ISSN 1750-9653, England, UK
International Journal of Management Science
and Engineering Management, 7(1): 36-42, 2012
http://www.ijmsem.org/

Comparison of diesel emission experiments in view of the environment: a case study at Dubai

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(*Received 11 June 2011, Revised 13 November 2011, Accepted 15 January 2012*)

Abstract. Because of the nature of the diesel engine combustion process, such engines produce more toxic emissions, more visible smoke and odour than gasoline engines. This has led to an increasing concern about the possible effects of diesel emissions on the environment and human health. This study examines emissions form two experimental diesel powered vehicles pilot schemes at a Dubai municipality; an inspection and maintenance experiment and a diesel particulate filter experiment. Comparing the two experiments with a baseline vehicle, the results indicate that after the inspection and maintenance experiment, a significant reduction in emissions was achieved in carbon monoxide (300%), nitrogen oxides (500%) and hydrocarbons (88%). The implementation of a diesel particulate filter lead to even better emission reductions but at a higher cost, with hydrocarbon emissions decreasing by 150%, carbon monoxide by 500% and nitrogen oxides by 700%. The results are promising for both experiments for future investigation.

Keywords: diesel, vehicle emissions, inspection and maintenance, diesel particulate filter

1 Introduction

With the increase in the vehicle population since 1972 numbers since 1972 vehicular emissions have also increased leading to a deterioration in the air quality in Dubai. In fact, vehicle emissions account for 75 to 80% of Dubai's air pollution with the remainder coming from the manufacturing industry and power plant from emissions (Raffia, 2007 [14]). Of special concern are diesel powered vehicles that emit a complex mixture of toxic gaseous pollutants and fine particles (Kagawa, 2002 [8]; Kerminen et al., 1997 [9]). Indeed, diesel vehicles are a major source of emitted air pollutants, particularly nitrogen oxides (NO_x), particulate matter (PM), and toxic compounds with volatile organic compounds (VOCs), which are hazardous to both health and the environment and have been investigated experimentally and epidemiologically. Results of the emission of a range of toxic compounds using in-service vehicles tested using urban driving cycles are broadly comparable to those observed in dynamometer and tunnel studies (Nelson et al., 2008 [13]). Where control devices are used there is an attenuation of emissions (Denis and Lindner, 2005 [4]). The carbon monoxide (CO) emission factors were found to agree with those driven from remote sensing and on-board vehicle emission systems in China (Westerdahl et al., 2009 [17]). Light-duty diesel vehicles and heavy-duty gasoline-powered vehicles have been tested and compared in order to provide useful information in evaluating the emissions measurement technology to be used (Streets et al., 2001 [16]). PM composition was found to depend on exhaust gas temperatures: low exhaust gas temperatures produce PM with more adsorbed soluble organics than high exhaust gas temperatures (Kishi et al., 1992 [10]). Studies have shown that toll booth workers, border station workers, vehicle inspectors, and parking attendants have elevated levels of exposure to CO and PM (Apol, 1983 [1]). Studies also have shown it is difficult to differentiate between gas and diesel exhaust, although numerous studies have combined them (IARC, 1989 [7]). In bus repair facilities, the highest exhaust emissions exposure levels were observed when buses were started at peak times of dispatch and return. During peak hours of bus activity there was an elevated level of diesel exhaust emissions which subsided to normal levels 10 to 15 minutes after peak time (Durbin et al., 2002 [5]).

Currently, there are about 71,628 diesel vehicles in Dubai, which causes severe air pollution, with the number of such vehicles increasing at 3% per year (Dubai Statistics Center, 2010 [2]). Factors affecting vehicle emissions include type and age of the vehicle, driving patterns, road conditions, engine lubricant, type of emissions control, and the extent of regular inspection and maintenance. According to the Road and Transportation Authority (RTA) and the Environmental Protection and Safety Section (EPSS), all vehicles must pass a mandatory annual emissions inspection test. This paper focuses on diesel engines from an experimental research point of view. In particular, CO, NO_x, and HC emissions from diesel-driven vehicles using RTA or EPSS standard emissions test procedures are examined. According to the United Arab Emirates (UAE) Ministry of Electricity and Environment, environmental regulations are mainly concerned with emissions of CO, HC and NO_x. The implementation of these regulations is conducted by the RTA. Whilst Dubai may not rank as one of the most polluted cities, research recently carried out by the Gulf News has revealed that Deira, Garhoud, and the International City have high levels of sulfur dioxide (SO_2) and nitrogen

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Published by World Academic Press, World Academic Union

dioxide (NO_2). Karama, Media City, and the Marina also rank high, with some results higher than international standard annual averages (Dubai Statistics Center, 2010 [2]).

This paper addresses these issues by studying the emission performance of new, used and highly polluting diesel vehicles equipped with a diesel particulate filter (DPF). Further, an overview of the current inspection and maintenance (I/M) program focused on testing diesel vehicles and its effect on vehicle emission is provided. The goal is to provide useful information for transportation fleet air quality managers in Dubai to decide whether such I/M programs and DPF systems would be worth pursuing in their respective areas.

2 The effects of toxic emissions on health

Mobile source emissions contribute greatly to air pollution and are the primary cause of air pollution in many urban areas. These emissions also produce several other important air pollutants, such as air toxins and greenhouse gases. Air toxins are pollutants associated with both long-term and short-term health effects in people, including heart problems, asthma symptoms, eye and lung irritation, cancer, and premature death, in addition to environmental effects. Greenhouse gases, such as carbon dioxide (CO_2), trap heat in the earth's atmosphere, contributing to global climate change. According to the United States Environmental Protection Agency (EPA), about 95% of the CO in typical US cities comes from mobile sources (Dubai Statistics Center, 2010 [2]). CO is detrimental to our health as it reduces the delivery of oxygen to our organs and tissues.

Diesel-powered vehicles and engines contribute more than half of all mobile source particulate emissions. Fine particulate matter associated with diesel exhaust is also thought to cause lung cancer. It can cause coughing, chest pains, and shortness of breath. The diseases that are taking such a big toll in Dubai are the same that are present in any other highly developed country. Regardless of the origin or underlying cause, the most common death-inducing illnesses in Dubai are heart disease and cancer (Dubai Statistics Center, 2010 [2]). Nonetheless, air pollution, both indoor and outdoor, is responsible for an estimated 850 deaths a year in the UAE, according to a study commissioned by the UAE Environment Agency. With so many sites under construction and ever-increasing traffic, UAE is likely to face trouble in the future. This may be the reason why around 15% of UAE residents (mostly children) are suffering from asthma (the most common allergy in the country) (Dubai Statistics Center, 2010 [2]). The wind dust surrounding desert landscape adds to the problem, which is why Dubai residents are continuously suffering from particulate matter (PM 10) circulating in the air. Many have accepted that the air pollution of PM 10 in Dubai is a result of its geographical location. But research has shown other possibilities, like the formation of PM 10 directly in the atmosphere. Today, 40 percent of diseases that affect children under the age of five are because of environmental conditions (Dubai Statistics Center, 2010 [2]). Table 1 shows the percentage of deaths due to non- transmissible diseases and the effects of toxic emissions on health, (Dubai Statistics Center, 2010 [2]). According to the newspaper Al Khaleej times May, 4, 2011, the level of indoor air pollution is rising at an alarming level and generating major health problems. Thirteen percent of all age groups in the UAE are prone to asthma.

3 Case study background

The latest statistics issued by the Dubai Municipality (DM) are that vehicles contribute about 53 percent of the air pollution in the emirate of Dubai, with a further 26 percent coming from the energy sector and 21 percent from industry (Corder, 2008 [3]). UAE has the world's highest per capital carbon footprint (Landais, 2008 [11]). Individual footprints can be reduced by shifting from private cars to public transport. Hence, the RTA has launched the Metro and significantly expanded bus routes. According to a Dubai Municipality study (Dubai Municipality, 2010 [12]), diesel vehicle pollution rate is around 19%. A study conducted under the project called On-road vehicle emission measurement using Remote Sensing Devices (RSD) has revealed that vehicle pollution in Dubai compared to American standards is 13% higher (for vehicle using petrol) whereas in Virginia 2.5%, in Michigan 2%, 4.7% in Canada (Corder, 2008 [3]). Five major air pollutants i.e. HC, CO, NO_x, CO_2 and smoke emissions were detected. The scoring system works by allocating a higher percentage based on two variables: the number of vehicles during the testing period, and the emission level of each vehicle. In a joint co-operation between the Dubai Municipality, the RTA and the Dubai police, 43 locations were surveyed. The objective was to collect relevant data to establish a new pollution reduction policy. According to Corder (Corder, 2008 [3]), the main two factors worsening air pollution in Dubai were rapid fast urbanization and increased motorization led by increased economic development. Statistical data has revealed that Dubai's vehicular growth is increasing by an annual rate of approximately 12 percent. The ratio of vehicle to population in Dubai is 541/100,000. However, this is higher than New York (444/100000), London (345/100000), and Singapore (111/100000). Statistics also revealed that the current percentage of vehicles in Dubai over seven years old for both petrol and diesel vehicles are 17 and 24 percent, respectively (Corder, 2008 [3]).

4 Case study application

A total of 120 Mercedes vehicles were tested. The vehicle sample consisted of two types: Mercedes Actors 3332 trucks and Mercedes Benz buses. The test was conducted using 113 vehicles as experiment 1 for the Dubai municipality clean diesel campaign (DMCDC) and the remaining 7 vehicles as experiment 2 for the diesel particulate filter. Fewer vehicles were selected for the latter test due to the higher cost. The emission control standard was Euro III. The technical specifications for both types of vehicles are shown in Table 2. The average running mileage was 300,000 km. These highly polluting vehicles (HPV) were selected by a remote sensing program of the EPSS which is responsible for monitoring air quality and controlling air pollution in Dubai. In 1994, a new air monitoring network was set up to greatly expand this air monitoring capability. From that time on, additional air analyzers were placed to meet the air quality monitoring demand for determining the exposure of the public to air pollution. The air monitoring network sites were chosen to reflect the exposure of the majority of the population to air pollution. Fully automatic air analyzers and data acquisition systems were installed at these sites. Data reception was managed by computer program software called SCANAIR, which performed data validity and consistency checks. The computer system interrogated each site and printed the requested hourly, daily, monthly, and annual reports (Dubai Municipality, 2010 [12]). To qual-

Table 1 Distribution of mortality in Dubai due to non transmissible diseases

NON TRANSMISSIBLE DISEASES	DISTRIBUTION PERCENTAGE	EFFECTS OF TOXIC EMISSIONS ON HEALTH
Cardiovascular diseases	41%	Strong effect
Cancer	21%	Strong effect
Injury	11%	No relation
Endocrine	7%	Low effect
Digestive	5%	Low effect
Mental & Nervous	2%	Medium effect
Respiratory	4%	Strong effect
Genitourinary	9%	No relation

Table 2 Technical specification of tested vehicles

CHARACTERISTICS		SPECIFICATIONS	
		TRUCKS	BUSES
Engine	Type	Mercedes Actors 3332, 12 liter turbo-intercooled, 4 valves per cylinder, V6 direct injection diesel.	Mercedes-Benz 170 hp, 2 Valves per Cylinder (Total of 8 Pieces), common rail direct diesel injection.
	Max. power	@ 1800 rpm	@4200 rpm
	Max. torque	@ 1080 rpm	@1600 rpm

ify as an HPV, the vehicle must exceed the remote sensing critical-point of 400 ppm for HC or 2% for CO or exceed the emission standard of Euro IV (CO 1.5 g/kWh, NO_x 3.50 g/kWh, HC 0.46 g/kWh). The diesel fuel used in these experiments has a sulfur content of 50 ppm (or 0.005 wt%). The lubrication oil used was a 15W-40 grade (HPSD) with 6000 ppm wt sulfur content. It contained a semisynthetic component hence offering highly improved performance in the fields of detergency, lubricity, and reduced exhaust smoke.

Two types of technical experiments were implemented in the Dubai Municipality fleet to test emissions control. These were the inspection and maintenance experiment and the diesel particulate filter experiment. The primary objective of these experiments was to evaluate the performance of each experiment and to select the most appropriate system. The test period was three months. The procedures for the experiments is described below.

4.1 Dubai municipality clean diesel campaign

The Dubai Municipality Clean Diesel Campaign builds on the success of the Environmental Protection and Safety Section's regulatory and non-regulatory efforts to reduce diesel engines emissions. Reducing emissions from diesel engines is one of the most important air quality challenges facing the country. Large amounts of CO, HC, NOX and PM continue to be emitted due to current diesel engines in Dubai. Thus, introducing more rigorous emission standards on these gasses should have the potential to improve both the environment and human health. Reducing and managing diesel vehicles emissions requires the implementation of new control strategies and collaboration between the Authority, and diesel vehicle repairers and operators. Building on the success of the EPSS's regulatory efforts to reduce diesel engines emissions, DM created the Clean Diesel Campaign. This campaign intends to work aggressively to reduce the diesel engine pollution across the city through the implementation of new control strategies and the aggressive involvement of national and local partners. DMCDC participants are committed to reducing diesel emissions and finding innovative ways to protect human health and the environment. To fully address the challenges of reducing diesel emissions, the DMCDC is using the following approach:

- Commitment to the successful implementation of the EPSS air emissions rules or standard emission IV.
- Promoting the reduction of emissions for existing diesel engines through cost-effective and innovative strategies, including the use of cleaner fuels, retrofitting and repairing existing fleets by implementing inspections, and maintaining I/M programs through preventive maintenance.

Vehicles were tested on a chassis dynamometer, housed in a certified laboratory, following the test procedures of the RTA. They were visually examined for safety prior to testing. Highly polluting vehicles were tested again after a tune-up that included a change of parts (lubricant oil, air filter, spark plug, and air cleaner), fuel injection pump calibration, and flushing of the engine to assess the extent of emission reduction. Exhaust samples were taken from a constant volume dilution sampling system, connected to a constant volume sampling system to dilute the exhaust flow rate to 9 m3/min. Exhaust samples, taken at the end of each individual phase, as well as at the end of the entire cycle, of the test, were analyzed for CO, HC, and NO_x by an equipment tester; auto-monitors emission equipment. The tester was used to diagnose smoke emission, full throttle testing for engine adjustment work, graphic correlation of the RPM to turbidity line, and provided graphic and digital documentation of the measurement values.

The background concentration of pollutants was also analyzed and deducted from the test results. Background concentrations were about 2 ppm for CO, 6 ppm for HC (as C), and 0.1 ppm for NO_x. The errors for CO, HC and NO_x were approximately 0.01-0.08%, 0.01-0.17% and 0.02-0.06% respectively. Based on best estimates, the reproducibility of the emission factors results be accurate to within 5 per-

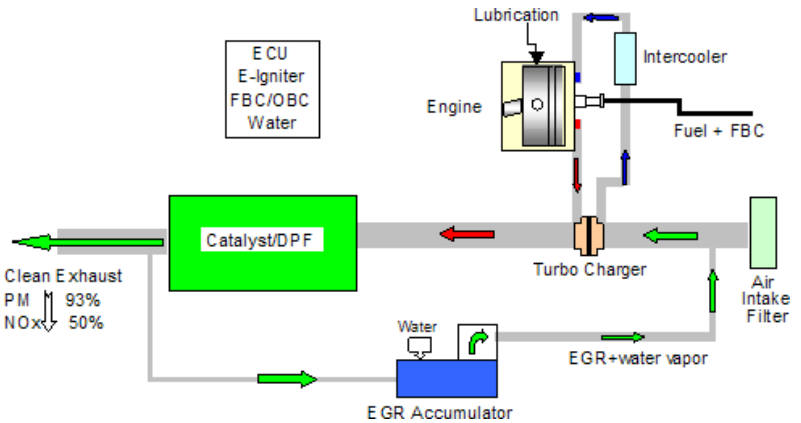

Fig. 1 System schematic of diesel particulate filters DPF (Stephan, 2008 [15])

cent. Current auto inspection and maintenance programs require the testing of motor vehicles with unhealthy emission and the repair of those that do not meet standards. I/M tests use special equipment to measure the pollution in the car's exhaust. These tests check that the car's key emission controls are installed as designed and then analyze the exhaust to check for an acceptable control of carbon monoxide and hydrocarbons. Advanced tests also check nitrogen oxide emissions. If the car exceeds standard emission (Euro IV) limits, it usually passes a retest after minor adjustments, maintenance and repairs.

4.2 Diesel particulate filter

A catalytic converter is an anti-pollution device designed to trap particles in diesel exhaust before they can escape into the atmosphere and is located between a vehicle's engine and tailpipe. Catalytic converters convert exhaust pollutants, such as carbon monoxide and nitrogen oxides, to normal atmospheric gases such as nitrogen, carbon dioxide, and water. A DPF was fixed on only seven highly polluting vehicles because of the high cost. The team modified the existing exhaust area to adjust for the DPF fitting, and a control box was fixed for monitoring and generating the result data. Three months after installation, the technical team generated the data and conducted the analysis.

A diesel particulate filter (DPF) is a device designed to remove diesel particulate matter or soot from the exhaust gas of a diesel engine. The DPF is a ceramic device that collects the particulate matter in the exhaust stream. The high temperature of the exhaust heats the ceramic structure and allows the particles inside to break down (or oxidize) into less harmful components. DPFs reduce emissions of particulate matter by 60 to 90 percent. DPFs also reduce emissions of hydrocarbons and carbon monoxide by 60 to 90 percent (Stephan, 2008 [15]). DPFs for buses currently cost between $5,000 and 10,000$. Diesel particulate filters are used with diesel engines to remove PM also called soot. The process of emptying the filter to maintain performance is known as "regeneration" - the burning-off of the collected particulate on a regular basis. The accumulated soot is burned off at high temperatures to leave only a tiny ash residue. Regeneration may be either passive or active. Normally passive regeneration occurrs automatically during highway-type driving when the exhaust temperature is high. But unfortunately, most vehicles do not get this sort of use. In view of this, manufacturers designed an engine management computer (ECU) to take control of the process of "active" regeneration. The ECU will make small adjustments to the fuel injection to increase the exhaust temperature and kick-off the regeneration when the soot loading in the filter reaches a set limit of approximately 45%. During start/stop type runs where regeneration may not be completed, a warning light is illuminated to indicate that the DPF is partially blocked (Stephan, 2008 [15]).

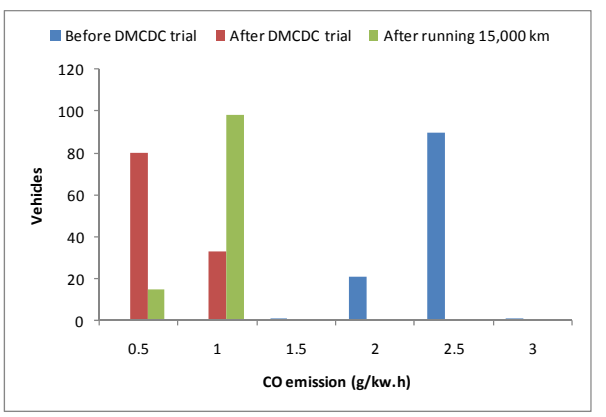

Fig. 2 Comparison result of the CO emission rate

The ECU data logger is a monitoring device for diesel particulate filter systems. The monitoring of the filter is made automatically through the exhaust back pressure. This information is communicated visually via a display module informing the user about the current load status of the diesel particulate filter. Advantages of ECU data logger are permanent monitoring of the exhaust back pressure, reduction of fuel consumption, prevention of overloading of the particulate filter, and reduction of maintenance costs.

This trial was run on DPF-fuel borne catalyst (FBC) system so it could clearly demonstrate the significant emission benefits that can be achieved when using this technology. The primary objective of these trials was to evaluate the performance of the DPFs in DM vehicle applications and to select the most appropriate system based on the exhaust gas temperature profiles of the chosen vehicles. Particulate filters hold back combustible particulates and also residual ash from the combustion of engine oil, which cannot be regenerated. Fig. 1 shows the schematic layout of the DPFs.

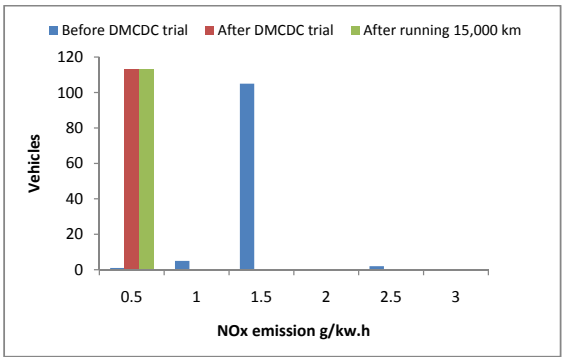

Fig. 3 Comparison result of the NO_x emission rate

5 Results and discussion

The DMCDC experiment showed reduced emission rates. Figs. 2, 3 and 4 illustrate the effect of the DMCDC experiment on the regulated gaseous pollutants from the tested vehicles. All figures also include the vehicle emission standard level (Euro IV) for each pollutant. Fig. **??** shows that CO emission is almost three times below the emission standard (1.5 g/kWh). This can be explained by the DMCDC experiment process effectiveness in reducing high carbon monoxide emissions caused by incomplete fuel combustion due to poor vehicle maintenance such as improper air/fuel mixture, a dirty air filter, a broken air pump or control valve and wear and tear on the fuel pump.

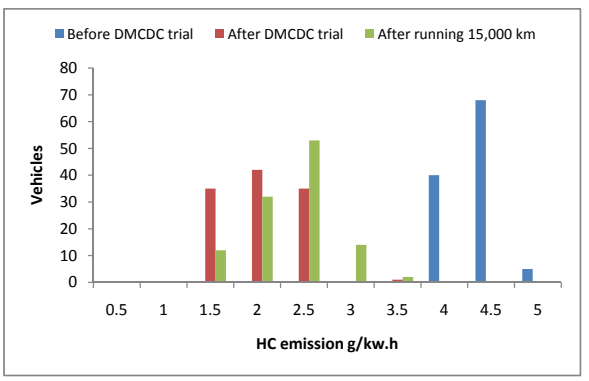

Fig. 4 Comparison result of the HC emission rate

NO_x emissions are shown in Fig. 3. The average reduction of NO_x emissions after the DMCDC experiment is about five times lower in comparison with the baseline vehicle and almost three times below the NO_x emission standard of 0.46 g/kWh. This is due to an improvement in the auto-ignition which makes the ignition delay shorter allowing for maximum in-cylinder pressure and lower temperatures and prohibits the formation of NO_x.

It is believed that through further modification of the injection timing, NO_x emissions can be effectively reduced.

The HC emissions of a sample of 113 HPV vehicles before and after the experiment are shown in Fig. 4. The average reduction in HC emissions after the DMCDC experiment was about 88 percent lesser in comparison with the baseline vehicle and almost 100 percent below the HC emission standard of 3.5 g/kWh. These Lower hydrocarbon emissions may be attributed to the steps taken during the I/M process to repair improper ignition timing, faulty ignition, misfiring problems, vacuum leaks, worn piston rings or valves or an exhaust gas recirculation system incorrectly operating at idle or a fouled spark plug which can result in extremely high hydrocarbon emissions.

The emission rates of the three pollutants (CO, NOx and HC) were also monitored during the scheduled preventive maintenance of the retrofitted vehicles, through the DMCDC experiment, after running 15,000 km. As shown in Figs. 2 ∼ 4, the outcome is still below the target, which means this scheme is recommended for all fleet organizations in order to reduce emissions.

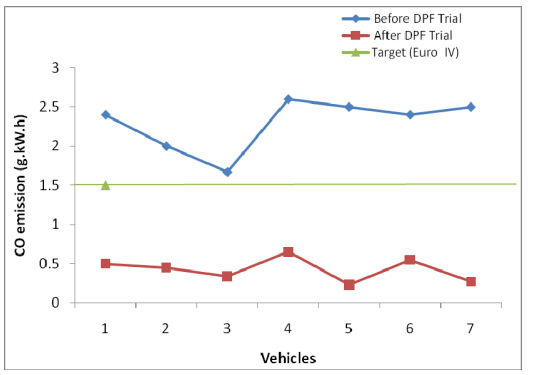

Fig. 5 Comparison result of the CO emission rate

The second technique and technology used in this study to reduce diesel pollution from existing trucks and buses consisted of upgrading (or retrofitting) existing engines with pollution control devices, namely, diesel particulate filters. The significant emission benefits that were achieved are depicted in Figs. 5 ∼ 7. The latter show the comparison between the emission rate before the trial and after the trial, as well as the target. The results after the trial were below the Euro IV target and indicate a good result for the trial. On the other hand, the disadvantage was that the cost of the particulate filter and control box is more than $12,000 a unit. This is not economical for most organizations with a big fleet, such as the DM, which has around 2,000 vehicles.

CO, NO_x and HC emissions are shown in Figs. 5 ∼ 7. The average emission reduction after the DPF experiment was respectively about five, seven and two times, respectively, lower in comparison with the baseline vehicle and almost 37 percent, 45 percent and 55 percent below the emission standards of 1.5 g/kWh, 0.46 g/kWh and 3.5 g/kWh, respectively. The effect of the particulate filter on CO emissions is shown in Fig. 5. The catalyst mixture coated on the surface of the filter carrier served to promote the oxidation of CO into CO_2 as the exhaust gas passed through the porous, solid filter material. Hence, much lower CO emissions were found for the diesel engines installed with a catalyzed particulate filter.

NO_x are considered to be produced primarily from the high temperature reaction of the nitrogen and oxygen components in the reaction zone. This is the so-called extended Zeldovich thermal NO mechanism (Glassman, 1996 [6]). The composition of NO_x emitted from a combustion system consists of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), particularly the former. Fig. 6 reveals that the installation of a catalyzed particulate filter is shown to reduce NO_x emissions. This is due to the effect of higher gas temperatures on NO_x production based on the extended

Zeldovich thermal NO mechanism. Since the installation of a particulate filter results in a slight reduction in gas temperature, lower NO_x emissions were observed for diesel engine mounted with a catalyzed particulate filter in the tail pipe.

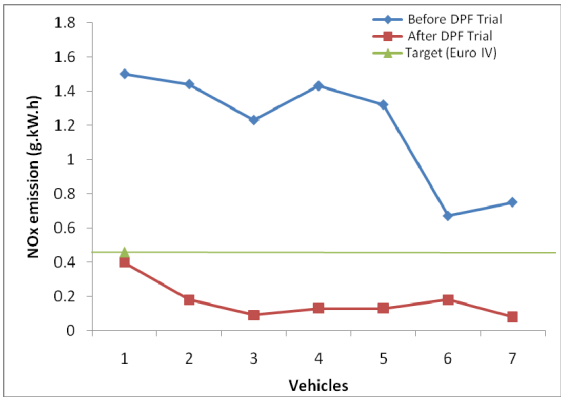

Fig. 6 Comparison result of the NO_x emission rate

Fig. 7 shows the HC emission reduction when DPFs were used to remove HC from the diesel exhaust. In this case, oxidation catalysts convert unburned hydrocarbons to water. Thus, much lower HC emissions were found for the diesel engine installed with a catalyzed particulate filter.

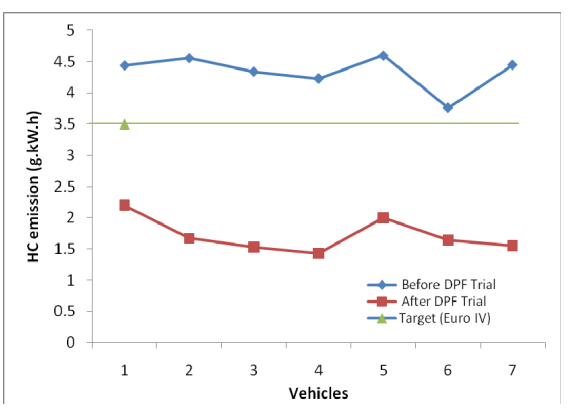

Fig. 7 Comparison result of the HC emission rate

Both emission control technologies showed the potential to reduce diesel vehicle emissions. Compared with the DMCDC experiment, almost the same results were observed for NO_x reduction and a slightly better reduction in CO and HC emissions were achieved for vehicles with DPFs installed (Fig. 8). However, the latter seemed to be more complicated and costly while the DMCDC experiment is simple and can meet the budget of most fleet organizations. Therefore, it is highly recommended that the Dubai RTA create a policy for renewal and registration of diesel vehicles that requires an I/M program card from an approved shop. This will help contribute to a healthier and cleaner environment.

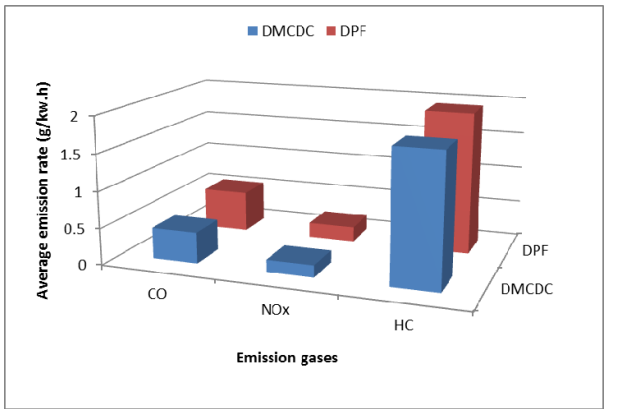

Fig. 8 Comparison of DMCDC and DPF average emission rates

6 Conclusions

Vehicle emissions exponentially increase due to incomplete fuel combustion affecting both human health and environmental quality. There are many environmental-technology experiments that can be tested to reduce the emissions rate from highly polluting vehicles. This study compared the inspection and maintenance experiment and diesel particulate filters. Over the hundred vehicles were tested in this study and data collected on driving engine cycles, engine conditions, maintenance, emissions and cost. The vehicles were measured in two experiments, the I/M and the DPF, with the aim fo covering the complete Euro-based range of emission standards with respect to preventive maintenance. Comparing the two experiments with a baseline vehicle the results indicated that, using the I/M experiment, a significant reduction in emissions was achieved in CO (300 percentage), NO_x (500 percentage) and HC (88 percentage). The implementation of the DPF showed slightly greater reductions at a significantly higher cost with HC emissions decreasing by (150 percentage), CO by (500 percentage), and NO_x emissions by (700 percentage).

After a comparison of the emission control of the two experiments, the preference was given to the I/M. Even though the DPF experiment had slightly better results, it is more complicated and costly whereas the I/M is simple and can meet the budget of most fleet organizations. The results are promising for future investigation. Both experiments show the potential for a diesel I/M and DPF. It is also important to study the dependence of different vehicle/engine types, fuels, ambient temperatures and driving conditions on the emission factors. Further studies can be conducted to reduce emissions and improve the environment for many sectors using fleet transportation in services such as school buses, ports, construction, freight, and agriculture.

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