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Technologies for retrofitting non-road mobile machinery to reduce diesel emissions: a review and recommendation

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ABSTRACT

Non-road mobile machinery (NRMM) in Hong Kong emits considerable emissions and has been a major contributor of environmental regression and harm to the health of citizens. The severe problem caused by considerable NRMM diesel emissions has drawn the attention of the Hong Kong Government. However, the existing measures for reducing NRMM emission mainly target new NRMM while old in-service ones are being left largely unregulated. After a long time of use, in-service NRMM becomes inefficient through deterioration, which results in higher levels of diesel emissions, which are extremely harmful to public health. Transforming in-use dirty NRMM which are exempted from regulations on being greener and more fuel-efficient is an extremely urgent direction for the Hong Kong Government to pursue. Retrofitting in-service high-emitting NRMM can remarkably reduce emissions by using emission reduction technologies, improve the air quality, and achieve notable health benefits for people living or working in or near construction sites. Technologies for reducing emissions from NRMM are crucial for making NRMM greener and cleaner. Thus, this study reviews the technologies widely used for retrofitting NRMM to reduce emissions, to provide some significant insights and recommendations in the case of Hong Kong for initiating retrofit programmes and promote the application of emission reduction technologies.

KEYWORDS Non-road mobile machinery (NRMM); retrofit; diesel emission reduction; costs of emission reduction technologies; benefits; suggestions
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1. Introduction

While diesel engines in non-road mobile machinery (NRMM) provide important advantages of high torque, excellent fuel economy, better safety and superior durability, NRMM produces considerable emissions of particulate matter (PM), nitrogen oxides (NOx), hydrocarbons (HCs), carbon monoxide (CO) and toxic air pollutants (Kubsh, 2017; MECA, 2006; Ning et al., 2020). More than 97% of diesel PM generated by NRMM is PM 2.5 less than 2.5 microns in diameter, which is able to enter the nose and throat, remain in the lungs, and even enter the bloodstream when inhaled. Health experts have suggested that diesel PM could also lead to or aggravate chronic lung diseases such as asthma and emphysema (Garshick et al., 2008). In 2000, the United States Environmental Protection Agency (US EPA) stated that diesel PM is a "likely human carcinogen". In 2005, the Clean Air Task Force reported in *Diesel and Health in America: The Lingering Threat* that annually diesel PM can shorten the lives of about 21,000 people in the United States. NOx and volatile organic compounds (VOCs) combine in the atmosphere to form ground-level ozone in sunlight, which is a respiratory inducement and can lead people with respiratory diseases to suffer from breathing problems (MassDEP, 2008). Obviously, the discharge of diesel emissions from NRMM cause an adverse impact to public health.

Hong Kong is suffering from a severe problem of extensive diesel emissions from NRMM. The *2020 Hong Kong Emission Inventory Report* issued by the Hong Kong Environmental Protection Department (HKEPD) reported that in 2020 NRMM operated in Hong Kong emitted about 8,000 tonnes, 630 tonnes and 590 tonnes of NOx, PM10 and PM2.5 respectively (HKEPD, 2022). Hong Kong is more sensitive to NRMM diesel emissions, because it has a dense population and high-rise buildings as well as considerable construction activities conducted within it. The dense high-rise buildings in Hong Kong prevent these diesel emissions from scattering and dissipating, resulting in a higher diesel emission concentration. It can be predicted that diesel emissions generated by existing NRMM will generate a considerable adverse impact on the health of people who live in Hong Kong. In addition, the issue of the Northern Metropolis Development Strategy (the Development Strategy) by the Hong Kong Government in 2021 will magnify the problem of diesel emissions from NRMM in Hong Kong (HKSAR Government, 2021). The construction of the Northern Metropolis will involve a lot of NRMM, consequently generating and emitting lots of diesel emissions into the atmosphere and resulting in a significant threat to the public health and welfare in Hong Kong.

While the issue of significant diesel emissions from NRMM is severe, efforts devoted by the Hong Kong Government to address this problem are insufficient. The first regulatory measure specially targeted at mitigating diesel emissions from NRMM adopted by the Hong Kong government is promulgating *Pollution Control (Non-road Mobile Machinery) (Emission) Regulation* (HKEPD, 2015). In 2018, some supplements and amendments were made to the second version of this regulation. However, this regulation and its second version exempt NRMM which existed in Hong Kong before 1 December 2015, from compliance with the stringent emission standards in this regulation. It is estimated by the Hong Kong Environmental Protection Department (HKEPD) that in 2015 NRMM numbering nearly 14,200 operated in Hong Kong (HKEPD, 2015). It can be predicted that extensive diesel emissions would be generated from the exempted NRMM if no further action is taken. In 2015, the Hong Kong Government issued the regulation of Emissions Control of Non-road Mobile Machinery in Capital Works Contracts of Public Works (HKEPD, 2015). Nevertheless, this regulation simply aims at phasing out four types of exempted NRMM used in new capital works contracts of public works with an estimated contract value exceeding $200 million, including generators, air compressors, excavators and crawler cranes. This regulation has slight effectiveness in controlling diesel emissions from NRMM because only a very small number of construction equipment employed in public works with an estimated contract value over $200 million is involved. The above discussion indicates that efforts for reducing diesel emissions from NRMM is inadequate in Hong Kong, particularly those directed at existing exempted NRMM.

Retrofitting exempted in-use dirty NRMM by employing diesel exhaust control technologies is widely considered to be an effective way to mitigate diesel emissions and would offer significant air quality benefits (Sparrevik et al., 2023). For example, the Massachusetts Department of Environmental Protection (MassDEP) launched a NRMM retrofit programme in 1998 (DTF, 2003). In this programme, about 70 pieces of NRMM used on the Project of Massive Central Artery/Tunnel (widely called the "Big Dig" project) were retrofitted by using oxidation catalysts and particulate filters, resulting in an annual emission reduction of about 36 tonnes of CO, 12 tonnes of HC, and 3 tonnes of PM (DTF, 2003). Although significant health benefits can be achieved by retrofitting NRMM, the cost of employing exhaust emission control technologies may be an important consideration for many governments such as Hong Kong which intend to initiate NRMM retrofit programmes for the purpose of diesel emission reduction.

Thus, this study conducted a review of NRMM emission control technologies, with the aim of providing some insightful references to the Hong Kong Government and other entities when making decisions related to retrofitting NRMM. First, a brief introduction of widely used retrofitting technologies is presented in Section 2, followed by Section 3, which introduces the emission reduction efficiency of these technologies. In section 4 the cost of NRMM emission reduction technologies is reviewed. Section 5 provides some recommendations to the Hong Kong Government by considering the context of the promotion of NRMM retrofit programmes, and Section 6 concludes this study.

2. Retrofitting technologies for reducing emissions from NRMM

Diesel emission control technologies, which can be employed to retrofit diesel engines in NRMM, have been developed. There are two groups of diesel emission reduction technologies, including in-cylinder engine control technologies and exhaust after-treatment ones (Dallmann and Menon, 2016). In-cylinder engine control technologies primarily modify and improve fuel injection and air handling systems, to achieve a full mixture of fuel and air and then prevent diesel emissions from formation in the combustion process. The typical in-cylinder engine control technologies installed in NRMM are exhaust gas recirculation (EGR) systems, fuel injection systems, air-handling systems, etc., among which EGR systems are widely used. Therefore, it was reviewed in this research. Exhaust after-treatment technologies, like Diesel Oxidation Catalyst (DOC), selective catalytic reduction (SCR) systems, Diesel Particulate Filter (DPF), etc., directly remove diesel emissions from the exhaust gas stream.

2.1. In-cylinder engine control technologies

2.1.1. EGR systems

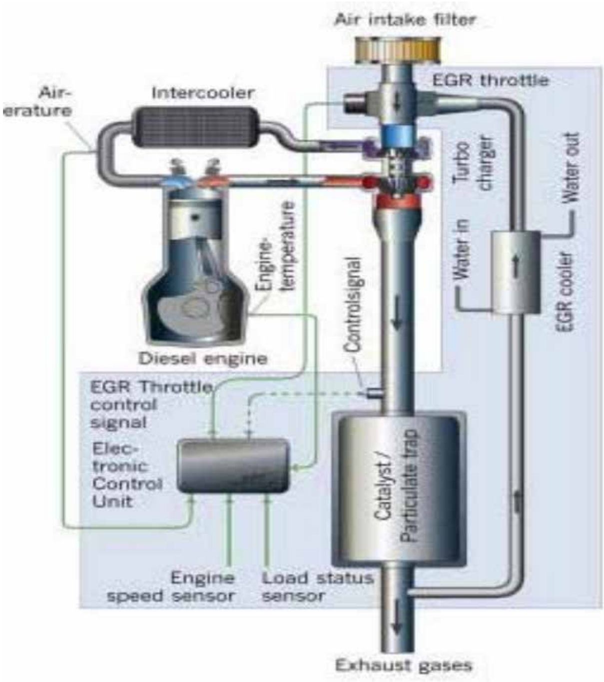


Figure 1. Schematic diagram of the EGR system (MECA, 2014).

EGR systems recirculate a percentage of engine exhaust gas back to the charger inlet or intake manifold of the engine (CDCH, 2021; Dallmann et al., 2018; DTF, 2003). The temperature of the recirculated exhaust gases can be lowered by exhaust gas recirculation intercoolers, the oxygen level of the recirculated engine exhaust gas is reduced through introducing it upstream of the engine, and the recirculated exhaust gases has a higher heat capacity and less oxygen than air (DTF, 2003). As a result, NOx formation is blocked (CDCH, 2021; MECA, 2014). The schematic diagram of the EGR system is shown in Figure 1.

EGR systems are high-pressure or low-pressure systems. Low-pressure EGR systems are more widely applied for retrofitting diesel engines because they usually do not require any modifications. Low-pressure ones are usually used along with a catalyst-based DPF (CDCH, 2021). High-pressure systems are often installed in new diesel engines (CDCH, 2021). It is reported by CDCH (2021) that over 3,000 EGR systems along with DPF systems have been installed in NRMM used in Europe and the United States. As reported by CDCH (2021), EGR systems cause a fuel economy penalty by a percentage of from 1% to 4%, depending on the type of engine and test cycles used.

2.2. Exhaust after-treatment technologies

2.2.1. DOCs

DOCs are one of the most commonly used technologies to control diesel emissions from NRMM because of their straightforward installation, no engine modifications, and barely no maintenance (CDCH, 2021). DOCs usually comprise a catalytic converter, in which there is a honeycomb-structure substrate outside covered by oxidation catalysts like platinum or palladium (Dallmann and Menon, 2016; DTF, 2003; MassDEP, 2008). CO, HCs, and liquid hydrocarbons can be oxidised by catalysts, adsorbed on carbon particles and then converted into CO_2 and water (MECA, 2014). A report issued by the Manufacturers of Emission Controls Association states that oxidation catalysts have been employed to retrofit NRMM over the past 30 years, and over 300,000 installations had been completed in the United States as of 2014 (CDCH, 2021; MECA, 2014). DOCs have been widely equipped on mining machinery, marine vessels, and other types of NRMM (DTF, 2003). Existing operating experiences suggest that DOCs usually can work trouble-free without maintenance for thousands of hours of use and usually are scrapped only when engines are rebuilt (CDCH, 2021; MECA, 2014). DOCs can work well on many applications when the temperatures of exhaust emissions are higher than 150ºC (MassDEP, 2008). DOCs can work well with both conventional diesel fuel and other greener fuels such as biodiesel (DTF, 2003). A schematic DOC is shown in Figure 2.

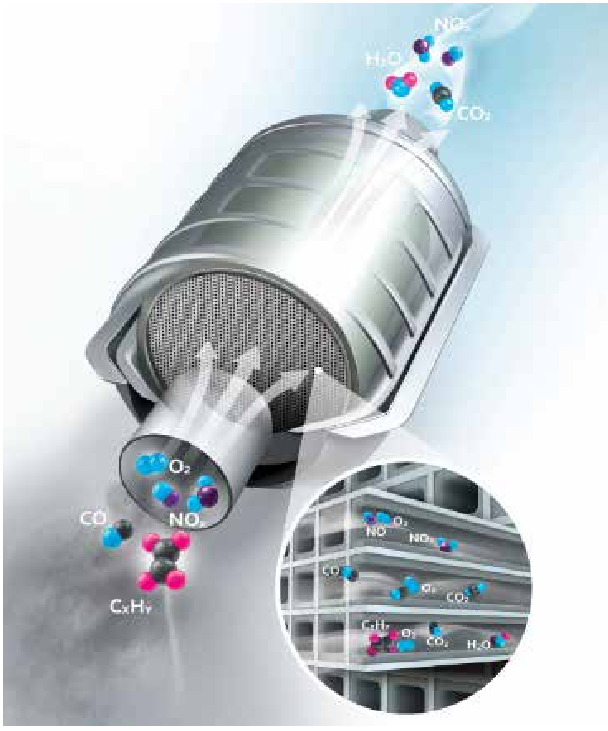


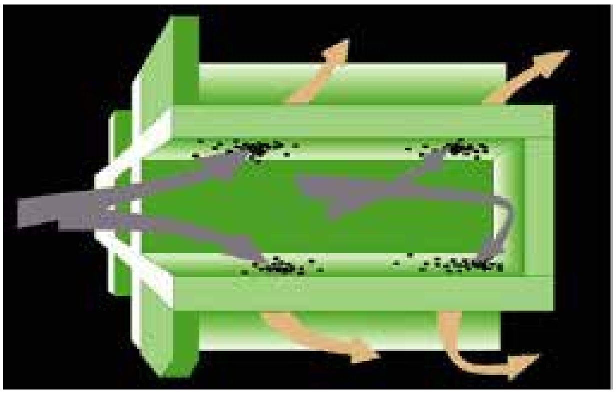
Figure 2. Schematic diagram of a DOC (Matthey, 2023).

The sulphur content of diesel fuel has an impact on the effectiveness of DOCs to reduce PM. Catalysts used to oxidise soluble particulate matter can also oxidise sulphur dioxide to form sulphates, which is one kind of particulate (MECA, 2014). The employment of ultra-low sulphur diesel fuel (15 ppm sulphur) could deliver PM emission reductions and facilitate wide application of DOCs (MassDEP, 2008).

2.2.2. DPFs

DPFs remove particles from NRMM exhaust streams through filtering the exhaust from engines (DTF, 2003; Janea et al., 2005; MECA, 2014). Wall-flow and metal flow-through filters are two typical modes of DPFs (MECA, 2014). Wall-flow filters direct exhaust gases through cell walls, thereby causing the particles in exhaust gases to be filtered and deposited on the inside wall of the channel and clean the exhaust (MECA, 2014). Wall-flow ones have a higher particle filtration level of over 90% (MECA, 2014). Metal flow-through ones usually consist of catalysed metal wire mesh structures, tortuous flow, metal foil-based substrates, sintered metal sheet, and specially designed ceramic filters. The metal flow-through technologies use perturbations to lead a portion of the exhaust upwards through metal mesh, and then trap the particles (MECA, 2000). The particle reduction efficiencies of metal flow-through ones are 50% to 80% (MECA, 2000). After a period of operating time, filters become filled up by particulate matter that has accumulated on them. The filter should be cleaned or regenerated by burning off or oxidising the trapped particulate matter (DTF, 2003). Schematic diagrams of wall-flow and metal flow-through diesel particulate filters are shown in Figure 3.

(a)



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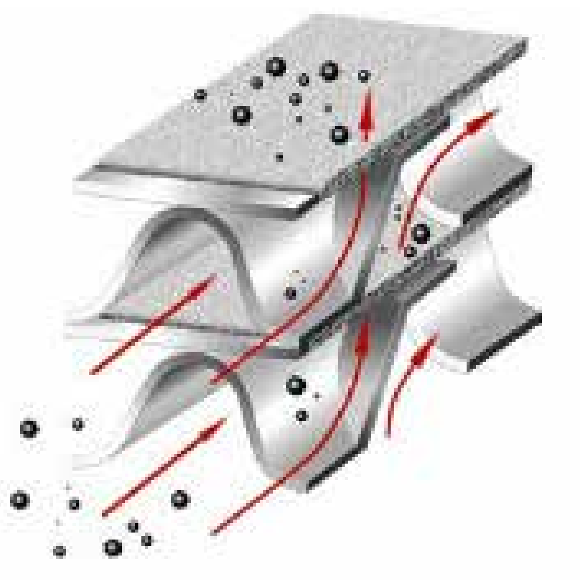

Figure 3. Schematic diagrams of wall-flow and metal flow-through diesel particulate filters (MECA, 2014).

DPFs can also be broadly classified into active and passive ones, according to the methods of regenerating filters (MassDEP, 2008). Passive ones utilise catalysts on the surfaces of filters to make the necessary ignition temperature lower, at which soot combustion is boosted, so that regeneration takes place as required (MassDEP, 2008). Active DPFs utilise heat from onboard or offboard burners or electrical heaters to provide the needed energy to burn the accumulated PM off and regenerate filters (MassDEP, 2008). The content of sulphur in diesel fuel can significantly negatively affect the reliability, durability, and emission reduction efficiency of passive DPFs (Kassel et al., 2013). This is because sulphur can restrain catalytic activity, compete with other exhaust constituents for chemical reactions and form catalytic sulphate, and then generate PM (MassDEP, 2008; MECA, 2000). Passive DPFs work best along with fuel sulphur levels above 15 ppm (MassDEP, 2008). MECA (2014) indicated that the use of DPFs may cause some fuel economy penalties with a low level from zero to 1%, and DPFs do not seem to cause any additional engine deterioration or NRMM maintenance.

2.2.3. SCR systems

SCR systems introduce chemical reductants such as ammonia to the exhaust stream over a metallic or ceramic wash-coated catalysed substrate or a homogeneously extruded catalyst and transfer NOx into nitrogen and oxygen, which is an oxidation catalyst-based technology (CDCH, 2021; Dallmann et al., 2018; DTF, 2003; MECA, 2014). Aqueous urea or diesel exhaust fluid (DEF) are usually the preferred reductant sources. Aqueous urea is usually injected into the exhaust upstream of the SCR system. The urea is hydrolysed into ammonia and CO_2 by the heat from the exhaust mixing. As diesel engine exhaust and reductant pass through the SCR catalyst, chemical reactions occur and then NOx emissions are converted to nitrogen and oxygen. A schematic diagram of a SCR system is presented in Figure 4.

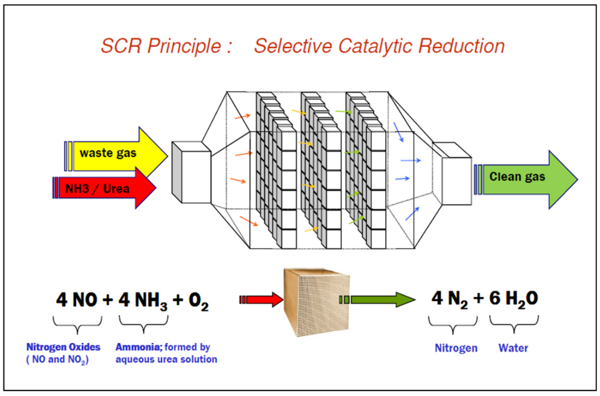

Figure 4. Schematic diagram of a SCR system (Tomorrow's Tech, 2023).

3. Emission reduction efficiency of various technologies for reducing emissions from NRMM

With regard to the emission reduction by using EGR systems, there are different conclusions in existing research. CDCH (2021) and MECA (2014) stated that EGR systems are usually applied along with DPFs on engines of NRMM in retrofit applications, which can achieve over 40%, 90% and 90% of NOx, PM, and CO and HC reductions respectively. The two research institutions also reported that low-pressure EGR systems can achieve NOx reductions of 25% to 50%, and the reduction level depends on EGR system design, the engine application and calibration, and the operating duty cycle.

The ability of DOCs to control diesel emissions depends on some factors including the temperature of exhaust emissions, the sulphur content in fuel used, and the amount of soluble particulate matter in the particulate. Researchers have found different percentages of diesel emission reductions by using DOCs on NRMM. For example, MECA (2014) suggested that DOCs could reduce approximately 50% to 90% of HC, 70% to 90% of CO, and 20% to 30% of PM. CDCH (2021) and DTF (2003) reported that DOCs could reduce PM emissions by 20% to 50% and HC and CO by up to 90%.

DPFs could significantly reduce PM, HC, and CO emissions by up to 90% and other toxic emissions like aldehydes (USEPA, 2004; DTF, 2003; MassDEP, 2008). However, DPFs cannot reduce NOx. DPFs could be used along with EGR, NOx absorber catalysts, or SCR systems to simultaneously achieve significant reductions of NOx and PM. Engines retrofitted by using low-pressure EGR systems and DPFs could reduce NOx by over 40% and PM by greater than 90%. Engines retrofitted by equipping SCR systems and a filter can reduce NOx by 70% to 90% and PM by greater than 90% (MassDEP, 2008). MECA (2014) reported that the cost of DPFs depends on the size of engines, the amount of emitted particular matter, emission reduction targets, and other factors. Janea et al. (2005) indicated that the cost of DPFs ranges from US$7,000 to US$12,000, which excludes installation costs. MassDEP (2008) estimated that a passive DPF installed on a NRMM diesel engine with horsepower under 250 hp costs from US$8,500 to US$10,000, and an active DPF costs from US$14,000 to US$20,000, including installation. Flow-through filters are capable of achieving PM reductions of about 30% to 75% (MECA, 2014).

Similarly, different studies show that the emission reduction abilities of SCR systems are different. This difference is caused by the variation in SCR system design, engine application, and the operating duty cycles. MECA (2014) and DTF (2003) stated that NOx emissions could be reduced by open-loop SCR systems by 70% to 90%, while closed-loop ones could achieve over 95% NOx reductions. SCR systems could reduce HC emissions by up to 80% and PM emissions by 20% to 30%. CDCH (2020) suggested that SCR technologies could reduce NOx emissions by 25% to 90%, PM emissions by 15% to 50%, and HC and CO emissions by 30% to 90%. CDCH (2020) also suggested that the NOx control efficiency of SCR systems is related to several factors, including 1) the design of SCR catalysts; 2) the application of engines; 3) the temperatures of operations; 4) the duty cycle (e.g., steady-state or transient); and 5) the sulphur content of the fuel. Although SCR catalyst applications do not require low-sulphur fuel, the emission reduction performance of SCR systems could be improved by using low-sulphur fuel. SCR catalysts could also be used along with DOCs or DPFs to jointly reduce emissions of PM, HCs, and CO (CDCH, 2020). The use of ultra-low-sulphur diesel could improve the synergistic emission reduction through combining DPFs and SCR systems generally. The joint use of SCR systems and DOCs can achieve emission reductions of 60% to 80% for NOx, 25% for PM, and 50% to 70% for HCs and CO (Janea et al., 2005). The cost of SCR systems greatly depends on the horsepower of diesel engines and the application situation (Kassel et al., 2013). The emission reduction efficiency of each technology is summarised in Table 1.

Table 1. Emission reduction efficiency of various technologies.

Technologies	Emission reduction efficiency	References
EGR system applied along with DPF	NOx (40%); PM (90%); CO (90%); and HC (90%).	CDCH (2021); MECA (2014)
DOC	HC (50% to 90%); CO (70% to 90%); PM (20% to 30%).	MECA (2014)
	PM (20% to 50%); HC and CO (by up to 90%).	CDCH (2021); DTF (2003)
DPF	PM, HC, and CO (by up to 90%)	USEPA, 2004; DTF, 2003; MassDEP, 2008.
Open-loop SCR system	NOx (70% to 90%); HC (80%); PM (20% to 30%).	MECA (2014); DTF (2003)
Closed-loop SCR system	NOx (95%); HC (80%); PM (20% to 30%)	-
SCR system	NOx (25% to 90%); PM (15% to 50%); HC and CO (30% to 90%).	CDCH (2020)

4. Cost of technologies for reducing CEE

The costs of NRMM diesel emission reduction technologies are not available and are known just to their manufacturers; therefore, precisely estimating the cost of technologies is difficult, as stated by Dallmann et al. (2018). In most cases, manufacturers are unwilling to disclose their cost information due to competitiveness concerns (Dallmann et al., 2018). Besides, the complex and diverse design of diesel engines in NRMM also aggravates the difficulty of obtaining the cost of technologies for reducing NRMM emissions. It is widely agreed that the costs of diesel emission control technologies are determined by several factors, typically including the engine model year, the engine size, the amount of emissions generated, the technology sales volume, the amount of emissions emitted by engines, and the installation and regeneration method of technologies. The report issued by the Rhode Island Department of Transportation (RIDT) in 2014 suggests that the cost of reducing the percentage of emissions increases as engine horsepower increases (RIDT, 2014). The costs of DPFs vary according to engine size, sales volume, the amount of PM generated by engines, the emission target intended to be achieved, the regeneration method, and other factors.

There is a strand of literature examining the costs of diesel NRMM retrofit technologies. For example, the USEPA (2007) estimated that the average cost per DOC and per DPF are US$1,000 and US$5,000, respectively, which is determined by the horsepower or displacement of engines. This estimation by the USEPA (2007) is based on two reports of *Nonroad Tier 4 Regulatory Impact Analysis (RIA)* by the USEPA (2004) and the Diesel Retrofit Technology report by USEPA (2006a). The first report suggested that the costs of passive DPF are from US$178 to US$6,405 and DOC from US$105 to US$734, depending on the horsepower and average engine displacement. These costs estimated by the USEPA (2004) exclude the cost of additional exhaust tubing, data logging and installation. The second report makes some improvements through containing the additional cost for exhaust tubing, data logging and installation. In this report, the cost of a passive DPF and a DOC are US$593 and US$280 respectively. Then, based on the cost estimates in the two reports and expert experience with NRMM retrofit technology, the USEPA (2007) re-estimated the costs of passive DPFs and DOCs. MECA (2014) stated that the cost of DOCs is mainly determined by the engine size, sales volume and installation methods. According to the report by MECA (2014), the cost of DOCs varies from US$500 to US$2,000 and for DPFs from US$5,000 to US$7,000 per unit.

The international council on clean transportation (ICCT) published the cost estimation of manufacturers' NRMM diesel emission reduction technologies to meet the emission standards promulgated by the EPA and EU at each regulatory tier or stage (Dallmann et al., 2018). The study first defines a single representative technology package for each power class and regulatory emission standard tier, which is commonly adopted by manufacturers. Then, this study estimates the cost of the defined typical technology package for engine group divided by power class and emission regulatory tier. Finally, the study calculates the total incremental cost of adopting NRMM diesel emission control technologies to meet each emission standard tier or stage for each power class, through matching the required technologies and their costs. For example, as estimated by this research, the cost of DOCs installed to meet Tier 4f emission standards, for a diesel engine with a displacement of 10.8 L and a horsepower of 224-447 kW, is US$470 (Dallmann et al., 2018).

CARB estimated the cost of NRMM diesel emission control technologies and disclosed the cost information in an open web-based database named Clean Diesel Clearing House (CDCH) (CDCH, 2021). The estimated costs of DOCs and DPFs in the mentioned database are summarised in Table 2.

Table 2. The costs of DOC and DPF estimated by CARB (2000).

Engine horsepower	Hardware cost of DOC	Hardware cost of DPF
40	US$400-US$600	US$3,300-US$5,000
100	US$680-US$1,356	US$5,000-US$7,000
275	US$2,100-US$3,700	US$6,900-US$9,000
400	US$2,800-US$3,700	US$10,500
1,400	US$10,000-US$20,000	US$32,000-US$44,000

CDCH (2021) further suggested that the costs of DOCs in NRMM engines retrofitted with a horsepower of 100-200 are from US$500 to US$1,250, and the costs of ones in the 200-500 horsepower category are from US$1,000 to US$1,750. In addition, DOC installation by technology suppliers or their agents usually takes one to two hours, and the installation cost is US$100 to US$200. Sometimes fleet technicians install the DOCs themselves because DOC installation is relatively straightforward, after receiving training from the DOC suppliers. Installing DOCs by themselves can avoid external costs. No maintenance costs are typically incurred in the use of DOCs, since they are virtually maintenance-free except for periodic checks.

CDCH (2021) suggests that sometimes the purchase price of DPF includes the installation cost, but it is usually billed as a separate item. The time spent to install DPFs on NRMM engines can range from two to over ten hours. At an estimated rate of US$65 per hour, DPF installation costs typically range from US$130 to US$650. The installation costs, however, could be significantly higher in some cases, when involving complex or time-consuming DPF installations. MECA (2014) estimated that high-efficiency passive filters for diesel NRMM retrofitting are currently being sold for about US$10,000 to US$16,000 per unit. Flow-through ones are being sold for about US$5,000 to US$7,000 per unit.

MECA (2014) reported that the cost of a low-pressure EGR system combined with a DPF installed on a bus or truck engine is about US$18,000 to US$20,000. The study also stated that the costs of SCR systems range from about US$18,000 with a DOC to US$30,000 with a DPF per installation on vehicles. The study by MECA (2014) focuses on the costs of various retrofitting technologies for on-road vehicles not on technologies for NRMM. Besides, the cost of various technologies in the study is directly given, without providing any more explanatory information. CDCH (2021) figured out that the costs of using SCR systems vary greatly and are affected by many factors such as engine size, engine application, and the availability of engine mapping. They estimated that the cost of an SCR system is from US$50 to US$60 per horsepower. Besides, CARB (2000) also estimated that the installation costs of SCR systems range from US$500 to US$5,000, depending on the engine application availability of engine mapping.

5. Recommendations

5.1. Description of NRMM in Hong Kong

This study collected NRMM inventory data in Hong Kong from the Hong Kong Environmental Protection Department. The NRMM in Hong Kong had reached a total of 43,382 by 2022, which covers about 15 categories including air compressor, bulldozer, drilling rig, dumper, excavator, lifting platform, loader, mobile crane, mobile generator, mobile pump, power pack, road works machine, stacker, tractor, and welder. The percentages of each type of NRMM are summarised in Figure 5.

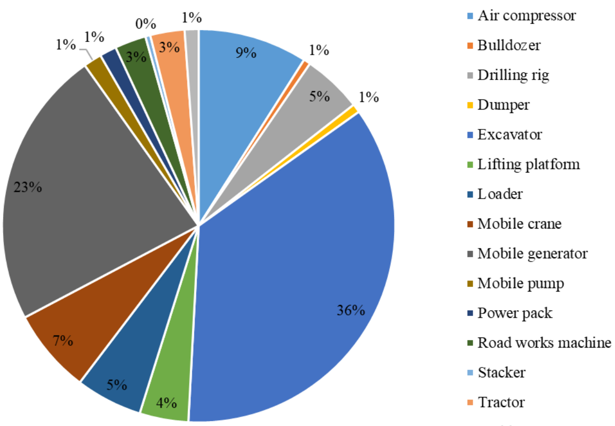

Figure 5. NRMM categories in Hong Kong in 2022.

Among the 43,382 pieces of in-use NRMM in Hong Kong, 24,770 are exempted from stringent emission standards, accounting for 57.10%. This heavy motorisation and larger number of pieces of exempted NRMM have caused increasing concerns regarding local air pollution in Hong Kong, which may be one of the reasons why most NRMM emissions remain at higher levels, as shown in Figure 6. It is obvious in this figure that there has been a sudden drop in SO_2 emissions since 2009. The significant decline in SO_2 emissions is attributed to the implementation of the Air Pollution Control (Fuel Restriction) Regulation by the HKEPD in October 2008, which tightened the cap on the sulphur content of diesel used in industrial and commercial sectors from 0.5% to 0.005%. Since January 2009, Euro V diesel (with sulphur content not exceeding 0.001%) has been imported for industrial and construction use.

In addition, about 16.88%, 34.89%, 30.70% and 23.47% of NRMM in Hong Kong comprises technology types of US Tier 1, US Tier 2, US Tier 3 and US Tier 4 respectively. Currently, cities or countries like the United States with higher levels of transforming NRMM into cleaner NRMM widely recommend Tier 4 emission standards and suggest that this can be achieved by employing the available technologies. Only 23.47% of NRMM in Hong Kong has reached Tier 4 emission levels, which indicates that making NRMM in Hong Kong cleaner still has a long way to go. Retrofitting exempted NRMM usually with technology types under Tier 4 provides a solution to the problem of extensive NRMM emissions.

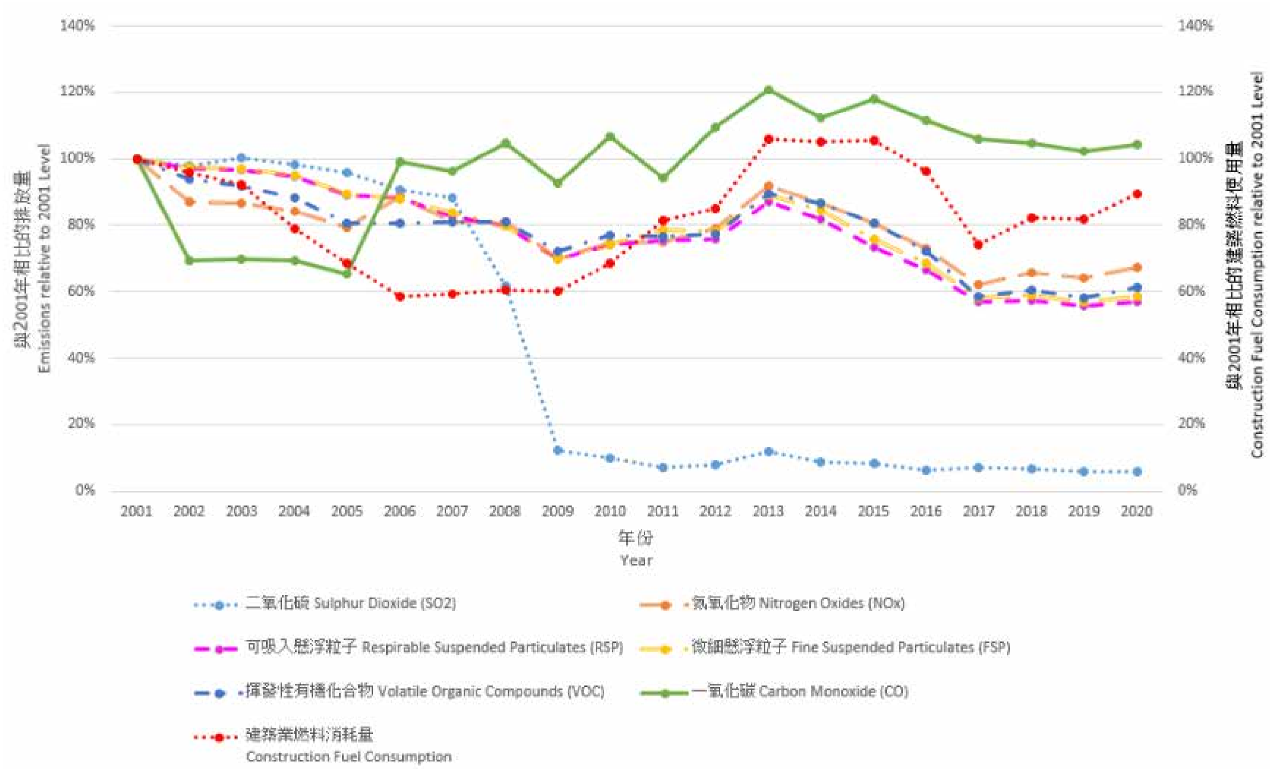

Figure 6. Diesel emissions from NRMM in Hong Kong (HKEPD, 2022).

5.2. Recommendations on regulatory and incentive policies

The discussion in Sections 2-4 has suggested that technologies that can effectively reduce diesel emissions from in-use NRMM are available, but there are no efforts devoted by the Hong Kong Government to promote their application. Currently, only public buses powered by gasoline are retrofitted in Hong Kong. Compared with public buses, NRMM in Hong Kong has received limited attention from the Government. To achieve emission reductions and realise air quality benefits in Hong Kong, this study presents some considerations for successfully promulgating and implementing retrofit programmes. In this section, some implications are suggested and some insights are provided to encourage the Hong Kong Government to launch and owners of NRMM fleets in Hong Kong to participate in retrofit programmes, which is a secure investment with the possibility of gaining multiple dividends.

To successfully promote retrofit programmes, some administrative issues should be carefully considered by the Hong Kong Government. As reported by MECA (2014), retrofit programmes should properly consider the following elements, including (1) defining which vehicles or equipment should be retrofitted, (2) determining the appropriate retrofit technologies for particular vehicles or equipment, (3) setting the desired targets of emission reduction intended to be achieved through retrofit programmes, (4) meeting the needs of fuel quality in order to ensure the efficient operation of retrofit technologies, (5) meeting the requirements of operating and maintaining retrofitted vehicles or equipment, and (6) training vehicle, equipment operators and the public. This is echoed by DTF (2006), which suggests that successful retrofit programmes should begin with proper selection of the diesel engines to be retrofitted, followed by identifying the most appropriate retrofit technologies for the previously selected fleet.

In addition, economic considerations should be taken into account when adopting retrofit programmes. In most cases, using emission reduction technologies incurs costs of purchase, installation, and maintenance, and thus for contractors few economic benefits will be offered by engaging in retrofit programmes. For some highly competitive industries that employ NRMM like marine shipping and construction, few contractors are able to bear the additional cost of retrofitting technologies without some form of compensation. Besides, contractors may be exposed to some potential risks due to the downtime associated with the installation of emission reduction technologies. Therefore, contractors usually have low enthusiasm in regard to participating in retrofit programmes.

Incentive policy instruments have been widely considered to be effective in promoting the retrofitting of vehicles and equipment, which may be a solution to the severe problem of extensive diesel emissions from NRMM in Hong Kong. Existing incentive policy instruments include grant programmes, tax incentives, modified contracting procedures, and non-monetary incentives. Among these policy instruments, monetary grants appear to be the most favoured type by contractors, which provide NRMM owners with the flexibility to make their own decisions about how to reduce the diesel emissions from their NRMM fleet in a cost-effective, practical manner. However, making grants to contractors usually poses a financial burden on the Hong Kong Government. Each type of incentive policy instrument has both weaknesses and strengths and a single type of incentive policy instrument cannot successfully motivate contractors to participate in retrofit programmes initiated by the Hong Kong Government. However, policy instruments can pair with each other, so that a mixture of various incentive policy instruments will work better. This study suggests that the Hong Kong Government can combine various incentive policy instruments. For example, the Hong Kong Government can adopt voluntary and incentive grant retrofit programmes as a dominant measure and other policy instruments like tax exemption as supplementary ones.

6. Conclusions

This study reviews the main technologies used for reducing emissions from NRMM, including in-cylinder engine control technology of EGR systems and exhaust after-treatment technologies of DOC, DPF and SCR systems. The costs and emission reduction efficiency of these available technologies are also reviewed. Moreover, some insightful implementations are derived from the existing retrofit practices for reference for the Hong Kong Government. This study suggests that the available emission reduction technologies have the potential to dramatically reduce diesel emissions from the NRMM in Hong Kong. This research provides some insight into the retrofit technologies, which can help the Hong Kong Government determine the appropriate level of emission reduction by employing certain emission reduction technologies. The costs and emission reduction efficiency of retrofit technologies are two of the most important, but not the only, factors to be considered throughout the retrofit programmes. Therefore, regulatory considerations for successfully promoting the use of retrofit technologies are discussed. This study suggests that a mixture of targeted incentive policies be implemented in Hong Kong to promote green construction fleets with the best use of the best available emission reduction technologies.

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References

[1] CARB (California Air Resources Board) (2000). *Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles*. [online report]. Available at:<https://ww2.arb.ca.gov/sites/default/files/classic/diesel/documents/rrpfinal.pdf>. [Accessed on 15 August 2023].

[2] CDCH (Clean Diesel Cleaning House) (2021). *Emissions advantage retrofit guidance document-EGR*. [online report]. Available at: <https://s3.amazonaws.com/cdch/uploads/document/file/95/EGR_2-20-15.pdf>. [Accessed on 15 August 2023].

[3] Dallmann T, Posada F and Bandivadekar A (2018). *Costs of Emission Reduction Technologies for Diesel Engines Used in Non-Road Vehicles and Equipment*. [online report]. Available at: < https://theicct.org/sites/default/files/publications/Non_Road_Emission_Control_20180711.pdf >. [Accessed on 15 August 2023].

[4] Dallmann T and Menon A (2016). *Technology pathways for diesel engines used in non-road vehicles and equipment*. [online report]. Available at: <https://theicct.org/wp-content/uploads/2021/06/Non-Road-Tech-Pathways_white-paper_vF_ICCT_20160915.pdf>. [Accessed on 15 August 2023].

[5] DTF (Diesel Technology Forum) (2003). *Clean Air, Better Performance: Strategies for upgrading and modernizing diesel engines*. [online report]. Available at: <https://www.dieselforum.org/files/dmfile/CleanAirBetter Performance.pdf>. [Accessed on 15 August 2023].

[6] DTF (Diesel Technology Forum) (2006). *Retrofitting America's Diesel Engines-A Guide to Cleaner Air Through Cleaner Diesel*. [online report]. Available at: <https://dieselforum.org/files/dmfile/Retrofitting-America-s-Diesel-Engines-11-2006.pdf>. [Accessed on 19 October 2023].

[7] Garshick E, Laden F, Hart J E, Rosner B, Davis M E, Eisen E A and Smith T J (2008). Lung cancer and vehicle exhaust in trucking industry workers. *Environmental Health Perspectives*, 116(10), pp. 1327-1332.

[8] HKDB (Development Bureau of Hong Kong) (2015). Development Bureau Technical Circular (Works) No. 1/2015—Emissions Control of Non-road Mobile Machinery in Capital Works Contracts of Public Works. [online report]. Available at: <https://www.devb.gov.hk/filemanager/technicalcirculars/en/upload/335/1/C-2015-01-01.pdf>. [Accessed on 19 October 2023].

[9] HKEPD (The Environmental Protection Department of Hong Kong) (2015). *A New Regulation on Controlling Emission from Non-road Mobile Machinery (NRMM)*. [online report]. Available at: <https://www.epd.gov.hk/epd/sites/default/files/epd/epd/english/environmentinhk/air/prob_solutions/files/NRMM_trade_briefing.pdf>. [Accessed on 27 August 2023].

[10] HKEPD (The Environmental Protection Department of Hong Kong) (2022). *2020 Hong Kong Emission Inventory Report. Hong Kong*: The Environmental Protection Department.

[11] HKSAR Government (2021). *Northern Metropolis Development Strategy Report*. [online report]. Available at: <https://www.policyaddress.gov.hk/2021/eng/pdf/publications/Northern/Northern-Metropolis-Development-Strategy-Report.pdf>. [Accessed on 27 August 2023].

[12] Janea S, Isabelle S and Stephanie T (2005). *Cleaner Diesel Handbook-Bring cleaner fuel and diesel retrofits into your neighbourhood*. [online report]. Available at: <https://www.edf.org/sites/default/files/4941_cleanerdieselhandbook.pdf>. [Accessed on 15 August 2023].

[13] Kassel R, Couch P, Conolly M and Hammer-Barulich A (2013). *Ultrafine particulate matter and the benefits of reducing particle numbers in the United States*. United States: Gladstein, Neandross & Associates.

[14] Kubsh J (2017). *Diesel Retrofit Technologies and Experience for On-road and Off-road Vehicles*. [online report]. Available at: <https://olis.oregonlegislature.gov/liz/2019I1/Downloads/CommitteeMeetingDocument/207997>. [Accessed on 15 August 2023].

[15] MassDEP (Massachusetts Department of Environmental Protection) (2008). *Diesel engine retrofits in the construction industry: A how to guide*. [online report]. Available at: <https://www.mass.gov/doc/diesel-engine-retrofits-in-the-construction-industry-a-how-to-guide-0/download>. [Accessed on 15 August 2023].

[16] Matthey J (2023). *Diesel oxidation catalyst (DOC)*. [online]. Johnson Matthey. Available at: <https://matthey.com/products-and-markets/transport/mobile-emissions-control/diesel-applications/diesel-oxidation-catalyst>.

[17] Mayor of London (2014). *The control of dust and emissions during construction and demolition (supplementary planning guidance)*. [online report]. Available at: <https://www.portsmouth.gov.uk/wp-content/uploads/2020/04/dust-emissions.pdf>. [Accessed on 15 August 2023].

[18] MECA (Manufacturers of Emission Controls Association) (2000). *Catalyst-Based Diesel Particulate Filters and NOx Adsorbers: A summary of the Technologies and the Effects of Fuel Sulfur*. [online report]. Available at: <http://www.meca.org/galleries/files/cbdpf-noxadwp.pdf>.[Accessed on 15 August 2023].

[19] MECA (Manufacturers of Emission Controls Association) (2006). *Case Studies of Construction Equipment Diesel Retrofit Projects*. [online report]. Available at: <http://www.meca.org/galleries/files/Construction _Case_Studies_0306.pdf>. [Accessed on 15 August 2023].

[20] MECA (Manufacturers of Emission Controls Association) (2014). *Retrifitting Emission Controls for Diesel-Powered Vehicles*. [online report]. Available at: <http://www.meca.org/galleries/files/MECAdiesel_retrofit_white_paper_1009.pdf>. [Accessed on 15 August 2023].

[21] Ning L, Duan Q, Chen Z, Kou H, Liu B, Yang B and Zeng K (2020). A comparative study on the combustion and emissions of a non-road common rail diesel engine fueled with primary alcohol fuels (methanol, ethanol, and n-butanol)/diesel dual fuel. *Fuel*, 266.

[22] Preston M (2018). *Why construction machinery must be included in the Clean Vehicles Directive. Www.Euractiv.Com*. [online report]. Available at: <https://www.euractiv.com/section/air-pollution/opinion/why-construction-machinery-must-be-included-in-the-clean-vehicles-directive/>. [Accessed on 15 August 2023].

[23] RIDT (Rhode Island Department of Transportation) (2014). *Diesel Emission Reduction in Construction Equipment*. [online report]. Available at: <https://rosap.ntl.bts.gov/view/dot/27095/dot_27095_DS1.pdf>. [Accessed on 15 August 2023].

[24] Sparrevik M, Qiu X, Stokke R A, Borge I and Boer L (2023). Investigating the potential for reduced emissions from non-road mobile machinery in construction activities through disruptive innovation. Environmental Technology & Innovation, 31.

[25] Tomorrow's Tech (2023). *What Is Selective Catalytic Reduction?* [online]. Available at: <https://www.tomorrowstechnician.com/what-is-selective-catalytic-reduction/>.

[26] United Nations (2019). *Difference Between Developed Countries and Developing Countries (with Comparison Chart)—Key Differences*. [online report]. Available at: <https://keydifferences.com/difference-between-developed-countries-and-developing countries.html>. [Accessed on 15 August 2023].

[27] USEPA (United States Environmental Protection Agency) (2004). *Nonroad Tier 4 Regulatory Impact Analysis (RIA), (EPA420-R-04-007, May 2004)* [online report]. Available at: <www.epa.gov/nonroad-diesel/2004fr.htm>. [Accessed on 15 August 2023].

[28] USEPA (United States Environmental Protection Agency) (2006a). *Diesel Retrofit Technology: An Analysis of the Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits (EPA420-S-06-002). 37*. [online report]. Available at: <https://nepis.epa.gov/Exe/ZyPDF.cgi/P10023OA.PDF?Dockey=P10023OA.PDF>. [Accessed on 15 August 2023].

[29] USEPA (United States Environmental Protection Agency) (2006b). *Progress Report on EPA's Nonroad Mobile Source Emissions Reduction Strategies. Report No. 2006-P-00039. 35*. [online report]. Available at: <https://www.epa.gov/office-inspector-general/report-progress-report-epas-nonroad-mobile-source-emissions-reduction>. [Accessed on 15 August 2023].

[30] USEPA (United States Environmental Protection Agency) (2007). *Diesel Retrofit Technology-An Analysis of the Cost-Effectiveness of Reducing Particulate Matter and Nitrogen Oxides Emissions from Heavy-Duty Nonroad Diesel Engines Through Retrofits*. [online report]. Available at: <https://nepis.epa.gov/Exe/ZyPDF.cgi/P10023OA.PDF?Dockey=P10023OA.PDF>. [Accessed on 15 August 2023].

[31] USEPA (United States Environmental Protection Agency) (2009). *First REPORT TO CONGRESS: Highlights of the Diesel Emissions Reduction Program*. [online report]. Available at: <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1005PP1.pdf>. [Accessed on 15 August 2023].