5.6 ppm for car 1 and are 2.0%, 0.02% and 5.3 ppm for car 2, respectively. The results show that the reduction efficiencies do not decrease after long term driving.

### PAHs

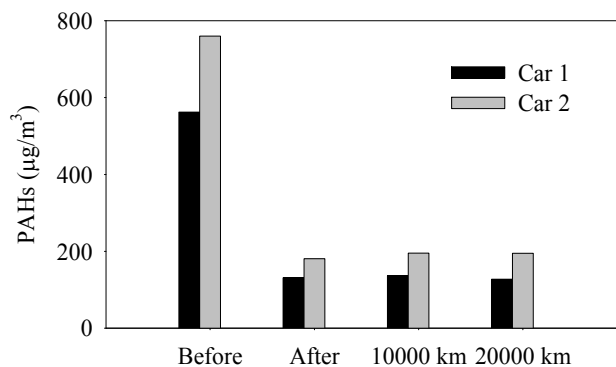
PAH concentrations in the exhaust of the test HDVs before and after DPF installation and driving for 10000 and 20000 km are shown in Fig. 2. PAH concentrations

**Table 1.** Criteria air pollutant emissions before and after DPF installation of HDV.

Car	Car 1		Car 2	
	Before	After	Before	After
Smoke (%)	33	4.2	16	2.3
CO (%)	0.04	0.01	0.04	0.02
HC (ppm)	14	6.0	18	4.8



**Fig. 1.** Emissions of criteria air pollutants for DPF installation of HDV after long term.



**Fig. 2.** PAH emissions before and after DPF installation of HDV.

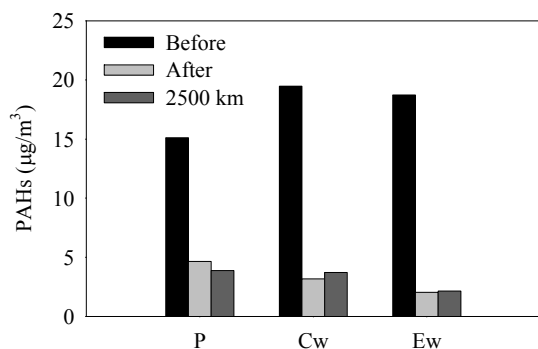
before DPF installation are 562 and 760  $\mu\text{g}/\text{m}^3$  for car 1 and car 2, respectively. When DPFs are installed, the concentrations are significantly reduced to 80.9 and 80.5  $\mu\text{g}/\text{m}^3$  and the reduction efficiencies are 85.6% and 89.4%, respectively. The reduction percentages are similar with smoke. After driving for 10000 and 20000 km, PAH emissions do not change significantly (Fig. 2). For car 1, PAH concentrations are 76.3 and 77.2  $\mu\text{g}/\text{m}^3$  after driving for 10000 and 20000 km and the reduction efficiencies are 86.4% and 86.3%, respectively in comparison with that

before installation. For car 2, the reduction efficiencies are 87.4% and 88.8% after driving for 10000 and 20000 km. The results show that the DPF do not deteriorate after driving for 20000 km.

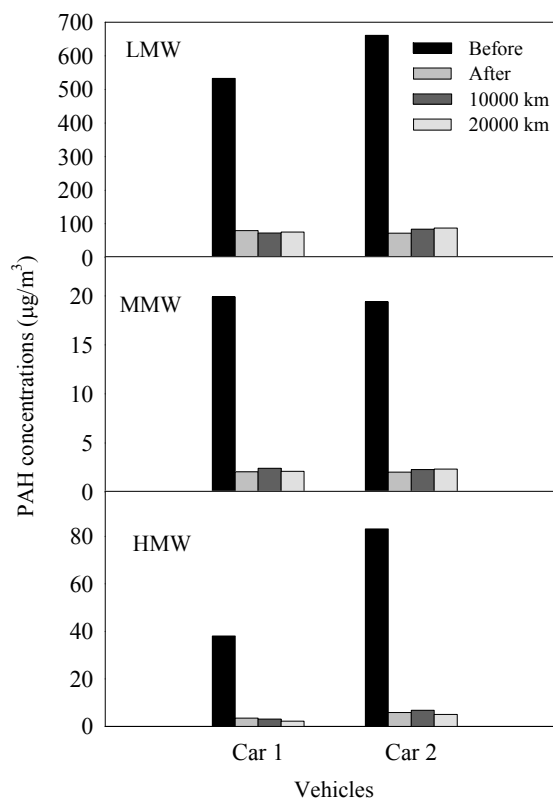
Fig. 3 shows the PAH concentrations in the exhaust of the test LDVs before and right after DPF installation and driving for 2500 km. PAH concentrations before DPF installation are 15.1, 19.5 and 18.7  $\mu\text{g}/\text{m}^3$  for car P, Cw and Ew, respectively. When DPFs are installed, the concentrations are all reduced. The reduction percentages are 69.3%, 83.7% and 89.2%, respectively. The results show that wall-flow DPF has higher removal efficiency than that of partial flow as expected. Heeb *et al.* (2005) measured the PAHs conversion efficiencies of a sintered metal filter with reference diesel additive fuel and found that the DPF reduced PAHs by 28–91%. The study by Wenger *et al.* (2008) investigated the emissions of PAHs of a heavy-duty diesel engine with and without DPF. Their results show that DPF decreases concentrations of individual PAHs by 70–80%. The PAH reduction rates in this study are in agreement with the previous studies. After driving for 2500 km, PAH emissions do not change significantly. PAH concentrations for car P, Cw and Ew are 3.88, 3.72 and 2.14  $\mu\text{g}/\text{m}^3$  (Fig. 3). In comparison with PAH concentrations before installation, the reduction percentages are 74.3%, 80.9% and 88.6%, indicating that the DPF do not deteriorate after driving for 2500 km.

#### PAH Concentrations for Different Molecular Weight

The analyzed 16 PAHs were grouped into low molecular weight (LMW containing 2 and 3 ringed PAHs), middle molecular weight (MMW containing 4 ringed PAHs) and high molecular weight PAHs (HMW containing 5, 6 and 7 ringed PAHs) categories. PAH concentrations in the exhaust of the test HDVs before and after DPF installation and driving for 10000 and 20000 km are shown in Fig. 4. The results show a higher abundance for the LMW PAHs. Two-ring PAHs account for most LMW PAHs. Two-ring PAHs are often the result of unburned aromatic compounds from the fuel (Lev-On *et al.*, 2002). It is clear that the DPF is very effective in removing all the 3 grouped PAHs. The mean reduction rates for the 2 tested HDVs are 87.1%, 89.7% and 91.9% for LMW, MMW and HMW PAHs, respectively. In general, PAHs with higher



**Fig. 3.** PAH emissions before and after DPF installation of LDV.

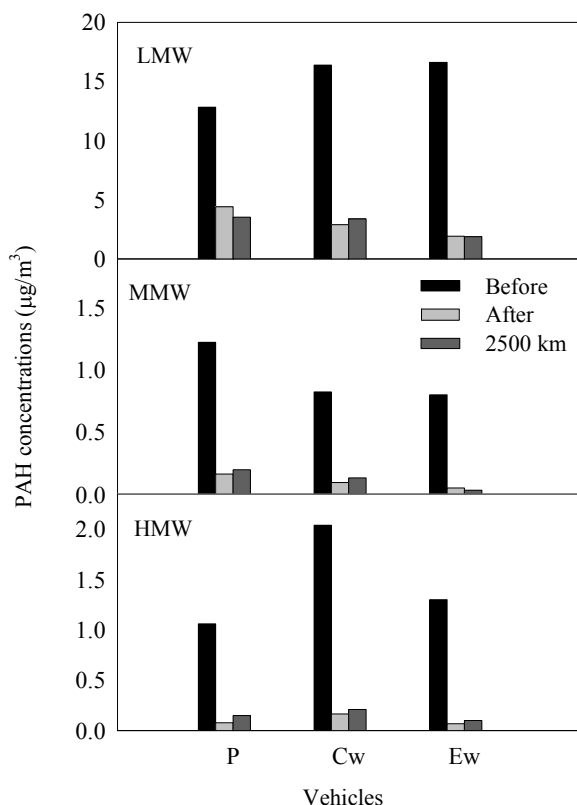


**Fig. 4.** PAH concentrations of different molecular weights for HDVs.

molecular weight tends to adsorb onto particles and they have higher carcinogenic potential. Higher molecular PAHs can be removed by DPFs along with the particles. Thus, the reduction rates are higher for higher molecular PAHs.

PAH concentrations in the exhaust of the test LDVs before and after DPF installation and driving for 2500 km are shown in Fig. 5. The results also show the highest abundance for the LMW PAHs, as expected. The mean reduction rates for the 3 tested HDVs are 77.0%, 87.3% and 92.3% for LMW, MMW and HMW PAHs, respectively. The same as HDVs, higher molecular PAHs have higher reduction rates for their high tendency to adsorb onto particles. The study by Norbert *et al.* (2008) show that 60–90% high ringed-PAHs can be removed by DPF and the reduction rate of lower for PAHs with ring number less than 4. Lev-On *et al.* (2002) evaluated the impacts of passive DPF in several different heavy-duty vehicle fleets. Their results also show that over 90% PAHs are removed by DPF and high ringed-PAHs have higher removing rate. The results of this study are in agreement with the previous studies.

After driving for a period of time, emissions of the grouped PAHs do not change significantly for both HDVs and LDVs. For HDVs, the mean PAHs reduction rates are 86.3%, 88.7% and 94.0% for LMW, MMW and HMW PAHs, respectively when the mileage reaches 20000 km (Fig. 4). For LDVs, the mean PAHs reduction rates are 76.0%, 83.6% and 87.8% for LMW, MMW and HMW PAHs, respectively when the mileage reaches 2500 km (Fig. 5).



**Fig. 5.** PAH concentrations of different molecular weights for LDVs.

## CONCLUSION

Used diesel-powered vehicles were installed with 3 kinds of DPFs to investigate their influences on air pollutant emissions. The deterioration effect was also studied. The results show that emissions of smoke, CO and HC are all reduced after DPF installation. The emission concentrations of the 3 criteria air pollutants do not increase after 20000 km driving. The emissions of PAHs are reduced by 85.6–89.4% and 69.0–89.2% for HDVs and LDVs, respectively after installation of DPFs. Wall-flow DPF has higher PAH removal efficiency than partial flow DPF. After driving specific mileages, PAH emissions do not increase in comparison with that after installation, indicating that the DPFs do not deteriorate after driving for the test mileages. The mean reduction rates for LMW, MMW and HMW PAHs are 87.1%, 89.7% and 91.9% for the 2 tested HDVs and are 77.0%, 87.3% and 92.3% for the 3 tested LDVs, respectively. PAHs with higher molecular weight tend to adsorb onto particles and they have higher carcinogenic potential. Higher molecular PAHs can be removed by DPFs along with the particulates. Thus, the reduction rates are higher for higher molecular PAHs.

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