SUBSIDY POLICIES FOR REDUCING DIESEL EMISSIONS FROM IN-USE CONSTRUCTION EQUIPMENT IN HONG KONG

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PhD

The Hong Kong Polytechnic University

2022

The Hong Kong Polytechnic University

Department of Building and Real Estate

Subsidy Policies for Reducing Diesel Emissions from In-use Construction Equipment in Hong Kong

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

December 2021

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Abstract

Construction equipment is responsible for a significant amount of emissions, which have been a major source of environmental degradation and considerable damage to human health. The challenges posed by extensive emissions from construction equipment have been motivating governments around the world to adopt measures. However, in Hong Kong, the policy instruments for reducing construction equipment emission (CEE) are insufficient, with only new construction equipment being bound by tighter emission standards while in-use ones being remarkably unregulated. After years of use, in-use construction equipment becomes inefficient through deterioration and consequently produces higher levels of pollutants, which are extremely dangerous to public health. Making in-use construction equipment cleaner and more fuel-efficient is an increasingly urgent task for governments. Replacing or retrofitting in-use construction equipment can dramatically reduce emissions, improve the air quality and deliver significant health benefits to those who live or work in or adjacent to construction sites. However, purchasing new equipment or emission reduction technologies will incur costs and brings financial burdens on contractors, which is one of the foremost barriers of governments promoting replacement and retrofit of in-use construction equipment. To accelerate the replacement and retrofit of in-use construction equipment, subsidy incentives have been widely recognized as a flexible and market-based policy instrument by many businesses and entities. Through paying money, subsidy policies motivate contractors to reduce the health and environmental risks posed by emissions from their construction equipment. The adoption of subsidy policies by governments is crucial for encouraging the transition to green construction equipment through promoting replacing and retrofitting in-use construction equipment. However, there is a lack of subsidy policies in Hong Kong for reducing CEE, and current models for determining subsidy levels are limited to formulating effective subsidy policies.

Thus, the primary aim of this research is to reduce CEE in Hong Kong through formulating proper subsidy policies. The specific objectives of this research are as follows: (1) To conduct a review on policy instruments for addressing CEE from a global perspective, and identify evolving trends, lessons, and accumulated experiences in developing policy instruments; (2) To conduct a review on the technologies for reducing CEE and examine their effectiveness; (3) To propose a quantitative model to determine appropriate subsidy levels for accelerating the replacement of exempted construction equipment in Hong Kong; (4) To propose a responsibility-sharing model to determine appropriate subsidy levels for promoting the replacement and retrofit of construction equipment fleet.

This research first conducts a holistic review and analysis on the development of CEE reduction policy instruments from a global perspective. Three groups of policy instruments are identified, including mandatory administration policy instrument (PI-A), economic incentive policy instrument (PI-B), and voluntary participation policy instrument (PI-C). Comparative analysis of CEE reduction policy instruments is conducted between advanced and developing-economy promoters. Then, the evolving trends, lessons, and accumulated experiences in developing policy instruments are identified. Secondly, this research examines academic journals, doctoral theses, conference papers, government reports, and other technical guidelines to summary technologies available for reducing CEE and identify emission reduction levels achievable by these technologies. Additionally, this research develops an effective quantitative model for determining the optimal subsidy levels to examine the relationship between emission reduction targets, early replacement of construction equipment, and subsidy levels to the equipment owners. The subsidy levels determined by the proposed model can effectively enable the early replacement of construction equipment and achieve the government's goal of reducing emissions from construction equipment. The subsidy levels determined by the proposed model can also avoid creating a financial burden on contractors to replace their equipment early for emissions reduction. Finally, a responsibility-sharing model is proposed, in which the subsidy level and the responsibility of the contractor and government assigned in proportion for emission reduction are determined with the attaining of minimum overall costs per ton of emissions reduced.

Key findings concluded from this research are from five perspectives. Firstly, advanced and developing-economy promoters have similarities and differences in developing CEE reduction policy instruments. For example, both advanced and developing-economy promoters overwhelmingly prefer to adopt PI-As. Developing-economy promoters may not have sufficient resources for implementing PI-Bs and PI-Cs. Advanced-economy promoters have devoted more efforts to developing PI-Bs and PI-Cs. Secondly, a mixture of PI-As, PI-Bs and PI-Cs can work better for reducing CEE, and policy instrument making should consider the contexts of promoters. Thirdly, the subsidy levels determined by the proposed model in Chapter 6 can effectively enable the early replacement of construction equipment and achieve the government's goal of reducing emissions from construction equipment. The subsidy levels determined by the proposed model can also avoid creating a financial burden on contractors when they replace their equipment early for emissions reduction. Setting emission reduction targets is closely related to the subsidy levels. Fourthly, subsidy levels set by governments have an impact on the decision-making of contractors in regards to the number of new purchased, replaced, retrofitted, salvaged and in-service construction equipment in each planning period. When governments change subsidy levels, contractors will adjust their equipment management strategies to minimize their costs. Therefore, through setting proper subsidy levels, governments can lead contractors to adopt optimal strategies of replacing and retrofitting construction equipment to reduce emissions with a minimum overall social cost. Finally, this study finds that one value of overall cost per ton of emissions reduced corresponds to many different apportionments of responsibility for emission reduction between the government and the contractor. Within the same overall cost per ton of emissions reduced, assigning less emission reduction responsibility to contractors can increase their motivation to participate in the subsidy incentive.

The review on global policy instruments for reducing CEE can promote the experience-sharing between developed and developing-economy promoters, which can help improve CEE reduction by formulating more effective policy instruments. On the other hand, this research provides valuable references for those countries and cities which have not yet introduced CEE reduction policy instruments to design effective policy instruments with the understanding of the development trends, lessons and experiences of the policy instruments adopted globally. Additionally, the quantitative model proposed in Chapter 6 targeted at exempted construction equipment is novel in its ability to ensure the achievement of emission reduction targets with subsidies, without exerting a financial burden on contractors. The responsibility-sharing model proposed in Chapter 7 innovatively incorporates the contractor and the government's emission reduction responsibility, determines the subsidy level to minimize the overall cost per ton of emissions reduced, and ensures emission levels of construction equipment fleet under limited levels. The proposed two models can also be used as an effective support tool by governments to determine optimal subsidy levels to accelerate and retrofit construction equipment replacement for emissions reduction. The development of these two models has significance in enriching the theoretical development of policy instruments for reducing extensive CEE, especially in the context of existing research mainly focusing on on-road vehicles.

Publications

Journal paper

1. Huang, Z., Fan, H., & Shen, L. (2019). Case-based reasoning for selection of the best practices in low-carbon city development. *Frontiers of Engineering Management*, 6(3), 416-432.

2. Huang, Z., Fan, H., Shen, L., & Du, X. (2021). Policy instruments for addressing construction equipment emission——A research review from a global perspective. *Environmental Impact Assessment Review*, 86, 106486.

3. Huang, Z., & Fan, H. (2022). A Novel Quantitative Model for Determining Subsidy Levels to Accelerate the Replacement of In-Use Construction Equipment for Emissions Reduction. *Journal of Management in Engineering*, 38(2), 04021100.

4. Huang, Z., & Fan, H. (2022). Responsibility-sharing subsidy policy for reducing diesel emissions from in-use off-road construction equipment. *Applied Energy*, 320, 119301.

Conference paper

5. Fan, H., & Huang, Z. (2020). Review of Learning Causal Bayesian Network for Diagnostical Analysis in Construction Resources Management. *In International Symposium on Advancement of Construction Management and Real Estate* (pp. 1099-1110). Springer, Singapore.

6. Huang, Z, & Fan, H. (2019). Smart pathway of cities responding to carbon emission in the context of China. *CIB World Building Congress construction smart cities*.

7. Huang, Z., & Fan, H. (2021). Formulation of construction equipment replacement and retrofitting strategies for emission reduction. *38th International Symposium on Automation and Robotics in Construction*. DOI: 10.22260/ISARC2021/0041.

Acknowledgments

I have gained a lot from the past three years of Ph.D. study in Hong Kong Polytechnic University. The successful completion of my studies and thesis owes to the kind support and help from many people. Here, I would like to take this opportunity to express my sincere thanks to all of them.

First of all, my heartfelt gratitude goes to my chief supervisor, Dr. Hongqin FAN, for the opportunity he offered me to study in the Department of Building and Real Estate of PolyU. I am also grateful for the continual guidance provided by Dr. Hongqin FAN to me through the three years. Without his valuable guidance and encouragement, I would not complete my research smoothly.

Next, my heartfelt thanks go to my co-supervisor, Prof. Linyin SHEN, who is also my M.sc supervisor, for recommending me to join Dr. Hongqin FAN's research team. I also thank the Research Grants Council of Hong Kong for fully funding my research. My thanks also go to all my friends, especially Ms. PENG Huiwen, Ms. Xie Yixin, Dr. LUO Ming, Mr. Yang Zhenchuan, Ms. CHEN Xi, Mr. WANG Dong, Dr. LIN Xuemei and Mr. HE Qun, for their kind company and support. Additionally, special thanks go to Chun Wo Engineering (H.K) limited for providing me with their historical recorded data on equipment performance, which is crucial to help me complete my thesis.

Last but not least, I would like to give my deepest gratitude to my family and boyfriend, Mr. XIA Houyi, for their continuous understanding, support, and unconditional love.

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Abbreviations

BAT	Best Available Technology
CBA	Community Benefits Agreement
CARB	California Air Resources Board
CDCH	Clean Diesel Clearing House
CEE	Construction Equipment Emission
CE_{con}	Cost Per Ton of Emission Reduced Incurred by the Contractor
CE_{gov}	Cost Per Ton of Emission Reduced Incurred by the Government
$CE_{con+gov}$	Overall Cost Per Ton of Emission Reduced Incurred by the Government and Contractor
CO	Carbon Monoxide
DERA	Diesel Emission Reduction Act
DERI	Diesel Emissions Reduction Incentive Program
DOC	Diesel Oxidation Catalysts
DPF	Diesel Particulate Filters
EER	Emissions Equivalent Reduction
EERT	Emissions Equivalent Reduction Target
EGR	Exhaust Gas Recirculation
ERIGP	Emissions Reduction Incentive Grants Program
EUAC	Equivalent Uniform Annual Cost

GNI	Gross National Income
HC	Hydrocarbon
HK EPD	Hong Kong Environmental Protection Department
LAEI	London Atmospheric Emissions Inventory
LAWA	Los Angeles World Airports
ICCT	The International Council on Clean Transportation
ILP	Integer Linear Programming
LCC	Life-cycle Cost
LP	Linear Programming
MIP	Mixed Integer Programming
NCDC	National Clean Diesel Campaign
NOx	Oxides of Nitrogen
NRMM	Non-road Mobile Machinery
PI-A	Mandatory Administration Policy Instrument
PI-B	Economic Incentive Policy Instrument
PI-C	Voluntary Participation Policy Instrument
PM	Particulate Matter
PM2.5	Fine Suspended Particulates with Diameters that are Generally 2.5 Micrometers and Smaller
PM10	Respirable Suspended Particulates with Diameters that are Generally 10 Micrometers and Smaller

SCR	Selective Catalytic Reduction
SJVAD	San Joaquin Valley Air District
SO2	Sulphur Dioxide
TCEQ	Texas Commission on Environmental Quality
TCFP	Texas Clean Fleet Program
TERP	Texas Emissions Reduction Plan
US EPA	The United States Environmental Protection Agency
VOCs	Volatile Organic Compounds

CHAPTER 1 Introduction

1.1 Introduction

This chapter depicts the fundamental blueprint of this study, which commences with introducing the research background and raising the research questions of this research. Then the research aim and objectives are stated, and the research scope is defined. Accordingly, the research design is undertaken, followed by the significance and contribution of this study. Finally, this chapter outlines the overall structure of this thesis.

1.2 Research Background

1.2.1 Emissions from Construction Equipment

Construction equipment has been increasingly recognized as a critical source of pollutant emissions in many countries and regions (Abbasian-Hosseini et al., 2016; Heidari & Marr, 2015; Lewis & Rasdorf, 2017; Masih-Tehrani et al., 2020, Yu et al., 2020). The use of construction equipment generates about 50% of the emissions in construction processes (Guggemos and Horvath, 2006). The United States Environmental Protection Agency (US EPA) (2006) claimed that in 2005 more than 37% of land-based non-road respirable suspended particulates (PM10) emissions and approximately one-third of land-based non-road oxides of nitrogen (NOx) emissions were produced by construction equipment in the United States. According to London Atmospheric Emissions Inventory (LAEI) 2016 (London Datastore, 2019), 34% of PM10 emission, 15% of fine suspended particulates (PM2.5) emissions and 7% of NOx emissions were emitted from construction equipment in London. Hong Kong Legislative Council stated that in 2015, non-road mobile machinery (NRMM) primarily construction equipment mitted 8% and 10% of local emissions of NOx and PM10 respectively (Legislative Council of HK, 2018b).

Construction equipment is mainly powered by diesel engines that emit considerable emissions, including significant amounts of PM and NOx, and lesser amounts of hydrocarbon (HC), carbon monoxide (CO) and toxic air pollutants (Kubsh, 2017; MECA, 2006; Ning et al., 2020). Diesel PM is generally composed of a carbon soot core with other materials adsorbed on the surface, including hydrocarbons, toxins, metals, and sulfates, of which more than 97% is PM 2.5 (RIDT, 2014). PM 2.5 is small enough to pass through the nose and throat, lodge deep in the lungs, and even enter the bloodstream directly through the lungs when inhaled. NOx combined with volatile organic compounds (VOCs) in the atmosphere produces ground-level ozone in the presence of sunlight, which is a respiratory irritant and can cause breathing problems for people with respiratory diseases (MassDEP, 2008). NOx can also contribute to the formulation of particulates. Therefore, the increase of CEE has posed a threat to public health. Short-term exposure to CEE can harm people with existing heart and respiratory problems like asthma, heart attacks and arrhythmias through aggravating these diseases (MassDEP, 2008b). Long-term exposure to these emissions would lead workers and citizens living near construction sites to suffer from respiratory and cardiovascular illness, lung cancer and even mortality (Mayor of London, 2014). Annually, about 500,000 deaths are caused by CEE around the world (Preston, 2018). Moreover, black carbon emissions, a dominant component of diesel PM, can contribute to adverse health impacts and climate change (US EPA, 2009).

The adverse impact of CEE is especially severe in urban areas. Urban areas usually have more construction activities than rural areas, leading to massive construction equipment use. Accordingly, a large volume of emissions is generated and emitted into the atmosphere. On the other hand, compared with rural areas, urban areas are more sensitive to CEE because they are usually densely populated and full of high-rising buildings. The canyon effect of high-rising buildings in urban areas prevents CEE from scattering and disappearing, resulting in a high emission concentration. According to a report issued by the Department of Economic and Social Affairs of the United Nations, the global population in 2018 was 7.6 billion, of which 4.2 billion in the urban areas (United Nations et al., 2019). It is predicted that by 2050 the global population will reach 9.7 billion, and 68% of the population will live in urban areas. Therefore, the accelerated urbanization process would also deteriorate the problem of extensive CEE, and mitigating its adverse outcomes is critical to improving the air quality.

1.2.2 Emissions from Construction Equipment and Existing Reduction Policy Instruments in Hong Kong

Since March 2000, the Hong Kong Environmental Protection Department (HK EPD) has annually published the *Hong Kong Air Pollutant Emission Inventory Report* on its website (HK EPD, 2021). This emission inventory comprises emissions from seven sectors of public electricity generation, road transport, navigation, civil aviation, other combustion sources, non-combustion sources, and hill fires. In this report, the amount of CEE is not available. However, construction equipment, a dominant contributor of other combustion sources, accounted for 52%, 54% and 53% of PM10, PM2.5 and NOx from other combustion sources, respectively, in 2019 (HK EPD, 2021). Thus, the amount of CEE can be roughly estimated according to emissions from other combustion sources, shown in Fig.1.1. From Fig.1.1, it can be noted that only emission sulfur dioxide (SO2) has been significantly reduced during the past two decades, and others remain at higher levels.

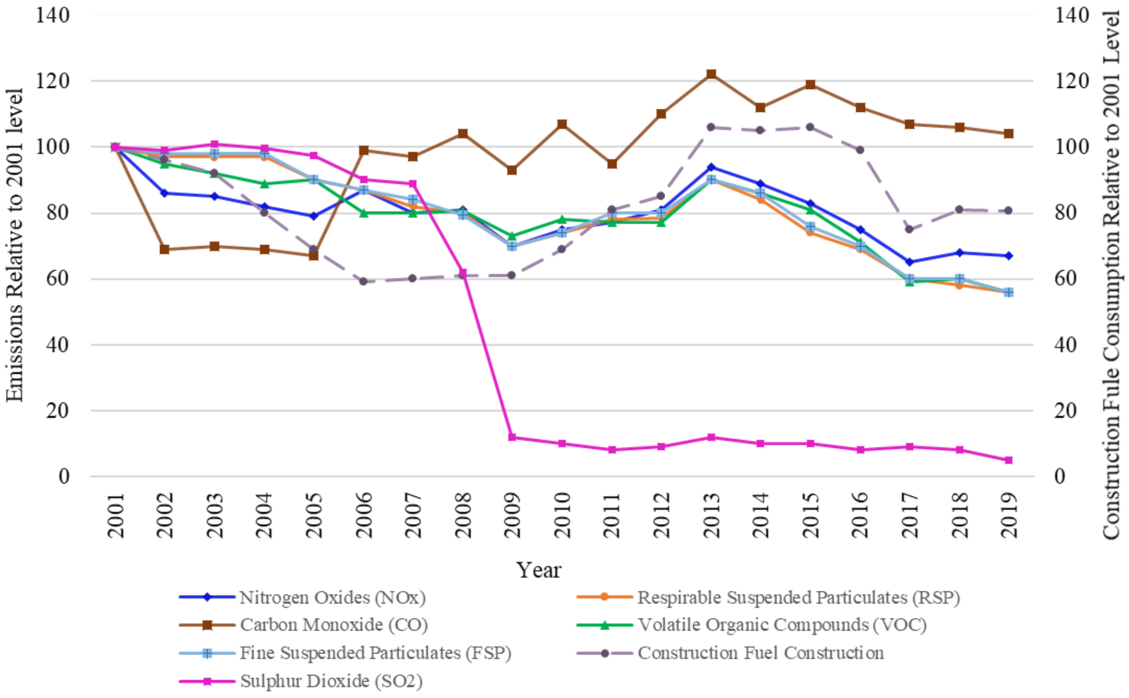

Fig.1.1 Emissions from other combustion sources

Moreover, the promulgation of the *Northern Metropolis Development Strategies (the Development Strategy)* by the former Chief Executive Carrie Lam of Hong Kong in October 2021 will aggravate the challenges of CEE mitigation in Hong Kong (Hong Kong, 2021). The Northern Metropolis generally covers two district administration areas, mainly including Yuen Long District and North District, with about 30,000 hectares. With the construction of the Northern Metropolis, many infrastructures will be built. As a result, the number of construction equipment is expected to grow even more quickly over the next few decades, consequently generating many emissions. Therefore, if appropriate reduction policy instruments are not taken soon, the problem of extensive CEE in Hong Kong is likely to worsen, posing a significant threat to the health and welfare of Hong Kong citizens.

However, efforts devoted by the Hong Kong government to address the problem of CEE are insufficient, with several regulations being released as shown in Table 1.1.

Table 1.1The existing related regulations issued by Hong Kong governments to control emissions from construction equipment

Regulation	Release time
Air Pollution Control (Smoke) Regulations	1983
Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation (First version)	2015
Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation (Second version)	2018
Emissions Control of Non-road Mobile Machinery in Capital Works Contracts of Public Works	2015

The earliest regulation implemented by the government is the *Air Pollution Control (Smoke) Regulations* issued in 1983, which is a subsidiary regulation of the *Air Pollution Control Ordinance* (HK EPD, 1983). According to this regulation, if any chimney or plant emits dark smoke for more than 6 minutes in any period of 4 hours or for more than 3 minutes continuously at any one time, its owner commits an offense. This regulation could only regulate the emission of dark smoke and is not specific for construction equipment or NRMM. Until June 2015, the HK EPD implemented the first specific regulation, *Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation*, to control emissions from NRMM (HK EPD, 2015). In 2018, the second version of this regulation was released with some amendments. According to this regulation, the NRMM in Hong Kong before 1 December 2015 are exempted from compliance with emission standards prescribed in this regulation. HK EPD estimates that in March 2015, approximately 14,200 NRMMs were in operation in Hong Kong, with more than 11,000 of these machines at construction sites (HK EPA, 2015). It can be perceived that a significant amount of emissions must be generated from applying these exempted construction equipment in construction works. In 2015, the Secretary for the Environment of Hong Kong Development Bureau promulgated the regulation of *Emissions Control of Non-road Mobile Machinery in Capital Works Contracts of Public Works* (HKDB, 2015). In this regulation, only four types of exempted NRMM must be phased out, including generators, air compressors, excavators and crawler cranes in new capital works contracts of public works, including design and build contracts with an estimated contract value exceeding $200 million. This regulation has slight effectiveness in controlling CEE because only a tiny fraction of construction equipment used in public works with an estimated contract value exceeding $200 million is regulated. The above introduction suggests that the development of measures for mitigating CEE is still in an early stage, and the existing policy instruments are insufficient in Hong Kong, especially those targeted at exempted construction equipment.

1.2.3 Subsidy Policies are Effective Instruments for Reducing Emissions from Construction Equipment

After years of use, construction equipment becomes inefficient through deterioration and produces higher levels of pollutants, which are extremely dangerous to public health (Dill, 2004; Gorji et al., 2021; Shao, 2016). For example, a bulldozer with a 175 hp engine emits as much PM as 500 new automobiles (US EPA, 2010). However, in Hong Kong, only newly imported construction equipment is bound by tighter emission standards, while these in-use ones are remarkably unregulated. The continuous use of old and high-emitting construction equipment also counteracts the reduction in emissions made by newer construction equipment that comply with more stringent emission standards (Hahn, 1995). Therefore, making construction equipment cleaner and more fuel-efficient is an increasingly urgent task for the Hong Kong government.

Replacing or retrofitting in-use construction equipment can dramatically reduce emissions, improve the air quality and deliver significant health benefits to those who live or work in or adjacent to construction sites (Alex et al., 2012; DTF, 2006; MECA, 2006). Newer construction equipment are generally more technically advanced and typically generate fewer emissions than older ones (Abbasian-Hosseini et al., 2015; Van Wee et al., 2000; Wee et al., 2011; Zaman &

Zaccour, 2020). Installing emission reduction technologies for retrofitting is also a good choice for reducing CEE in the context of Hong Kong, where contractors are likely to acquire used construction equipment, as reported by the Legislative Council of HK (2010). However, purchasing new equipment or emission reduction technologies will incur costs and bring financial burdens on contractors, which is one of the foremost barriers of governments promoting replacement and retrofit of construction equipment (AGCA, 2008; Bari et al., 2011; DTF, 2006). Consequently, adopting timely economic incentives like subsidy policies is crucial for encouraging the transition to green construction equipment by promoting replacement and retrofit of construction equipment.

Subsidy policies are instruments adopted by governments, which through paying money encourage contractors to replace or retrofit construction equipment for reducing the health and environmental risks posed by CEE (Dill, 2004; Gorji et al., 2021; Laborda & Moral, 2019; Lavee & Becker, 2009; Moretto, 2000; Zaman & Zaccour, 2021). Subsidy policies have been widely recognized as a flexible and market-based policy instrument by many businesses and entities, which can harness the market forces to give large, medium and small contractors motivation to find the minimum-cost way to reduce emissions. Consequently, environmental inspections and enforcement of governments become less necessary. In addition, subsidy policies can shift the burden of demonstrating compliance from governments to contractors. This feature of subsidy policies makes them especially appropriate in mitigating emissions from construction equipment. This is because construction sites are usually widely dispersed, and some are smaller. If traditional mandatory regulations are implemented to control emissions from construction equipment used on construction sites, many governance resources are needed for enforcement and frequent inspections.

Moreover, contractors usually have no incentive to do more than the mandatory regulations require, but subsidy policies can provide contractors with continuous inducements to reduce more emissions (US EPA, 2014). Thus incentive-based subsidy policies have been widely considered an effective tool for addressing the problem of extensive CEE. In addition, such subsidy incentives could bring significant environmental benefits. For example, from 2009 to 2013, US EPA provided subsidy incentives of $520 million to retrofit or replace 58,800 vehicles, vessels, construction equipment, and other pieces of equipment. It was estimated that this subsidy incentive program reduced 312,500 tons of NOx, 12,000 tons of PM2.5, 18,900 tons of HC, and 58,700 tons of CO (US EPA, 2016).

1.3 Research Problem Statement

The efforts of the Hong Kong government in addressing the severe problem of extensive CEE does not meet the challenges brought by CEE. The policy instruments in Hong Kong for reducing CEE are insufficient, with only newly imported construction equipment being regulated but in-use ones not. Especially, the government has not adopted any subsidy policies, which are effective tools for reducing CEE.

Before designing subsidy policies, it is necessary to have a better understanding of the development of policy instruments for reducing CEE from a global perspective, for providing some references to the Hong Kong government. Thus, the first research question is formulated.

(1) What CEE reduction policy instruments have been adopted worldwide? Are there any evolving trends, lessons, and accumulated experiences in developing policy instruments for reducing CEE?

The essence of making subsidy policies is to determine appropriate subsidy levels, which can offset partial or all contractors' costs of adopting CEE reduction technologies or purchasing new equipment and provide them with enough motivation to retrofit or replace their equipment for reducing emissions. Therefore, when determining subsidy, we should know what technologies are available for reducing CEE, their costs and degrees of emission reduction. Thus, the second research question is proposed.

(2) What are emission reduction technologies available for reducing CEE, their costs and degrees of emission reduction?

The exempted construction equipment in Hong Kong is usually inefficient through deterioration after many years of use and produces higher levels of pollutants. Replacing exempted construction equipment as early as possible can bring a lot of health benefits, therefore providing enough motivation to contractors for early replacement of their equipment is crucial. The following research question is proposed.

(3) How to make appropriate subsidy levels, which can provide contractors with enough motivation to replace their exempted construction equipment early?

When the harmful health effects are mitigated to some extent by providing contractors with subsidies for replacing their exempted construction equipment, contractors as the polluters should take some emission reduction responsibility. This is because subsidies are usually at the taxpayers' expense. If contractors do not shoulder any emissions reduction responsibility, taxpayers would ultimately bear the emission reduction responsibility that should be borne by contractors, inequity problems would be caused, and contractors would not be motivated to innovative more cost-effective emission reduction strategies. Accordingly, the last research question is proposed.

(4) How to assign responsibility for reducing emissions in proper proportions between contractors and the Hong Kong government?

1.4 Research Aim and Objectives

The primary aim of this research is to reduce CEE in Hong Kong through formulating proper subsidy policies. As discussed previously, the development of policy instruments for reducing CEE in Hong Kong is insufficient. Especially, any subsidy policies have not been developed in this city. For formulating effective subsidy policies for reducing CEE, it is necessary to have a better understanding of the evolving trends, lessons and accumulated experiences in the development of policy instruments in other cities, countries or regions. The analysis and empirical study of these lessons and experiences can provide significant insights for Hong Kong government. Thus, the first objective of this research is to conduct a review on policy instruments for addressing CEE from a global perspective, and identify evolving trends, lessons, and accumulated experiences in developing policy instruments.

Making appropriate subsidy levels is the key in formulating subsidy policies. Appropriate subsidy levels could provide contractors enough motivation to adopt CEE reduction technologies and achieve emission reduction targets, with not posing heavy financial burdens on Hong Kong Government. To find such subsidy levels that could partly or fully tradeoff the incremental costs incurred by adopting CEE reduction technologies and motivate contractors to adopt them, we should review technologies available for reducing CEE, their costs and degree of emission reduction. Therefore, the second objective of this research is to conduct a review on the technologies for reducing CEE and examine their costs and degrees of emission reduction.

As introduced previously, construction equipment in Hong Kong before December 2015 are exempted, which are very old and high-powered with extensive emissions. Quickly replacing these exempted construction equipment can achieve significant emission reductions and bring a lot of health benefits. Thus, the third objective of this research is to propose a quantitative model to determine appropriate subsidy levels for accelerating the replacement of exempted construction equipment and achieving the emission reduction targets. The subsidy levels determined by this model totally offset the costs incurred by early replacement, contractors will have enough motivation to replace their equipment.

After exempted construction equipment was gradually replaced, the problem of extensive CEE in Hong Kong would be mitigated to a certain degree. The government should consider assigning some emission reduction responsibility to contractors in the next stage. Therefore, the last objective of this research is to propose another one quantitative model, which assigns responsibility for reducing emissions in proper proportions between governments and contractors to minimize the overall costs per unit of emissions reduced. Furthermore, the subsidy levels determined by the responsibility-sharing model can encourage contractors to replace or retrofit their equipment and ensure the emission levels of construction equipment under set emission limits pre-set.

In summary, specific objectives of this research are as follows:

(1) To conduct a review on policy instruments for addressing CEE from a global perspective, and identify evolving trends, lessons, and accumulated experiences in developing policy instruments.

(2) To conduct a review on the technologies for reducing CEE and examine their costs and degrees of emission reduction.

(3) To propose a quantitative model to determine appropriate subsidy levels for accelerating the replacement of exempted construction equipment, not putting financial burdens on contractors, and ensuring the achievement of emission reduction targets set by the government.

(4) To propose a responsibility-sharing model to determine appropriate subsidy levels and assign responsibility for reducing emissions in proper proportions between governments and contractors.

1.5 Research Scope

This research is motivated by the severe problem of CEE in Hong Kong and the urgent need of the government for proper subsidy policies to address this problem. However, before conducting this research, the research scope should be defined.

(1) The essential elements of subsidy policies usually include funding, administration, subsidy levels, criteria of eligible applicants, and so on. Among these elements of subsidy policies, making proper subsidy levels are foremost and challenging. Therefore, this research mainly focuses on determining appropriate subsidy levels. Appropriate subsidy levels may have different meanings in different contexts. In this research, appreciate subsidy levels can achieve emission reduction targets, provide contractors enough motivation for accelerating the replacement or retrofit of construction equipment, and assign emission reduction responsibility in appropriate portions between the government and contractor.

(2) Construction equipment refers to all the heavy-duty self-propelled appliances and equipment, specially designed for executing construction tasks such as lifting, excavating and digging (Naskoudakis & Petroutsatou, 2016). Typical Construction equipment includes excavators, backhoe, bulldozers, wheel tractor scraper, loaders, tower cranes and so on. This research includes all the construction equipment used in construction projects such as building construction projects, road or transport projects.

(3) Construction equipment in Hong Kong can be classified into two groups, exempted construction equipment by the *Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation* and newly imported ones after the regulation took effect. The first proposed model in Chapter 6 mainly

targets these exempted construction equipment. The second model presented in Chapter 7 is for the two groups of construction equipment, namely, all construction equipment in Hong Kong.

(4) Construction equipment is mainly powered by diesel engines and emits significant amounts of PM and NOx, and less amounts of HC, CO and toxic air pollutants. Thus, in this research, CEE refers to emissions of PM, NOx, HC and CO generated by construction equipment.

1.6 Research Design

To achieve the aim and objectives stated before, the research path is designed and explained, see Fig.1.2.

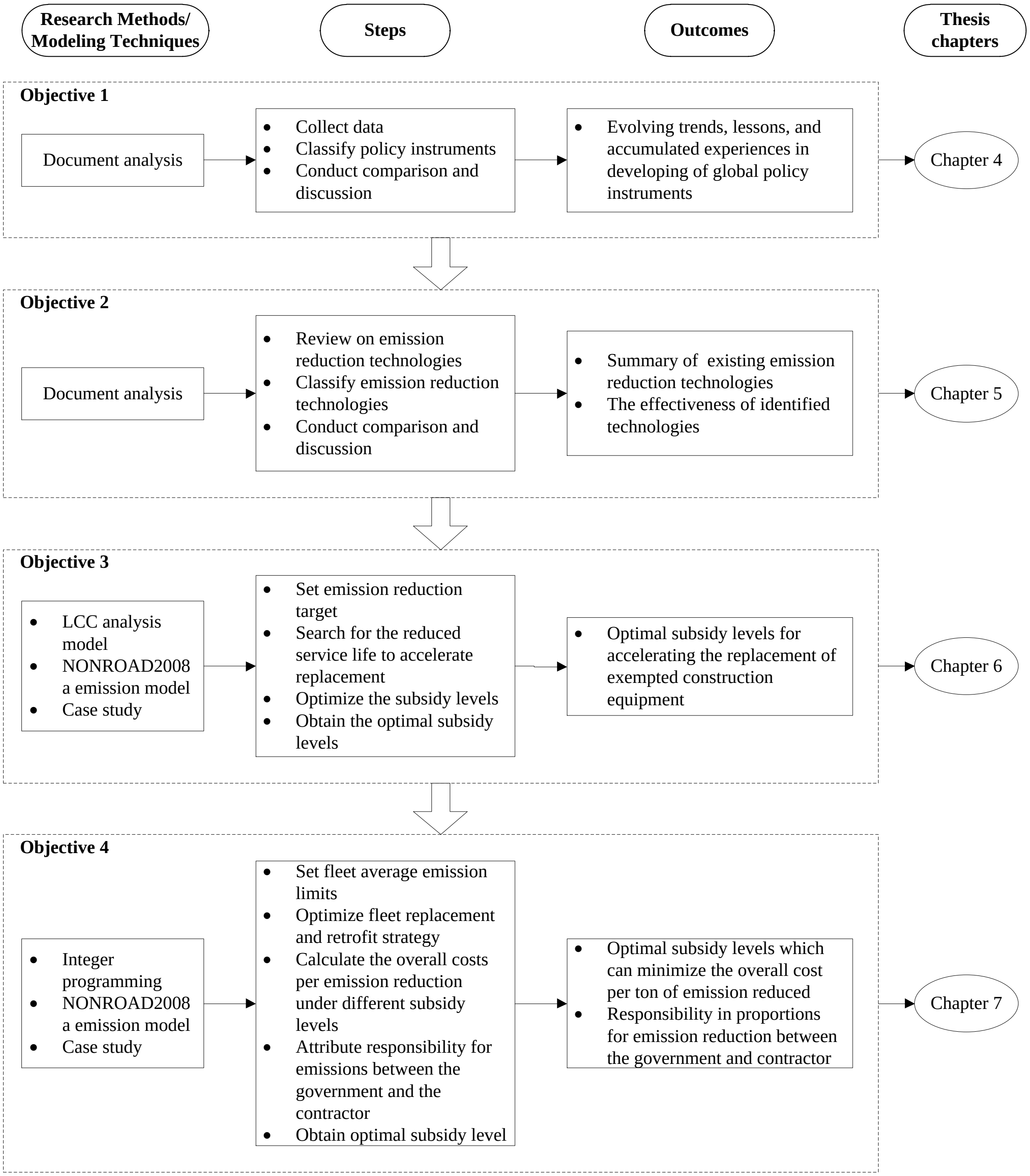

Fig. 1.2 The overall research path of the thesis

The first stage of this research intends to achieve Objectives I & 2. First, literature review on the policy instruments for reducing CEE from a global perspective is conducted. This review suggests that although subsidy policies are widely recognized as an effective tool to promote emission reduction technologies, the Hong Kong government has not formulated any subsidy policies. Moreover, the global evolving trends, lessons, and accumulated experiences in developing policy instruments are identified, providing some reference for the Hong Kong government. Then, a literature review on technologies for reducing CEE is conducted, suggesting that CEE mitigation can be achieved at the technology level. However, the main impediment to the widespread application of effective emission reduction technologies is that installing these technologies on construction equipment would put financial burdens on contractors. This stage leads to Chapter 4 and Chapter 5 of the thesis.

The second stage of this research is to achieve Objectives 3&4. In this stage, two quantitative models are established to determine appropriate subsidy levels for progressive reduction of CEE. The first model is developed using the life-cycle cost (LCC) analysis model, case study, and NONROAD2008a emission model. In this model, the reduced service life of an item of construction equipment for early replacement is first calculated according to emission reduction targets set by the government. In this process, the NONROAD2008a emission model is employed. Then, the economic life of construction equipment and its corresponding equivalent uniform annual cost (EUAC) can be determined by using a traditional LCC analysis model. Appropriate subsidy levels are obtained on the basis that the subsidized EUAC of a piece of construction equipment over its shortened service life is not more than that over its normal economic life. Finally, through a case study, the applicability of the first model can be demonstrated. The development of the first model leads to Chapter 6 of the thesis.

The second model employs the integer programming technique, case study, and NONROAD2008a emission model. First, the fleet average emission limits are set. Then an optimization model is proposed by using the integer programming technique to make optimal construction equipment replacement and retrofitting strategies with the financial subsidies and the constraint of meeting fleet average emission limit set before. Under the optimal replacement and retrofitting strategy, the amount of emission reduced by using the NONROAD2008a emission model and the costs per ton of emissions reduced of the government and the contractor can be obtained. Accordingly, the overall cost per ton of emissions reduced can be obtained. Then, by changing subsidy levels, the overall cost per ton of emissions reduced corresponding to each level of subsidy can be obtained. This study recommends reducing CEE with the minimum overall cost per ton of emissions reduced, ensuring the greatest emission reductions per dollar from the overall social perspective. Then, the responsibility for emission reduction between the government and contractor can be attributed, and the optimal subsidy is derived. Finally, through a case study, the applicability of the second model can be demonstrated. The development of the second model leads to Chapter 7 of the thesis.

1.7 Significance and Contribution of the Research

The significance and contribution of this research are reflected in the following aspects:

1) The review on global policy instruments for reducing CEE can promote the experience-sharing between developed and developing-economy promoters, which can help improve CEE reduction by formulating more effective policy instruments. On the other hand, this research provides valuable references for those countries and cities which have not yet introduced CEE reduction policy instruments to design effective policy instruments with the understanding of the development trends, lessons and experiences of the policy instruments adopted globally. For example, the Hong Kong government can take these existing subsidy policies as references when controlling CEE. These development trends, lessons and experiences can also help practitioners understand related CEE reduction policy instruments, thus gaining comparative competitiveness in the global market. The construction market has started to favor those construction businesses who engage in green practice in operating construction equipment and generate less CEE. The policy instrument classification framework established by this study can serve as an effective tool for studying policy instruments in other fields.

2) The proposed first quantitative model targeted at exempted construction equipment is novel in its ability to ensure the achievement of emission reduction targets with subsidies, without exerting a financial burden on contractors. The proposed quantitative model contributes to the development of research in formulating proper economic incentive policy instruments for emissions reduction. Governments can also use the proposed model as an effective support tool to determine optimal subsidy levels to accelerate construction equipment replacement for emissions reduction. The proposed model developed in this study could not only be applied to determine optimal subsidy levels for accelerating the replacement of construction equipment, but also could be used for early replacement of other in-service vehicles or equipment for environmental benefits. The development of this model also contributes to the body of knowledge of equipment replacement, which is a specific knowledge area of engineering management.

3) The proposed responsibility-sharing model has significance in enriching the theoretical development of policy instruments for reducing extensive CEE, especially in the context of existing research mainly focusing on on-road vehicles. This model innovatively incorporates the contractor and the government's emission reduction responsibility, determines the subsidy level to minimize the overall cost per ton of emissions reduced, and ensures emission levels of construction equipment fleet under limited levels. The proposed model could be used as an effective tool by Hong Kong and other countries to reduce CEE. Besides, by implementing the proposed responsibility-sharing model, the governance burden of governments could be reduced since contractors themselves will determine where the emission abatement efforts are most cost-effective.

1.8 Structure of the Thesis

This thesis includes eight chapters.

Chapter 1 sets the context of this research for the discussion in the following chapters, including the research background, research problem statement, research aim and objectives, research scope, research design, significance and contribution, and structure of the thesis.

Chapter 2 conducts a thorough review of the literature regarding technologies and policy instruments for reducing CEE, and the issues of vehicle or equipment replacement or retrofit subsidy incentives.

Chapter 3 presents the methodology of this study, which commences with establishing the methodology framework. Then, the detailed research methods and modelling techniques employed in this study are explained, including document analysis, case study, LCC analysis model, integer programming method, and NONROAD2008a emission calculation model.

Chapter 4 conducts a holistic review and analysis on the development of CEE reduction policy instruments from a global perspective. Three groups of policy instruments are identified, including PI-A, PI-B, and PI-C. Comparative analysis of CEE reduction policy instruments is conducted between advanced and developing-economy promoters.

Chapter 5 introduces and summarizes the existing emission reduction technologies for reducing CEE and the costs of these available technologies.

Chapter 6 proposes a quantitative model to determine the appropriate subsidy levels for voluntary early replacement of high-emission exempted construction equipment. The model is established by integrating emission reduction targets and LCC of construction equipment to calculate the reduced service life of an item of construction equipment for early replacement. The economic life of construction equipment and its corresponding EUAC can be determined by using a traditional LCC analysis model. Appropriate subsidy levels are obtained on the basis that the subsidized EUAC of a piece of construction equipment over its shortened service life is not more than that over its normal economic life. The applicability of the proposed model is demonstrated through a case study of a crawler crane used in Hong Kong. An interview with the contractor’s equipment manager responsible for the crawler crane is conducted to validate the model.

Chapter 7 proposes a responsibility-sharing model to determine appropriate subsidy levels. First, an optimization model is proposed to optimize construction equipment replacement and retrofitting strategies with the financial subsidies and the constraint of meeting the fleet average emission limit set before. Under the optimal replacement and retrofitting strategy, the amount of emissions reduced, the costs per ton of emissions reduced of the government and contractor, and the overall cost per ton of emission reduced are obtained. Then, by changing subsidy levels, the overall cost per ton of emissions reduced corresponding to each level of subsidy can be obtained. This study selects the subsidy level, which reduces CEE with the minimum overall cost per ton of emissions reduced. Then, the responsibility for emission reduction between the government and contractor is assigned, and the proper subsidy level is obtained. Finally, through a case study, the applicability of the model can be demonstrated.

Chapter 8 concludes this research by summarizing the findings of this research, highlighting the contribution, and discussing the limitations and future work.

1.9 Chapter Summary

This chapter first sets the context of this research by introducing the research background. Then, the research problems are indicated, followed by the aim and objectives. Then, before designing this research, the research scope is narrowed. Finally, the significance and contribution of this research are highlighted, and the structure of the thesis is presented.

CHAPTER 2 Literature Review

2.1 Introduction

This chapter begins with reviewing the literature on technologies for reducing CEE. Review on policy instruments for reducing CEE and the practices of making subsidy policies then be presented, followed by a discussion of existing models for determining subsidy levels. The purpose of literature review is to provide an understanding of the previous research in this area.

2.2 Technologies for Reducing CEE

Previous studies mainly focused on explaining how emission reduction technologies work. For example, a technical report issued by the John Deere Power Systems Division of Deere Company in the United States presented the applications of the platinum group metal-based diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) technologies installed on US Tier 4i non-road machines (Dou, 2012). In this study by Dou (2012), the design and performance of engine emission reduction after-treatment systems are discussed. RIDT (2014) described the available retrofit technologies for construction equipment, including DOC, flow-through filters, DPF and closed crankcase ventilation systems. The study of Zhong et al. (2017) evaluated the emission characteristics of a non-road diesel engine retrofitted with a DPF, suggesting that a DPF could effectively lower the mass and number concentrations of PM emissions. MECA (2000) summarized the technologies of catalyst-based DPF and NOx adsorbers for reducing emissions from NRMM and the effects of fuel sulfur on these technologies. Another important strand of literature has presented the cost of emission reduction technologies and the ability of emission reduction of these technologies. For example, Zhong et al. (2017) suggested that using DPF can effectively trap the mass of PM more than 90% and the number of PM was over 99%. Moreover, some web-based tools have been developed to help users determine the best available emission reduction technologies. For example, to promote New York state governments to comply with the Best Available Technology (BAT) regulations for retrofitting construction equipment, the Clean Diesel Clearing House.Org was created by the New York State Energy Research and Development Authority. The Clean Diesel Clearing House.Org is a web-based tool, which can contain options available for reducing emissions of in-use diesel engines and can help users to determine BAT for emission reduction.

2.3 Policy Instruments for Reducing CEE

2.3.1 Policy Instruments

Policy instruments are the techniques, methods, or tools used by governments to promote certain policies to achieve a predefined set of goals (Hettiarachchi & Kshourad, 2019; Shen et al., 2016). Hettiarachchi & Kshourad (2019) further explained that policy instruments are interventions designed by governments to motivate all stakeholders involved in the issue at stake. Policy instruments are also the linkage between policy formulation and implementation, and the intention of policy formulation is reflected in policy implementation through instruments (Ali, 2013). Making clear and realistic objectives during policy formulation is critical to success because a lack of objectives may lead to losing directions in the long run of policy implementation. Motivation is another key component of effective policies, and without motivation policies would fail in the implementation process. Linder & Peters (1989) proposed that policy instruments have four essential attributes, including resource intensiveness, targeting, political risk, and difficulties with coercion and ideological principles limiting government activity, which are usually considered by the government when designing a policy.

Some literature classified policy instruments according to various criteria. McDonnell & Elmore, 1987) defined four generic classes of policy instruments, including mandates, inducements, capacity-building, and system-changing. Mandates are rules governing the action of individuals and agencies and are intended to produce compliance. Inducements transfer money to individuals or agencies in return for certain activities. Capacity-building is the transfer of funds to invest in material, intellectual, or human resources. System-changing transfers official authority among individuals and agencies to alter the public goods and service systems. Kirschen (1964) classified policy instruments into 64 generalized types. Lowi (1964) noted that policy instruments are regulative or non-regulative. Hood (1995) grouped policy instruments into government information, government authority, government finance, and government formal organization from the perspective of governmental resources. Howlett et al. (2009) classified policy instruments into voluntary instruments, administrative instruments, and hybrid instruments based on mandatory degrees. From a similar classification perspective of mandatory degree, Zhang (2008) grouped policy instruments into direct financial support and service, government-commissioned subsidy, format franchising, voluntary service, and market operation. Schneider and Ingram (1997) classified policy instruments into incentive, symbol and advice, capability-building, and learning instruments according to the purpose of policy instruments. Bemelmans-Videc et al. (1998) defined three groups of policy instruments, including legal instruments, communication instruments, and economic instruments according to the value of policy instruments. Similarly, Chen (1999) also classified policy instruments according to instrument value, including business management technology, marketization, and socialization instruments. Elliott (2002) identified ten types of policy instruments, including direct management, society regulation, economic control, contract, finance allocation, direct loan, loan credit, insurance, tax, and government corporation. These policy instruments are technically substitutable because there are some similarities between them, and they can be employed to achieve the same policy objectives (Ali, 2013; Landry & Varone, 2005). There is also a body of research focusing on combining multiple policy instruments for designing “instrument mixes” (Howlett & Rayner, 2007). These classification criteria or fundamental attributes can provide different analytical frameworks to identify similarities, differences, strengths, and weaknesses among various policy instruments for policy makers (Henstra, 2016).

2.3.2 Research on the Development of Policy Instruments for Reducing CEE

This section examines previous studies related to policy instruments for reducing CEE. The emissions generated by off-road construction equipment have been regulated since the mid-1990s in the United States and more recently in Canada, Japan, China, and India. The regulation of off-road emissions far lags behind that of emissions generated by on-road diesel engines (MECA, 2006; MSW EPA, 2014; US EPA, 2006). Some existing studies have pointed out the importance of policy instruments for reducing CEE. Lewis et al. (2009) stated that construction equipment is mainly powered by diesel engines and is a primary non-road source of air pollution. They believed that policy instruments like regulatory and incentive programs should be developed to achieve emissions reduction. Waluś et al. (2018) claimed that air pollution concentrations are still high in Europe and NRMM is one of the main contributors of extensive emissions. Thus, Waluś et al. (2018) emphasized that emission reduction through implementing legal regulations is necessary due to its direct influence on humans’ health who live in Europe. According to the report by Environ Australia Pty Ltd (2010), implementing US EPA emission standards for NRMM in Australia will lead to annual NOx emission reductions of between 44,100 and 65,600 tons by 2020 and between 57,000 to 92,300 tons by 2030. These emission reductions can bring to Australia annual environmental benefits estimated to range from \$2.5 to \$4.7 billion. Others suggested that the promotion of environmental policy instruments in the domain of construction could accelerate technology innovation to reduce emissions from construction activities (Noailly, 2012; Popp, 2002).

This is particularly the case in the development of policy instruments and technologies for reducing CEE.

Moreover, previous studies have cast light on the importance of subsidy policies as helpful economic incentives in addressing the problem of emissions generated by vehicles or equipment. For example, Dill (2004) stated that subsidy policies can reduce emissions from older and polluting in-use vehicles through replacing them earlier than would normally occur by offering a financial incentive. Fan et al. (2020) indicated that subsidy policies are effective tools that governments can employ to address the problem of considerable energy consumption and environmental pollutions by vehicles. This is echoed with the study of Gorji et al. (2021), suggesting that subsidy policies can incentivize users to retire vehicles as soon as possible and mitigate the environmental degradation caused by the proliferation of vehicles. Jeanrenaud (1997) indicated that subsidy incentives that rely on market-based incentives generally offer better efficiency and effectiveness, which are more flexible and directly give the concerned agents greater freedom to choose means, thus reducing abatement costs and achieving environmental targets faster and more reliably.

There is a limited number of studies in addressing the policy instruments for reducing CEE. This conclusion is based on web research by inputting keywords “policy instrument”, “emission”, “emission reduction”, “construction equipment” and “Non-road Mobile Machinery”. In extending web search, this study also examines government regulatory documents and reports published by various international organizations. However, it is appreciated that government regulatory documents and reports are generally designed for a specific country. For example, Environ Australia Pty Ltd (2010) suggested no specific policy instruments in Australia to address CEE. Based on the fact that in Australia the construction equipment is imported rather than manufactured domestically, Environ Australia Pty Ltd (2010) recommended policy instruments to ensure the supply and purchase of cleaner construction equipment. Another research on policy instruments for reducing non-road diesel emissions in Australia is conducted by MSW EPA (2014), which summarized the current regulation framework and programs in Australia. The current regulatory framework for non-road diesel engines in Australia primarily includes fuel quality specifications and the regulation of ambient air quality (MSW EPA, 2014). Emission standards are applied for on-road vehicles in Australia, while no emission standards have been issued for non-road diesel vehicles and equipment including construction equipment. The Mayor of London (2014) reviewed air quality legislation in the EU by introducing the regulations and laws for reducing CEE. It presented a number of CEE reduction policy instruments adopted by London, including emission standards of the London Low Emissions Zone, policy instruments of reducing idling time of construction equipment, Construction Logistics Plans in construction sites, and the regulation for using railways and waterways when construction sites are located close to waterways or railways. The California Air Resources Board (CARB) (2010) summarized the local regulations that address PM emissions from diesel-fueled engines and recommended choosing proper technologies to control PM emissions. The Transportation Division Environment Canada (2012) has published two versions of guidance documents to provide detail information about the requirements of Off-Road Compression-Ignition Engine Emission Regulations in Canada. Lewis et al. (2009) introduced the existing primary policy instruments for reducing CEE in the United States, which are mandatory regulations including technological standards that impose emission limits on diesel engines and air quality standards that limit the acceptable level of air pollutant emissions in the atmosphere. US EPA (2006) examined EPA’s efforts to reduce nonroad mobile source emissions, opportunities for emission reduction and challenges to addressing nonroad emissions problems. As of 2006, EPA has since issued 14 regulations to control pollutants from nonroad mobile sources, with a total of 20 standards for various nonroad categories (US EPA, 2006). However, there were still about 5 million nonroad diesel engines in the United States in 2006, and many of them are not subject to EPA emissions standards (US EPA, 2006). It can be predicted that these exempted engines would produce high levels of pollution over the next 20 years or more. US EPA (2006) also suggested that technical challenges, the diversity of nonroad engines, and the wide range of applications posed some challenges to meeting air quality standards and emission reduction goals of the United States. In the report issued by the US EPA, incentive programs are introduced and assessed, which are implemented at the federal, state, regional, and local levels of the United Stated to reduce emissions from off-road diesel engines used in the construction sites and port sector (IFC Consulting, 2005). According to this report, incentive programs mainly include grant programs, tax incentives, modified contracting procedures, and non-monetary incentives (IFC Consulting, 2005). The report issued by European Commission Joint Research Centre in 2014 suggested that the European Union addressed the issue of extensive emissions from NRMM by implementing the European Commission directives, including the Directive 97/68/EC8 and the amendments to this Directive like Directive 2002/88/EC9 and the Directive 2004/26/EC10.

A body of studies mainly focuses on the retrofit technology strategies for reducing CEE. This body of studies has demonstrated the effectiveness of retrofitting diesel engines in reducing emissions and thus can provide some reference and guidance to policymakers for making effective policy instruments to promote the retrofit of construction equipment. For example, Frey (2010) investigated the relationship between the amount of CEE and the equipment attributes such as speed and engine age, and suggested that emissions reduction can be achieved by adjusting the equipment attributes. MECA (2006) conducted case studies on projects for retrofitting diesel-powered construction equipment with emission reduction technologies and highlighted some technology-based lessons or experience which may be helpful in initiating other construction equipment retrofit projects. MassDEP (2008) proposed a technology-based “road map” for completing construction equipment retrofit, including choosing the right technology and procuring and installing a device. In the study by MassDEP (2008), case studies of several successful retrofit projects were also introduced. Kubsh (2017) summarized important features and experiences of successful retrofit program efforts primarily in the United States and Europe, as well as highlighted the range of retrofit technologies that have been successfully used to reduce exhaust emissions from older, existing on-road and off-road diesel engines. Kubsh (2017) concluded several important aspects of successful retrofit programs, including selecting the appropriate retrofit technologies based on the engine application, duty cycle and available fuel quality, continued maintenance of the engine and retrofit technology, professional installation of the retrofit device, and training programs for end users.

2.4 Subsidy Policies for Reducing CEE

2.4.1 Practices of Developing Subsidy Incentive Programs

This section reviews the development of subsidy incentive programs for promoting early replacement and retrofit of construction equipment to examine how subsidy levels are determined in practice. IFC Consulting (2005) stated that most subsidy incentive programs are initiated in the United States. Thus this section mainly examined the subsidy incentive programs implemented in this country, which are designed by a top-down approach.

Since 2008, the Diesel Emission Reduction Act (DERA) has authorized EPA to offer grant funding to eligible entities for accelerating the replacement and retrofit of highway vehicles, marine engines, locomotives and nonroad engines, equipment, or vehicles such as these used in construction, agriculture, mining or energy production, with a goal of reducing diesel emissions (US EPA, 2019). Eligible entities include regional, state, and local agencies, tribal governments, native villages, port authorities with jurisdiction over transportation or air quality, and nonprofit organizations or institutions (US EPA, 2019). Eligible diesel emissions reduction solutions include verified retrofit technologies such as exhaust after-treatment technologies, engine upgrades, and cleaner fuels and additives, verified idle reduction technologies, verified aerodynamic technologies, verified low rolling resistance tires, certified engine replacements and conversions, and certified vehicle or equipment replacement (US EPA, 2019). The total amount of DERA funding is usually determined by the availability of funds, the quantity and quality of applications received, and other considerations. DERA funding is first dispersed among ten EPA regions according to 1) the percentage of the population that is living in PM2.5 and Ozone nonattainment areas that is attributable to the region, and 2) the percentage of the total NOx and diesel PM emissions from mobile sources that is attributable to the region. The ten EPA regional offices are responsible for selecting and managing awards (US EPA, 2020).

The DERA program has two components: a national competition program and a state allocation program, which utilize 70% and 30% of the funding, respectively (US EPA, 2009). The national clean diesel programs offer competitive grants in three categories: the National Clean Diesel Funding Assistance Program, the National Clean Diesel Emerging Technologies Program, and the SmartWay Clean Diesel Finance Program (US EPA, 2009). The National Clean Diesel Funding Assistance Program reduces diesel emissions through retrofitting school buses, repowering locomotives used at seaports, and replacing high-emitting construction equipment used to build hospitals and roads (US EPA, 2009). The National Clean Diesel Emerging Technologies Program mainly fosters the deployment of innovative technologies, which have not yet been verified or certified by EPA or the California Air Resources Board (US EPA, 2009). Finally, the SmartWay Clean Diesel Finance Program establishes national low-cost revolving loans and other financing programs to fund fleets to reduce diesel emissions (US EPA, 2009). The DERA national Grants program is a competitive grant program that uses ten criteria with different points to rank applications and select awarded programs. These criteria include projects summary, programmatic priorities, past performance, environmental results, budget, clear description of the target fleet, leveraging resources and partnering, staff experiences and regional significance.

The State Clean Diesel Grant program is not a competition but an allocation process. The states interested in participating apply for the funds, and the EPA awards a specific allocation based on the total number of states whose applications are approved. The eligible states and territories then distribute funds to states' air quality management districts, which have the discretion to set their own subsidy levels with the guidance provided by EPA about the process for applications (US EPA, 2020). DTF (2006) reported that in most states or territories, financial subsidy allocation is a competition, in which a "cost-effectiveness formula" is used to rank the applicants, and the applicants with low cost-effectiveness will be awarded. The Carl Moyer Memorial Air Quality Standards Attainment Program (the Moyer Program) implemented since 1998 by California Air Resources Board (CARB) and the Texas Emissions Reduction Plan (TERP) program implemented by the Texas Commission on Environmental Quality (TCEQ) since 2001 are two major statewide subsidy incentive programs.

In the Moyer Program, repower projects of existing equipment, retrofit purchase, and equipment replacement are eligible for funding (CARB, 2017). These funded projects are subjected to maximum eligible funding amounts and cost-effectiveness limits. Maximum eligible funding amounts for diesel repower, equipment replacement, and retrofit projects are 85%, 80%, and 100% of the incremental costs, respectively (CARB, 2017). Project cost-effectiveness limits change over time based on the Consumer Price Index, increasing from $ 12,000 in 1998 to $ 18,262 in 2016 per weighted ton of emissions reduced (CARB, 2017). In 2017, two cost-effectiveness limits were proposed for the Moyer Program, including base limit and optional advanced technology limit. The base cost-effectiveness limit is $30,000 per weighted ton of emissions reductions, allowing full funding for a wide range of currently typical projects, such as diesel replacement projects (CARB, 2017). The optional advanced technology limit is $100,000 per weighted ton of emissions reductions. The optimal advanced technology limit is used for zero-emission advanced technology projects to achieve incremental emission reductions that conventional projects would not achieve

(CARB, 2017). To ensure the greatest emission reductions per dollar, districts usually selected the applicants with estimated cost-effectiveness far beyond these cost-effectiveness limits (CARB, 2011).

The TERP program comprises eleven different funding programs, including emissions reduction incentive grants, rebate grants, small business grants, third-party grants, PM reduction grants, and other programs (TCEQ, 2020). Under the emissions reduction incentive grants program, non-road equipment including construction equipment with engines rated at 25 horsepower or greater is eligible for subsidy (TCEQ, 2020). Eligible activities include lease or purchase of new construction equipment, replacement, retrofit and repower of old construction equipment, and adding emission reduction technologies on construction equipment (TCEQ, 2020). The TERP program also gives special consideration to small businesses that own and operate not more than five pieces of equipment. Small businesses reducing NOx emissions through repower, replacement, and retrofit equipment or engines are eligible for this subsidy incentive program (TCEQ, 2020). The allocation of fundings among applications is also a competitive progress. Similar to the Moyer program, projects eligible for funding under the TERP program are subjected to maximum eligible funding amounts and cost-effectiveness limits (TCEQ, 2020). Eligible replacement projects can reimburse up to 80% of the incremental cost through the TERP program, and projects of retrofit and repower can reimburse 100% of the incremental cost (TCEQ, 2020). All applications also should reduce NOx with the cost-effectiveness limits specified by the TERP program. From 2015 through 2017, the cost per ton limits was set by the TCEQ program at $15,000 per ton of NOx reduced for projects of replacing and retrofitting construction equipment (TCEQ, 2020). From 2018, the cost per ton limits have been set by TCEQ at $17,500 per ton of NOx reduced. After the procedure of project solicitation, all eligible applicants will be ordered by their estimated cost-effectiveness (TCEQ, 2020). The applicants with lower cost-effectiveness and ranking top would be awarded.

2.4.2 Drawbacks in Existing Subsidy Incentive Programs

However, there are some drawbacks to this competitive approach. For example, most subsidy incentive programs aim at off-road equipment, which means that both construction equipment and other off-road equipment like agricultural equipment compete for subsidy funding (US EPA, 2009, 2012, 2016, 2019). However, under the cost-effectiveness based competitive subsidy allocation mechanism, construction equipment usually does not have enough of a competitive edge. This is because construction equipment is usually less intensively used than other frequently used equipment like agricultural equipment and so they have greater difficulty in achieving the cost-effectiveness criterion (IFC Consulting, 2005). Thus, a model specialized for construction equipment that quantifies the relationship between emission reduction and subsidy levels is essential for governments to find the proper subsidy levels to reduce emissions from construction equipment.

Except for a cost-effectiveness threshold, the San Joaquin Valley air district (SJVAD) imposes a funding cap of $40,000 on subsidies, which can just cover a small fraction of the replacement costs of construction equipment like scrapers (SJVAD, 2008). The replacement cost of construction equipment is prohibitive to small construction companies without sufficient financial subsidies. This situation is common in the United States, where the majority of companies are quite small, with 92 percent of firms having fewer than 20 employees (DTF, 2006). Thus, although replacement of construction equipment can provide more cost-effective emission reductions and usually has higher scores in the project selection process, construction companies typically hesitate to apply for the grants because of the subsidy cap. A subsidy model that objectively considers the financial burden on owners of construction equipment is needed but not yet available. There are some subjective methods adopted by state or local governments of the USA. For example, according to the guidelines of the Carl Moyer Memorial Air Quality Standards Attainment Program's Off-Road

Voucher Incentive Program implemented by CARB, the subsidy amounts for replacement of agriculture tractors are directly given without any theoretical analysis (US EPA, 2020).

Most subsidy policies implemented in the United States do not consider the responsibility of contractors for reducing emissions from construction equipment. This feature of the existing subsidy policies is sometimes criticized (US EPA, 2004). This is because subsidies are an expenditure of taxpayers' money. When governments provide subsidies to offset the full cost of reducing emissions, taxpayers ultimately totally bear the emission reduction responsibility that should be borne by contractors (Zhou et al., 2011). Therefore, attributing responsibility for emission reduction only to taxpayers is not equitable, and this issue should be considered when formulating policy instruments. Otherwise, emission reduction will remain a challenge (Bastianoni et al., 2004). Moreover, when governments totally bear the responsibility for emission reduction, it will be tough to stimulate contractors to innovate more cost-effective emission reduction strategies. Thus, to address these problems, a subsidy policy for reducing emissions of construction equipment is necessary, in which the responsibility for reducing emissions is shared between contractors and governments.

2.5 Research on Determining Subsidy Levels for Promoting Replacement or Retrofit of Equipment

This section reviews the key literature concerned with determining subsidy levels for prompting replacement or retrofit of equipment. Clearly understanding the impact of subsidies on the replacement or retrofit of equipment is an essential premise to determination of appropriate subsidy levels. Thus, this section first reviews the literature on this concern. The academic models are then reviewed as a counterpart of making subsidy levels in practice.

2.5.1 The Impact of Subsidies on the Replacement or Retrofit of Equipment

By reviewing previous studies, this research finds that limited attempts have been made to investigate the impact of subsidy incentive programs on equipment replacement or retrofit. Existing studies mainly focus on other factors impacting equipment replacement, such as obsolescence, downtime, and inflation. Obsolescence is the reduction in value caused by the fact that newer equipment is superior to older equipment due to technological improvement (Gunawardena, 1990). Obsolescence can be subdivided into two types of technological obsolescence and market-preferred obsolescence (Gransberg et al., 2006). Technologically newer equipment usually has good performance and high productivity, which can reduce the cost of maintenance and operation as well as make more revenues. Thus, as revealed by Al-Ghamdi (2001) and Nair & Hopp (1992), obsolescence can result in changes in the cash flow of equipment and further affect replacement decision-making. Some traditional equipment replacement models considered obsolescence and incorporated it in a deterministic manner (Aronson & Aronofsky, 1983.; Bean et al., 1994; Chand & Sethi, 1982; Sethi & Chand, 2008) or a stochastic manner (Goldstein et al., 1986, 1988; Hopp & Nair, 1991; Nair & Hopp, 1992). Downtime is also widely considered as an important factor influencing equipment replacement. Alarcón et al. (2011) stated that downtime means unavailability of equipment, which can cause loss of ownership cost, operating cost, operator cost and productivity and make equipment owners change their replacement decisions. Various methods have been existed in previous research for estimating downtime cost. For example, Chen & Keys (2009) relied on historical data to measure downtime cost. Lucko (2011) and Vorster & Sears (1987) estimated downtime cost based on failure cost profiles, which are obtained from meetings with some equipment manufacturers and owners. Alarcón et al. (2011) conducted a simulation case study to qualify the downtime cost for a company engaged in tunnel construction. Inflation is another economic factor affecting the equipment replacement in a manner of buy power loss of national currency and increased price of new equipment (Thuesen and Fabrycky,1994; Al-Ghamdi, 2001). Existing research considers the effect of inflation under some assumptions when making equipment replacement decisions. For example, Thuesen and Fabrycky (1994) assumed that the inflation rate influences each cash flow equally and then removed inflation from the interest rate by using an inflation-free discount rate, which was calculated by dividing one plus the discount by one plus the inflation rate. And some studies measured inflation by using various indexes, including Consumer Price Index, Wholesale Price Index, the Engineering News-Record Cost Indexes (Building and Construction), and the Federal Highway Administration Bid Price Index (Al-Ghamdi, 2001).

Previous studies have also suggested that compliance with environmental policy instruments usually leads equipment owners to incur costs or earn revenues and further impacts equipment replacement. As Kim et al. (2003) presented, strict environmental regulations can result in a shorter lifetime and accelerate equipment replacement. Spielmann and Althaus (2007) also affirmed that equipment replacement programs initiated by governments for reducing emissions might result in greater financial burdens on contractors and change their equipment replacement schedule. Stasko and Gao (2012) indicated that equipment retrofit regulations would bring two types of changes in equipment value. One change is that relatively new non-compliant equipment would decrease in value and be replaced earlier than previously planned, and the other change is that compliant equipment that is a few years old increases in value. The existing research on the impact of environmental policy instruments on equipment replacement is at the stage of discussion. With the impact of environmental policy instruments on equipment replacement revealed by previous studies, a body of research has incorporated the impact into making replacement decisions. For example, Afrinaldi et al. (2017) developed a mathematical model optimizing the preventive replacement schedule to minimize equipment's total economic and environmental impacts. In the model by Afrinaldi et al. (2017), the decision variables of the models are equipment replacement policies or schedules, and the objective function is the minimization of economic costs and environmental impacts. In order to reduce the impact of replacement activity on the environment, Liu et al. (2016) presented a remanufacturing time model minimizing the global warming potential of components based on reliability and replacement theories. Some studies incorporated emission costs into equipment replacement models. For example, Ahani et al. (2016) developed an optimization framework using the method of integer nonlinear programming, which takes into traditional costs like purchase cost and emission costs, for determining an optimal combination of electric vehicles and internal combustion engine vehicles. Ansaripoor et al. (2014) proposed a stochastic mixed integer linear programming model that incorporated carbon prices to replace some vehicles.

Only limited literature has investigated the impact of subsidy policies on the replacement of equipment or vehicles. For instance, Zaman and Zaccour (2020) applied a dynamic model to examine the impact of different subsidy levels paid by the government on the different groups of owners of vehicles. The study of Zaman and Zaccour (2020) indicated that increasing subsidies does motivate low-value owner groups to replace their vehicles earlier but sometimes delays the vehicle replacement of groups with high net trade-in valuation. To examine the ability of financial subsidies to encourage owners to replace old vehicles, Moretto (2000) calibrated the simple stochastic model proposed by Alberini et al. (1996) to help vehicle owners make optimal decisions with regards to deciding whether to participate in a vehicle-replacement program. Feng and Figliozzi (2014) indicated that subsidies from governments have a significant impact on the replacement time of vehicles. In the study by Feng and Figliozzi (2014), vehicle life cycles are significantly decreased when governments reward a lot of subsidies to contractors because considerable subsidies can reduce the initial purchase cost of new vehicles. Yang and Tang (2019) investigated the effectiveness of the fuel-efficient vehicle subsidy program implemented by the Chinese government and found that it effectively promoted the replacement of old vehicles with new fuel-efficient vehicles. Huang et al. (2021) examined the impact of various environmental policy instruments, including subsidy policies, on the construction equipment replacement decisions of contractors.

Some studies investigated the impact of subsidy policies on the decision-making of various entities. For example, Gorji et al. (2021) investigated the impact of subsidy policies on the decision-making of the take-back center for used vehicles and the decision-making of the inspection and repair centers for recoverable vehicles by employing a game theory approach. Some studies focused on the environmental and economic impact of subsidy policies that encourage vehicle retirement. For instance, Wee et al. (2011) conducted a holistic literature review regarding the environmental impacts of car replacement subsidy policies. Ma et al. (2020) found that subsidies provided by governments to electric vehicles manufacturers for reducing the use of fuel vehicles have a negative impact on the market and drive the market to be uncontrollable. There has been some research on the issues of vehicle or equipment replacement subsidy incentives. Hahn (1995) proposed a model in which the number of replaced cars can be determined by the subsidy levels. Li et al. (2013) evaluated the impacts of the “Cash-for-Clunkers” program in the United States on auto sales and the environment, which provided about $3,500 or $4,500 subsidy to each of the eligible contractors. By reviewing the Norwegian electric vehicles subsidy policy, Holtsmark and Skonhoft (2014) concluded that the subsidy policy, designed to replace conventional vehicles with electric vehicles, should be ended. They found that offering subsidies to make buying and running electric vehicles cheaper is not a good solution to the problem of extensive emissions in the transportation sector.

In summary, much research has been done to examine how the factors such as obsolescence, downtime, and inflation affect equipment replacement. Only limited research has discussed the impact of environmental policy instruments, especially subsidy policies, on construction equipment replacement. The impact of subsidy policies on equipment retrofit has not been investigated.

2.5.2 Academic Models to Determine Subsidy Levels for Promoting Replacement or Retrofit of Equipment

Only a few studies have proposed models to determine subsidy levels for accelerating the replacement of vehicles. Lorentziadis and Vournas (2011) established a dynamic model to determine the subsidy levels, replacement rate and subsidy program duration to achieve a specific replacement target of high-polluting vehicles within a given time frame. In the model proposed by Lorentziadis and Vournas (2011), the demand for new vehicles is equal to the number of scrapped old vehicles with dependence on subsidy levels. Lavee and Becker (2009) established an economic model to identify the subsidy levels, for which a linear supply curve is established. For each subsidy level, the supply of vehicles for replacement can be obtained. Then the amount of emission reduction and corresponding net total benefit because of the replacement of old vehicles is calculated. The optimal subsidy level maximizes the net benefit of vehicle replacement programs. However, these two previous studies assume that the amount of subsidy is independent of vehicle age, which has an impact on the decision to replace. This assumption contradicts the findings of the study by Alberini et al. (1996), which insist that subsidy incentive is more attractive to older vehicles with lower economic value than newer ones with higher economic values. The study by Lavee et al. (2014) also indicated that giving owners subsidies according to the vehicle’s age has a higher net benefit than a uniform subsidy payment without considering the vehicle’s age. Zaman and Zaccour (2020) also suggested that the age of vehicles is an important driver of replacement decisions, and not taking them into account may not be realistic and can impair the effectiveness of the proposed model. Another drawback of the studies by Lorentziadis and Vournas (2011) and Lavee and Becker (2009) is connecting the replacement decision with purchasing decision, which means that owners of construction equipment must purchase a new vehicle when replacing an old one. However, in some cases, owners of old vehicles may have other better solutions to meeting equipment needs. Hahn (1995) also estimated a supply curve of vehicles replaced for different subsidy levels through a case study in Los Angeles. In the study by Hahn (1995), the number of vehicles of various categories and ages in Los Angeles is first determined; then, the average prices for old vehicles are estimated based on the prices in the second-hand vehicle market. When the subsidy level exceeds the average price of a vehicle category of a certain age, participation in the scrappage program is justified. Therefore, for each subsidy level, the number of old vehicles to be replaced is obtained. There are also some models designed to give subsidies to manufacturers of new vehicles rather than owners of older vehicles. The effectiveness of these models is debatable. Lorentziadis and Vournas (2011) claimed that offering subsidies to manufacturers of new vehicles rather than owners of older vehicles may limit the participation in vehicle replacement programs. Fan et al. (2020) proposed a subsidy policy, which provided financial subsidies according to the mileage of new energy vehicles and shared subsidies between vehicle sharing companies and consumers. Huang et al. (2014) determined the optimal subsidy levels by investigating the automobile supply chain where manufacturers and retailers serve consumers with fuel-efficient automobiles. In the study by Huang et al.(2014), a manufacturer's profit function was developed, and governments can obtain the optimal subsidy levels through maximizing it. Li et al. (2015) proposed an approach called remaining life additional benefit-cost analysis. Based on the proposed approach, two perspectives for optimal bus fleet replacing and retrofitting strategies are provided by Li et al. (2015), including the profitability of the private bus company, as well as the overall social benefit in emissions reduction. Then, the subsidy level was determined, which is the cost difference under the two management strategies and could lead bus owners to implement the socially optimal bus fleet replacing and retrofit plan. It can be seen that existing studies do not consider the emission reduction responsibility that contractors should bear.

2.6 Research Gaps

Through the systematic literature review, a broad scope of research topics in CEE emission reduction technologies, policy instruments especially subsidy policies, and models for determining subsidy levels have been examined. Previous studies have contributed significantly to the body of knowledge in the formulation of subsidy policies for reducing CEE, providing valuable and constructive information for scholars, contractors and governments. However, several research gaps exist in previous literature that should be addressed. These research gaps are summarized as follows.

(1) Existing studies have focused on the policy instruments used to reduce emissions from agricultural and commercial sectors. However, limited existing research has been conducted to examine the development of policy instruments for CEE reduction. Although previous studies present various policy instruments implemented by a specific country in the form of government regulatory documents or research projects, the contents of these policy instruments have not been systematically examined from a global perspective with comparative analysis. Moreover, the existing government regulatory documents also have not explicitly and systematically investigated evolving trends, lessons, and accumulated experiences in advanced and developing-economy promoters.

(2) The competition-based subsidy allocation mechanisms that are widely applied in practice are designed for all off-road equipment, which usually renders construction equipment uncompetitive due to the special characteristics of the construction business. Moreover, funding caps imposed on subsidies in some programs can not relieve the financial burden of construction equipment owners, which is incurred from earlier replacement or retrofit of construction equipment. As a result, a

heavy financial burden may hinder the participation of construction equipment owners, especially small to medium size contractors.

(3) The models proposed in earlier studies for determining subsidy levels do not consider the age of vehicles or equipment, which is not reasonable. In fact, the cash flows of vehicles or equipment over their lifespans differ significantly, which requires different subsidy levels to entice their replacement or retrofit. Therefore, the attractiveness of the same subsidy levels for vehicles or equipment with different ages is different.

(4) From the perspective of a government, these models do not integrate with the emission reduction targets assigned to the subsidy incentives, which may underestimate the problem of extensive emissions from construction equipment.

(5) Existing studies mainly focus on the replacement of on-road vehicles, but they lack the development of subsidy policies to promote the retrofit of off-road equipment, especially for construction equipment. Construction equipment usually has a higher rated power and its purchase cost is also higher than on-road vehicles. Thus, retrofitting is a better choice than replacing in some situations where contractors are small and old construction equipment can still work well. This is because retrofitting as an effective emission reduction strategy is relatively cheaper. This characteristic of construction equipment makes it different from on-road vehicles, which requires designing a subsidy policy specifically for replacing as well as retrofitting construction equipment.

(6) The existing studies do not consider the emission reduction responsibility that should be borne by contractors. The assignment of emission reduction responsibilities by proportions between contractors and governments and the overall cost for reducing CEE has not been examined, when determining subsidy levels.

2.7 Chapter Summary

This chapter first reviews the research on technologies for reducing CEE. Then, policy instruments for reducing CEE are reviewed to show the concepts and theory of policy instruments and identify if experiences or lessons have been summarized by previous studies. Additionally, practices of developing subsidy policies for promoting the replacement and retrofit of construction equipment are illustrated, and the drawbacks in existing subsidy incentive programs are explored. Existing academic models for determining subsidy levels are also reviewed and assessed to identify gaps. Finally, research gaps are well discussed.

CHAPTER 3 Research Methodology

3.1 Introduction

This chapter illustrates the methodology established by this research for formulating proper subsidy policies to reduce CEE. Firstly, the methodology framework is established, and it is explained how various research methods and modeling techniques are combined to achieve the objectives of this research ideally. Then, research methods of literature review, document analysis and case study, and modeling techniques of LCC analysis model, integer programming and NONROAD2008a emission model employed by this research are introduced and explained.

3.2 The Framework of Methodology

To achieve the four research objectives set in Section 1.4, the research methods and modeling techniques employed in this research are shown in Fig. 3.1, which form the framework of the methodology.

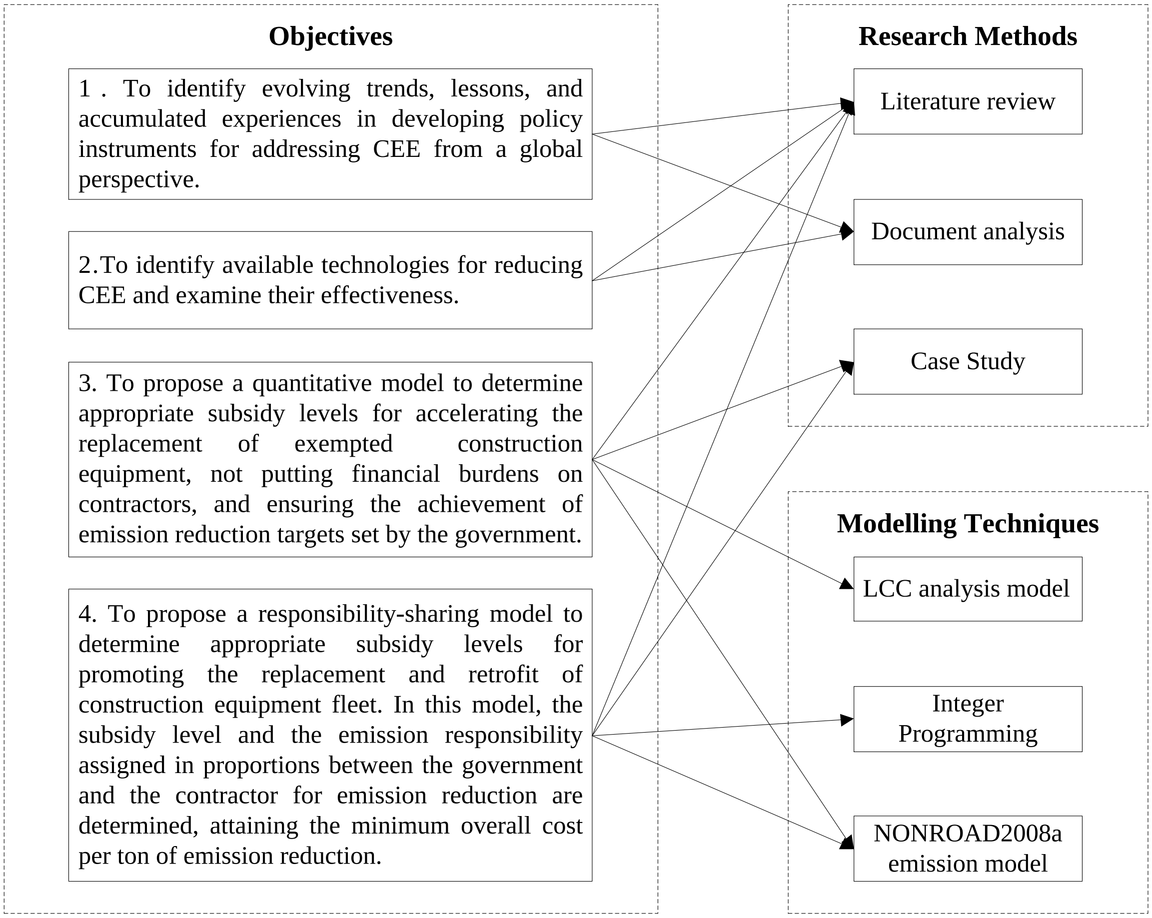

Fig.3. 1 The framework of methodology

3.3 Research Methods

3.3.1 Literature Review

The method of literature review is widely used by researchers to conduct a thorough and systematic examination of previous articles, books, and other documents (Tsai & Lydia Wen, 2005). The entire research commences with a literature review on the background knowledge of subsidy policies for reducing CEE, directing and moving this research toward developing specific research questions to be answered. For the first objective, a literature review is conducted to collect CEE reduction policy instruments from a global perspective and to select a proper policy instrument classification framework. For the second objective, academic journals, doctoral theses, conference papers, government reports, and other technical guidelines are examined to summary technologies available for reducing CEE and identify emission reduction levels achievable by these technologies. For the third and fourth objectives, the method of literature review is employed to examine the practice of subsidy incentives and the available models for determining subsidy levels to identify drawbacks existing in previous research.

3.3.2 Document Analysis

Document analysis, synonymously called ‘document review’, is a systematic method used to access data and information in different types of recorded data, reports published by governments or organizations, published articles, and other documents (Kayesa & Shung-King, 2021). Document analysis usually involves the process of systematic collection, skimming, thorough reading, documentation, analysis, interpretation, and organization of printed or electronic data (Bowen, 2009; Kayesa & Shung-King, 2021). In this research, the method of document analysis is employed to achieve the first objective. Firstly, policy instruments adopted globally are collected by various sources, such as informative websites and official websites of cities, countries and regions that have issued policy instruments for reducing CEE. Then, the collected policy instruments are classified. Finally, this research discusses and compares the classified policy instruments between two groups of promoters, including advanced and developing-economy promoters, for identifying their development trends, lessons and experiences.

3.3.3 Case Study

Case study method is an inquiry into a phenomenon's reality (Yin, 2018). The objectives of a case study can be understanding, describing, controlling, or predicting (Woodside & Wilson, 2003). The primary purposes of conducting case studies include conducting inductive, deductive, or abductive analysis to build theory, test theory, or refine theory (Dubois & Gadde, 2014; Eisenhardt, 1989; Johnston et al., 1999). This research employed case studies to demonstrate and validate the two proposed models. The performance data of construction equipment is derived from a large general contractor in Hong Kong. For the quantitative model to determine appropriate subsidy levels for accelerating construction equipment replacement, a Liebherr HS883HD crawler crane is employed to demonstrate its application. The subsidy level that should be granted to the contractor is determined, and the determined subsidy level is validated by the contractor's equipment manager responsible for the crawler crane. For the responsibility-sharing model to determine appropriate subsidy levels for promoting the replacement and retrofit of the construction equipment fleet, an excavator fleet is employed to demonstrate the application of the proposed model. In the excavator fleet case, emission reduction responsibility is assigned properly between the Hong Kong government and the contractor. The recommended subsidy levels are determined, which is reasonable and acceptable and can achieve the minimum overall cost per ton of emission reduced.

3.4 Modelling Techniques

3.4.1 LCC Analysis Model

Equipment owners are usually under pressure to minimize equipment life cycle costs through equipment replacement at its economic life. Therefore, considering equipment life cycle costs is more effective than only considering a single cost like purchase or maintenance cost when making informed equipment replacement decisions (Zakeri & Syri, 2015). Thus, a traditional LCC analysis model is employed by this study to find the economic life of construction equipment and the corresponding EUAC.

The traditional LCC analysis model considers all costs associated with the equipment's life cycle (Asghari et al., 2021; Ghadam et al., 2012; Seif & Rabbani, 2014). EUAC of equipment changes over time with a decrease in the first few years due to decreasing capital depreciation, followed by an increase when operating costs escalate due to reduced reliability and increased repair and maintenance costs (Weissmann, 2003). The economic life of construction equipment is determined by the year in which the EUAC is minimized. EUAC of construction equipment over its life cycle can be calculated by discounting the cash flow across the life span of the equipment, as described in Equation (3.1).

$$EUAC(n) = I(A/P, i, n) - S_n(A/F, i, n) + \sum_{j=1}^{n} OC_j\,(P/F, i, j)(A/P, i, n) \tag{3.1}$$

where, n is the time (in number of years) with $n \in N=\{\,0, \ldots\ldots, N\,\}$; N is the physical life of construction equipment, of which the value is recommended by the manufacturers of construction equipment; $EUAC(n)$ is the EUAC of construction equipment at the age of n; I is the initial cost; S_n is the salvage value of construction equipment in the nth year; OC_j is the operating costs of construction equipment in the jth year, which is the costs associated with the operation of a piece of construction equipment including fuel cost, maintenance and repair cost, and so on; $(A/P, i, N)$ is equal payment series capital recovery factor, which is equal to $\frac{i(1+i)^n}{(1+i)^n-1}$; $(A/F, i, n)$ is equal payment series sinking fund factor, which is equal to $\frac{i}{(1+i)^n-1}$; $(P/F, i, n)$ is a single payment present worth factor, which is equal to $\frac{1}{(1+i)^n}$; and i is the interest rate. When $n = n_1$, the value of $EUAC\,(n)$ is minimum. n_1 is the economic life of the construction equipment and the equipment should be replaced at the age of n_1 when there are no subsidies available.

3.4.2 Integer Programming

Integer programming is a mathematical optimization technique that usually involves optimizing a linear objective function to linear constraints, nonnegative conditions, and some or all integer variables. In practice, a wide variety of problems can be formulated and solved by using the technique of integer programming, such as capital budgeting problem and warehouse location problem (Balinski, 1965; Daniel G. Espinoza, 2005). This research will employ the modeling technique of integer programming to help contractors make optimal decisions on the mix of construction equipment that should be in-service, retrofitted, salvaged, and replaced in each period, with the aim of minimizing expected costs.

1) Mathematical form of integer programming

The general integer programming is a problem in the following format (Liberti, 2006; Conforti et al., 2014):

$$\text{Maximize} \quad \sum_{j=1}^{n} c_j x_j, \tag{3.2}$$

$$\text{Subject to:} \quad \sum_{j=1}^{n} a_{ij} x_j \leq b_i \qquad (i = 1, 2, \cdots, m) \tag{3.3}$$

$$x_j \geq 0 \qquad (j = 1, 2, \cdots, n) \tag{3.4}$$

$$x_j \text{ integer} \qquad (\text{for some or all } j = 1, 2, \cdots, n) \tag{3.5}$$

If all the variables x_j are integer, then the problem is called pure integer programming. If some but not all variables x_j are integer, the problem is called mixed integer programming (MIP). When all variables x_j are restricted to be 0 or 1, the problem is called a Binary (or 0-1) integer programming.

In this research, the objective function will be designed to optimize the total cost of adopting emissions reduction technologies, replacing and operating construction equipment, and receiving government subsidy funds. In addition, linear constraints are designed to present the emissions reduction targets required by government regulations or technology requirements which should be met when emission reduction technologies can successfully work.

Although a bounded Integer Linear Programming (ILP) has only a finite number of feasible solutions, integer variables make it difficult to search directly among the possible integer points of the solution space. Several practical algorithms have been proposed for generating the special constraints that will force the optimum point of the relaxed linear programming problem toward the desired integer solution, typically including the branch-and-bound algorithm and the cutting plane algorithm (Daniel. Espinoza, 2005). The branch-and-bound algorithm is widely used for discrete and combinatorial optimization problems, as well as mathematical optimization. The branch-and-bound algorithm is based on the principle that the total set of candidate solutions can be partitioned into smaller subsets of solutions, forming a rooted tree with the full set branches at the root. The algorithm explores branches of this tree by first checking against upper and lower estimated bounds on the optimal solution. If a branch cannot produce a better solution than the best one found so far by the algorithm, it is discarded. Or else, candidate solutions of this branch will be enumerated. When no bounds are available, the algorithm degenerates to an exhaustive search (Conforti et al., 2014). The cutting plane algorithm is to cut off parts of the feasible regions of the corresponding Linear Programming (LP) so that the optimal integer solution becomes an extreme point and therefore can be found. The cutting plane algorithm works by solving a continuous relaxation at each step. If the continuous relaxation solution fails to be integral, a separating cutting plane is generated and added to the formulation, and the process is repeated until the optimal point is found (Liberti, 2006).

3.4.3 NONROAD2008a Emission Model

Models used by previous studies to estimate CEE can be mainly categorized into fuel and time-based emission models (Jung et al., 2009; Westerdahl et al., 2009; Zhang et al. 2000). Fuel-based emission models estimate emissions based on fuel-based emission factors and the amount of fuel consumed, while time-based emission models based on time-based emission factors, the duration and the machine characteristics (Franco et al., 2013). Thus, as suggested by Frey et al. (2010), fuel-based emission models are less sensitive to engine size and load, while time-based emission models are highly sensitive to engine characteristics. Typical fuel-based emission models include Intergovernmental Panel on Climate Change (IPCC) emission model (IPCC, 2007), Australian Greenhouse Gas Accounts (NGA) model (Fruergaard et al., 2009) and model issued by European Environment Agency (EEA) standards (Kurokawa et al., 2013). Typical time-based emission models include NONROAD2008a emission model developed by US EPA (US EPA, 2018). The major advantage of the fuel-based models is the readily available fuel consumption data while it is practically difficult to get the usage hours of each machine for emission analysis (Frey et al., 2010). Past emission studies have also indicated that fuel-based emission model is more suitable for CO2 emissions evaluation while a time-based emission model is more appropriate for non-CO2 emissions (Kean et al., 2000; Hausberger et al., 2003). For example, IPCC model are usually used for estimated greenhouse gas (GHG) emissions including carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O), while NONROAD2008a emission model are suitable for calculating pollutant emissions of CO, NOx, PM, SO2 and HC. Because this research targets on pollutant emissions, time-based emission model of NONROAD2008a is employed.

This study employs the NONROAD2008a emission model (US EPA, 2018) to calculate CEE, including HC, CO, NOx and PM2.5. According to this model, the amount of emission k generated by one piece of in-use construction equipment in the *n*th year (g), denoted by $e_{k,n}$, can be calculated by Equation (3.6).

$$e_{k,n}=EF_{adj(k)} \times C_n \tag{3.6}$$

where $EF_{adj(k)}$ is the final emission factor of emission *k* after adjustments to account for transient operation and deterioration (g/hp-hr). C_n is the units of use (hp-hr) in the nth year.

For HC, CO, and NOx, the emission factors for a piece of in-use construction equipment of a given type are calculated by Equations (3.7) to (3.9).

$$EF_{adj(HC,\ CO,\ NO_x)}=EF_{ss}\times TAF\times DF \tag{3.7}$$

$$DF=1+A\times Age\ factor \tag{3.8}$$

$$Age\ factor=\frac{(cumulative\ hours\ \times\ load\ factor)}{median\ life\ at\ full\ load\ in\ hours} \tag{3.9}$$

where EF_{ss} is zero-hour, steady-state emission factor (g/hp-hr), which is mainly a function of the model year and horsepower category and defines the technology type. *TAF* is a transient adjustment factor (unitless), which varies by equipment type. *DF* is a deterioration factor (unitless), which is a function of the technology type and age of the engine. *A* is a constant for a given type.

Since PM2.5 emission is dependent on the sulphur content of the fuel the engine is burning, the equation used for PM2.5 is slightly modified from Equation (3.7) as follows:

$$EF_{adj(PM)}=EF_{ss}\times TAF\times DF\text{-}S_{PMadj} \tag{3.10}$$

$$S_{PMadj}=BSFC\times 453.7\times 7.0\times 0.02247\times 0.01\times(0.33\text{-}soxdsl) \tag{3.11}$$

where S_{PMadj} is adjustment to PM emission factor to account for variations in fuel sulphur content (g/hp−hr). *BSFC* is the in-use adjusted brake-specific fuel consumption (lb fuel/hp-hr). Variable *soxdsl* is the episodic fuel sulphur weight percent.

The model inputs for EF_{ss}, *TAF, A, load factor, median life at full load*, and *BSFC* are available from the EPA publication *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling* (US EPA 2018).

3.4 Chapter Summary

This chapter presents the methodology of this research. The research methodology framework established by this research shows the logic between research objectives and research methods. The research methods and modeling techniques adopted by this research to achieve the defined research aim and objectives include literature review, document analysis, case study, LCC analysis model, integer programming, and NONROAD2008a emission model. The principle of each research method or modeling technique, the primary purpose of employing them, and how they are applied in this research are explained.

CHAPTER 4 Policy Instruments for Addressing CEE——a Research Review from a Global Perspective

4.1 Introduction

Policy instruments have been initiated for addressing the severe problem of extensive CEE by governments around the world. Advanced and developing-economy promoters with distinctive background and constraints present differences in the development of CEE reduction policy instruments. However, there is little research looking into the evolving trends, lessons and accumulated experiences in the development of CEE reduction policy instruments. This section conducts a holistic review and analysis on the development of CEE reduction policy instruments from a global perspective. Three groups of policy instruments are identified, including PI-A, PI-B and PI-C. Comparative analysis of CEE reduction policy instruments is conducted between advanced and developing-economy promoters. This research also suggested that a mixture of PI-As, PI-Bs and PI-Cs works better, and policy instruments should be selected considering the context of promoters. This research aims to promote experience-sharing between policymakers and provide them with significant insights for formulating more effective CEE reduction policy instruments.

In this section, three research phases are planned to achieve objective 1 of this research, i.e. 1) collection of research data on policy instruments adopted globally for reducing CEE; 2) classification of the collected policy instruments by using the policy classification framework adopted by Word Bank (1997); 3) identification of policy instruments for reducing CEE; and 4) discussion and comparison of the classified policy instruments between their promoters.

4.2 Collection of Research Data

4.2.1 Data Source

Two types of data sources are examined in this research to collect CEE reduction policy instruments from a global perspective. First, this research collects research data by browsing through two informative websites including TransportPolicy.net (ICCT and DieselNet, 2018) and DieselNet (2018), which provide comprehensive, up-to-date, and secured information on energy and environment-related policy instruments in several sectors such as construction, transportation and agriculture. In these two information portals, there are contents listing some CEE reduction policy instruments adopted by some cities, countries and regions. Apart from browsing the two information portals, several key terms are used for searching related information using terms including “off-road engine”, “emission”, “construction equipment” and “Non-road Mobile Machinery”, etc.

Second, this research assumes that these policy instruments in the two electronic sources may not be comprehensive and there may be some other policy instruments that have not been incorporated into these two sources. Therefore, the official websites of these cities, countries and regions are visited with collection of publication information. Selected official websites are list in Table 4.1. By doing this, many policy instruments not incorporated by the two information portals are collected to make research data more comprehensive.

Table 4.1 Selected official websites publishing policy instruments for reducing CEEs

No.	Government agencies	Official website
1	United States Environmental Protection Agency	https://www.epa.gov/cleandiesel
2	Environment and Climate Change Canada	https://www.canada.ca/en/environment-climate-change.html
3	California Air Resources Board	https://ww3.arb.ca.gov/msprog/offroad/ofcie/ofciectp/ofciectp.htm
4	European Commission	https://ec.europa.eu/growth/sectors/automotive/environment-protection/non-road-mobile-machinery_en
5	Swiss Agency for the Environment, Forests and Landscape	https://www.bafu.admin.ch/bafu/en/home/office.html
6	Centre for Low Emission Construction of London	http://www.clec.uk/
7	Mayor of London and London Assembly	https://www.london.gov.uk/what-we-do/planning/implementing-london-plan/planning-guidance-and-practice-notes/control-dust-and
8	Ministry of Ecology and Environment of the People’s Republic of China	http://www.mee.gov.cn/
9	China Machinery Industry Federation	http://cmif.mei.net.cn/
10	Ministry of Environment and Forest (MoEF) of India	http://envfor.nic.in/
11	Bureau of India Standards (BIS)	http://www.bis.org.in/
12	Central Pollution Control Board (CPCB) of India	http://cpcb.nic.in/
13	Ministry of Petroleum and Natural Gas (MoPNG) of India	http://petroleum.nic.in/
14	German Environment Ministry	http://www.bmu.de/
15	Ministry of Environment of South Korea	http://eng.me.go.kr/eng/web/main.do
16	Environmental Protection Department of Hong Kong	https://www.epd.gov.hk/epd/english/environmentinhk/air/prob_solutions/air_problems/regulatory-control-emissions-nrmm.html
17	National Council on the Environment (Conselho Nacional do Meio Ambiente, CONAMA) of Brazil	http://www.mma.gov.br/port/conama/
18	Department of Health, Metropolitan Region of Chile	http://www.health.vic.gov.au/regions/southern/
19	Turkish Ministry of Science, Industry and Technology	https://pharmaboardroom.com/directory/the-republic-of-turkey-ministry-of-science-industry-and-technology/
20	Ministry of the Environment and Natural Resources of Mexico	http://www.semarnat.gob.mx/Pages/Inicio.aspx
21	Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan	http://www.mlit.go.jp/en/index.html
22	Ministry of the Environment (MOE) of Japan	http://www.env.go.jp/en/

4.3 Classification Framework of Policy Instruments

The second phase of this study is to classify the policy instruments collected by using a classification framework. In the discipline of policy instrument study, classification frameworks are often used to divide policy instruments into different groups from various perspectives for examining and investigating them (Lowi, 1964; Hood, 1995; Howlett, 2005; Schneider and Ingram, 1997; Van der Doelen, 1998; Chen, 1999; Salamon, L. M., 2002; Zhang, 2008). Classification framework as a useful policy instrument analysis tool has already been widely employed in the domain of public administrations (Howlett, 2005). The classification framework established by World Bank (1997) is used as a reference in this study, based on which three groups of policy instruments for reducing CEE are classified, including PI-A, PI-B, and PI-C. Accordingly, a two-layer policy instrument classification framework is formed, as shown in Table 4.2. This two-layer framework can help to conduct a more effective comparative research on the policy instruments adopted globally for reducing CEE and to illuminate their evolving trends, lessons and accumulated experiences between policy instrument promoters.

Table 4.1 The classification framework of policy instruments for reducing CEE

Policy instruments		
PI-A (mandatory administration policy instrument)	**PI-B (economic incentive policy instrument)**	**PI-C (voluntary participation policy instrument)**
• PI-AL. Law • PI-AR. Regulation • PI-APP. Pilot Program • PI-AES. Emission standards	• PI-BS. Subsidy • PI-BT. Tax • PI-BR. Rebate • PI-BLI. Loan Incentive • PI-BG. Grants	• PI-CVS. Voluntary emission standards • PI-CGS. Governmental service • PI-CCL. Certification and Label • PI-CVPP. Voluntary Pilot Program • PI-CID. Information disclose

4.4 Identification of Policy Instruments for Reducing CEE

By employing the data sources described in Section 4.2.1 and the policy instrument classification framework established in Table 4.2, a large volume of policy instruments is obtained across the three groups of PI-A, PI-B and PI-C, as shown in Appendix I-III.

4.5 Comparative Discussion

The last phase of this research is to conduct comparison and discussion on the PI-A, PI-B and PI-C between policy instrument promoters for identifying their development trends, lessons and experiences. Policy instrument promoters will be divided into different groups. There have been some criteria issued by international organizations for grouping economies, which can be used as references for helping group policy instrument promoters. For example, World Bank (2019) divides economies around the world into two groups including developing economics and developed economies using the indicator of Gross National Income (GNI) per capita. According to World Economic Outlook (International Monetary Fund, 2019), economies are grouped into advanced economies and emerging and developing economies according to per capita income level, export diversifications and degree of integration into the global financial system. By considering these two references, the policy instrument promoters in this study are divided into two groups, namely, advanced-economy promoters and developing-economy promoters.

4.5.1 Analysis of the Identification Results

The core information from the identified policy instruments presented in Appendix I-III can be shown in Table 4.3. It is evident from Table 4.3 that advanced-economy promoters have released 132 policy instruments, which is about twice as many as that issued by developing-economy promoters with 59 policy instruments. Furthermore, advanced-economy promoters have released more policy instruments than developing-economy promoters in almost all sub-groups of CEE reduction policy instruments. Another point that should be paid attention in Table 4.3 is that developing-economy promoters have not released any PI-B and have issued only one PI-C. The data collected in Appendix I-III can also be graphically presented in Fig. 4.1, according to the periods when policy instruments were released. It can be observed from Fig. 4.1 that the array of CEE reduction policy instruments evolved from PI-As to a mixture of PI-A, PI-B and PI-C. From 1975 to 1994, only PI-As were issued and employed to address the problem of CEE. From 1995, a complex mixture of PI-As, PI-Bs and PI-Cs was employed.

Table 4.2 Various types of policy instruments released by advanced and developing-economy promoters

Policy Instruments		Advanced-economy Promoters	Developing-economy Promoters
PI-A	PI-AL	PI-AL01, PI-AL02, PI-AL03, PI-AL04, PI-AL05, PI-AL06, PI-AL07, PI-AL08, PI-AL11, PI-AL12, PI-AL13, PI-AL14, PI-AL15, PI-AL16	PI-AL09, PI-AL10, PI-AL17
	PI-AR	PI-AR01, PI-AR02, PI-AR03, PI-AR04, PI-AR05, PI-AR06, PI-AR07, PI-AR08, PI-AR09, PI-AR10, PI-AR11, PI-AR12, PI-AR13, PI-AR14, PI-AR15, PI-AR16, PI-AR17, PI-AR18, PI-AR19, PI-AR20, PI-AR21, PI-AR22, PI-AR23, PI-AR24, PI-AR25, PI-AR26, PI-AR27, PI-AR28, PI-AR29, PI-AR30, PI-AR31, PI-AR32, PI-AR33, PI-AR34, PI-AR35, PI-AR36, PI-AR37, PI-AR38, PI-AR39, PI-AR40, PI-AR41, PI-AR42, PI-AR43, PI-AR44, PI-AR45, PI-AR72, PI-AR73, PI-AR74, PI-AR75, PI-AR76, PI-AR77, PI-AR78, PI-AR79	PI-AR46, PI-AR47, PI-AR48, PI-AR49, PI-AR50, PI-AR51, PI-AR52, PI-AR53, PI-AR54, PI-AR55, PI-AR56, PI-AR57, PI-AR58, PI-AR59, PI-AR60, PI-AR61, PI-AR62, PI-AR63, PI-AR64, PI-AR65, PI-AR66, PI-AR67, PI-AR68, PI-AR69, PI-AR70, PI-AR71, PI-AR80, PI-AR81
	PI-APP	PI-APP01, PI-APP02	PI-APP03
	PI-AES	PI-AES01, PI-AES02, PI-AES03, PI-	PI-AES22, PI-AES23, PI-AES24, PI-

		AES04, PI-AES05, PI-AES06, PI-AES07, PI-AES08, PI-AES09, PI-AES10, PI-AES11, PI-AES12, PI-AES13, PI-AES14, PI-AES15, PI-AES16, PI-AES17, PI-AES18, PI-AES19, PI-AES20, PI-AES21, PI-AES28, PI-AES37, PI-AES38, PI-AES39, PI-AES40	AES25, PI-AES26, PI-AES27, PI-AES29, PI-AES30, PI-AES31, PI-AES32, PI-AES33, PI-AES34, PI-AES35, PI-AES36, PI-AES41, PI-AES42, PI-AES43, PI-AES44, PI-AES45, PI-AES46, PI-AES47, PI-AES48, PI-AES49, PI-AES50, PI-AES51, PI-AES52,
PI-B	PI-BS	PI-BS01	
	PI-BT	PI-BT01	
	PI-BR	PI-BR01, PI-BR02, PI-BR03, PI-BR04	
	PI-BLI	PI-BLI01, PI-BLI02, PI-BLI03, PI-BLI04	
	PI-BG	PI-BG01, PI-BG02, PI-BG03, PI-BG04, PI-BG05, PI-BG06, PI-BG07, PI-BG08, PI-BG09, PI-BG10	
PI-C	PI-CVS	PI-CVS01, PI-CVS02	
	PI-CGS	PI-GS01, PI-GS02, PI-GS03, PI-GS04, PI-GS05, PI-GS06, PI-GS07, PI-GS08, PI-GS09, PI-GS10	
	PI-CCL	PI-CCL01	
	PI-CVPP	PI-VPP01, PI-VPP02	
	PI-CID	PI-CID01, PI-CID02	PI-CID03
Total number		132	59

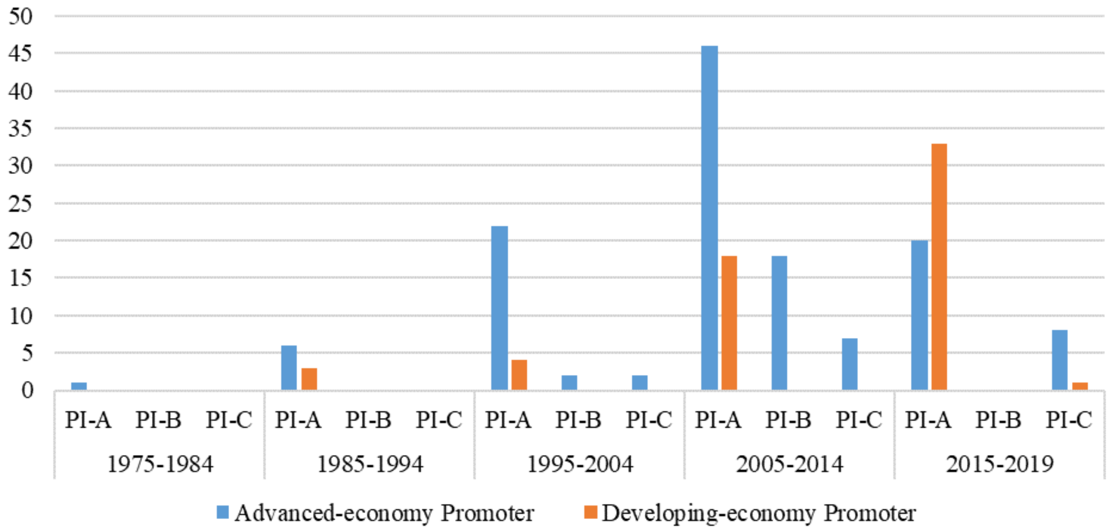

Fig.4. 1 Policy instruments adopted globally during different periods

Pie charts in Fig. 4.2 are plotted using the information in Appendix I-III. Fig. 4.2 shows that the proportions of PI-A, PI-B and PI-C adopted by advanced-economy promoters were 71.97%, 15.15% and 12.88%, respectively. The proportions of PI-A, PI-B and PI-C adopted by developing-economy promoters were 98.31%, 0%, and 1.69%, respectively. It can be inferred that advanced-economy promoters prefer a mixture of PI-A, PI-B and PI-C to mitigate CEE while developing-economy promoters mainly use PI-A to achieve the goal of reducing CEE.

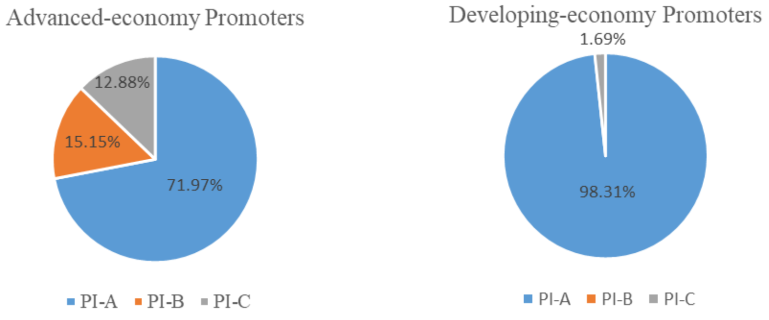

Fig.4. 2 The proportions of PI-A, PI-B and PI-C adopted by advanced-economy promoters and developing-economy promoters

4.5.2 Development Trends of Policy Instruments for Reducing CEE

(1) Both advanced and developing-economy promoters prefer PI-As

As shown in Table 4.3, 95 out of 132 (71.97%) policy instruments adopted by advanced-economy promoters are PI-As, and 58 out of 59 (98.31%) by developing-economy promoters are PI-As. Therefore, this study inferred that both advanced and developing-economy promoters overwhelmingly prefer PI-As. The popularity of PI-As in policy instrument promoters mainly attributes to two reasons.

On the one hand, the problem of extensive CEE has been severe in both advanced and developing-economy promoters, which has been amply demonstrated and explained in the introduction section. Extensive CEE has induced many adverse consequences, which attract the attention of global policymakers. On the other hand, in the process of rapid urbanization, considerable buildings and infrastructure projects have been constructed, which unavoidably employs lots of construction equipment and emits large amounts of emissions. It is a consensus that the rapid urbanization sacrifices the environment because of massive pollutant emissions from CEE. In this situation, PI-Bs and PI-Cs can not provide enough motivation and mandatory power for stakeholders of urbanization to take measures to reduce CEE. Whereas, PI-As is a comparatively reliable tool, which can offer the mandatory enforcement to formulate proper CEE reduction measures. This is because PI-As have the highest degree of mandatory governance and the strong ability to address problems that currently can not be effectively solved by the power of the market, including the issues of environmental pollution, industrial monopoly and information asymmetry (Spulber, 1989). Usually, PI-As can achieve desired objectives in a short time especially in the field of environment protection (Rosenthal and Kouzmin, 1997). Therefore, both advanced and developing-economy promoters prefer PI-As.

(2) Developing-economy promoters may not have sufficient resources for implementing PI-Bs and PI-Cs

It can be seen from Table 4.3 that developing-economy promoters have not issued any PI-Bs and have only issued one PI-C. Developing-economy promoters have not fully employed PI-Bs and PI-Cs to reducing CEE. This development trend may attribute to that developing-economy promoters do not have sufficient resources including funding and government support for implementing PI-Bs and PI-Cs.

The implementation of PI-Bs such as grant programs requires substantial amounts of dedicated funding as well as considerable government time and resources to administer. For example, in the first four years of California's Carl Moyer Grant Program, which began in 1998, more than $765,000 is spent per year to reduce CEE (IFC Consulting, 2005). Another example is the Diesel Emissions Reduction Act (DERA) program, which is implemented by EPA's National Clean Diesel Campaign (NCDC) within the Office of Transportation and Air Quality. From fiscal years 2008 to 2016, the DERA program has invested $629 million funds to reduce NOx emission from diesel-powered equipment including construction equipment. Developing-economy promoters in the earlier stages of industrialization usually have low per capita income and inadequate infrastructure (United Nations, 2019). For most developing-economy promoters, their main development task is eradicating poverty and improving living standards. Therefore, limited resources like funding and human resources can be utilized by them to create a better monitoring system, which is considered essential for the successful implementation of PI-Bs and PI-Cs (Goldmann, 2005). On the other hand, a lower level of urbanization in developing-economy promoters may have an impact on their development of PI-Bs and PI-Cs. Urbanization leads to strong demand of a large amount of residential housing and infrastructure (Xu et al. 2020). With the construction of buildings and infrastructure projects, extensive emissions have been generated from the operation of construction equipment. The problem of extensive CEE emerged earlier in advanced-economy prompters with a higher level of urbanization compared with developing-economy promoters. Advanced-economy promoters consider reducing CEE to be a priority in their development at a time earlier than developing-economy promoters. Therefore, the consciousness of the governments and general public of CEE reduction is stronger in advanced-economy promoters, their practice and knowledge can be transferred to the developing-economy promoters for promoting PI-Bs and PI-Cs.

Compared with PI-A and PI-B, PI-C has the lowest degree of mandatory governance and provides weak incentives. PI-C cannot compete with PI-A and PI-B and be widely considered as complements to PI-A and PI-B (OECD, 2003; Blackman et al., 2013). Therefore, PI-Cs are very seldom used as stand-alone instruments. PI-Cs are usually embedded in a broader policy mixture and function as complements to other types of policy instruments (Hanks, 2002). As discussed above, developing-economy promoters have not issued any PI-Bs. The lack of PI-Bs in developing-economy promoters may contribute to a few environmental management departments, incomplete legal foundations and scarce political willingness for implementing PI-Cs. According to Jiménez (2007), the implementation of PI-Cs always needs stringent monitoring and enforcement provisions, which are usually absent from developing-economy promoters.

(3) Advanced-economy promoters have devoted more efforts for developing PI-Bs and PI-Cs

In referring to Fig. 4.2, 15.15% CEE reduction policy instruments adopted by advanced-economy promoters are PI-Bs, and 12.88% are PI-Cs. Compared with developing-economy promoters, advanced-economy promoters have devoted more efforts to developing PI-Bs and PI-Cs. The relative prevalence of PI-Bs and PI-Cs in advanced-economy promoters may attribute to the strengths of PI-Bs and PI-Cs and the context of advanced-economy promoters.

PI-Bs provide polluters with continuous incentives and financial aids or ask them to pay for pollutions in the forms of charges, fees, rebate and taxes to achieve the goal of reducing emissions (Josef, 1997). The successful implementation of PI-Bs could lead construction equipment owners to comply better with the polluter pays principle. Namely, owners of construction equipment should pay for the environmental damage caused by their significant emissions. Although PI-Bs are usually weaker as problem-solving measures compared with PI-As, PI-Bs are practical and flexible for ecological protection often by providing owners of construction equipment with the flexibility to make strategies about how to reduce CEE practically and cost-effectively (Hillman, 2003). For example, PI-Bs such as emissions charge can give polluters flexibility for economic optimization by evaluating the two options of paying the charge or applying some low-emission construction equipment. On the other hand, advanced-economy promoters usually have a higher level of economic and social development and stronger environmental awareness, which provide advanced-economy promoters with sufficient resources for implementing PI-Bs.

PI-Cs have some advantages of greater flexibility, active stakeholder involvement and commitment, demonstration effects and diffusion of information (Brink, 2017). Currently, PI-Cs are usually employed by advanced-economy promoters to introduce and promote the application of innovative technologies or cost-effective methods to reduce CEE. For example, to encourage manufacturers to adopt innovative technologies to control emissions under mandatory levels, the US EPA created a voluntary program of “Blue Sky Series Engines” in 2002, which had lower emission levels than the mandatory standards at more than 40 percent cleaner. When manufacturers meet these voluntary emission standards, engines manufactured by them would be designated as “Blue Sky Series Engines”. To promote the application of “Blue Sky Series Engines”, state governments had specified that if companies employ construction equipment with “Blue Sky Series Engines” they can gain a competitive edge in bidding on construction contracts. Manufacturers would be encouraged and motivated by the benefit of having an advantage in bidding on construction contracts to adopt innovative technologies to limit emissions from engines.

4.5.3 Lessons or Experiences Generated from the CEE Reduction Policy Instrument Development

(1) A mixture of PI-As, PI-Bs and PI-Cs works better

In referring to Fig. 4.2, the policy instrument types adopted by advanced-economy promoters cover PI-A (71.97%), PI-B (15.15%) and PI-C (12.88%). In comparison, the policy instrument types adopted by developing-economy promoters cover PI-A (98.31%) and PI-C (1.69%). Therefore, this study reasonably assumes that developing-economy promoters mainly rely on PI-As to reduce CEE. The diversity of policy instrument types adopted by advanced-economy promoters, to some extent, may contribute to the remarkable achievements in reducing CEE. As discussed before, every type of policy instrument has both strengths and weaknesses, so a single type of policy instrument can not offer effective solutions to the problem of extensive CEE. Effectively curbing CEE depends on a mixture of PI-As, PI-Bs and PI-Cs, which will work better when paired with each other (IFC Consulting, 2005). For example, *the Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation* of Hong Kong would work better if implemented along with PI-Bs or PI-Cs. According to this regulation, existing construction equipment which were in Hong Kong before December 2015 could exempt from complying with emission requirements. Under this regulation, currently, there are at least 11,300 units of construction equipment which are not subject to Hong Kong's emission requirements. The estimated average remanent service life of these existing construction equipment is about 14 years. If no other PI-Bs or PI-Cs are taken, these existing construction equipment will operate on construction sites for a long time and emit a lot of emissions. In this situation, PI-Bs and PI-Cs such as rebate programs or tax incentives can be very significant to address the problem of extensive emissions from exempted construction equipment as supplemental measures.

In practice, some advanced-economy promoters have demonstrated that a mixture of PI-As, PI-Bs and PI-Cs can work better. For example, from Appendix I-III, it is evident that the U.S as a leading advanced-economy promoter has employed a mixture of PI-As, PI-Bs and PI-Cs to address the severe problem of extensive CEE. Promising outcomes and a range of benefits have been achieved by the U.S in reducing CEE. According to US EPA' third report to congress (US EPA, 2016), EPA estimated that from 2009 to 2013, a series of CEE reduction policy instruments have resulted in emission reductions of 312,500 tons of NOx, 12,000 tons of PM2.5, 18,900 tons of HC and 58,700 tons of CO. Another report from US EPA (US EPA, 2019) suggested that from fiscal years 2008 to 2016 a reduction of 472,700 tons of NOx and 15,490 tons of PM2.5 have been achieved owning to promoting CEE reduction policy instruments. US EPA (2019) also estimated that these emission reductions achieved can help avoid between 1,000 and 2,300 premature deaths.

(2) Policy instruments making should consider the contexts of promoters

It is widely appreciated that many alternative policy instruments can be adapted to address the same issues (Landry & Varone, 2005). However, policy instruments making should not only consider the targeted issues themself but also consider the contexts of their promoters. This is mainly because that policy instruments making will affect scarce public resources deploy and the distribution of benefits from implementing policy instruments. On the other hand, advanced and developing-economy promoters are different in some dimensions, such as industrialization, development stages, resource endowment and standards of living. Therefore, when making policy instruments for reducing CEE, policymakers should consider their contexts.

From the examination on the identified policy instruments listed in Appendix I-III, there have been some policy instruments made in consideration of contexts of promoters. For example, advanced-economy prompter Switzerland whose economy has highly progressed adopted the CEE reduction strategy of using Best Available Technology (BAT) to limit CEE or prevent CEE in advance. Guided by this CEE reduction strategy, without considering the costs of installing Diesel DPF, the Swiss Environmental Protection Agency has required the installation of DPF on construction equipment to reduce emissions in 2002, which can bring about maximum efficiency in reducing particulate emissions. From 2003 to 2008, the Swiss federal government recommended that the use of DPF on construction equipment should be implemented on large construction sites. After 2009, the federal government required that DPF must be installed for all construction equipment with a power greater than 37 KW.

4.6 Chapter Summary

Various CEE reduction policy instruments have been established globally in past years, and it is widely appreciated that promoting these policy instruments is essential. This study reveals the development trends, lessons and accumulated experiences of CEE reduction policy instruments from a global perspective. The results of this study suggest that advanced and developing-economy promoters have both similarities and differences in the development of CEE reduction policy instruments. For example, both advanced and developing-economy promoters overwhelmingly prefer to adopt PI-As. Developing-economy promoters may not have sufficient resources for implementing PI-Bs and PI-Cs. Advanced-economy promoters have devoted more efforts to developing PI-Bs and PI-Cs. The study concludes that a mixture of PI-As, PI-Bs and PI-Cs can work better for reducing CEE, and policy instruments making should consider the contexts of promoters.

This research can promote the experience-sharing between developed and developing-economy promoters, which can help improve the reduction of CEE through formulating more effective policy instruments. On the other hand, this research provides valuable references for those countries and cities which have not yet introduced CEE reduction policy instruments to design effective policy instruments with the understanding of the development trends, lessons and experiences of the policy instruments adopted globally. These development trends, lessons and experiences can also help practitioners understand related CEE reduction policy instruments thus to gain comparative competitiveness in global market. The policy instrument classification framework established by this study can serve as an effective tool for studying on policy instruments in other fields.

Chapter 5 Technologies for Reducing CEE

5.1 Introduction

This section reviews the main technologies used for reducing emissions from construction equipment. Moreover, the costs of these technologies available are reviewed.

5.2 Technologies for Reducing CEE

Various emission reduction technologies are developed to retrofit non-road diesel engines, including those installed on construction equipment. Available emission reduction technologies can be broadly divided into two groups of in-cylinder engine control technologies and exhaust after-treatment technologies (Dallmann & Menon, 2016). In-cylinder engine control technologies primarily through modifying and improving fuel injection and air handling systems promote a full mixture of fuel and air and limit emission formation during the combustion process. The key in-cylinder engine control technologies applied to construction equipment include exhaust gas recirculation (EGR) systems, fuel injection systems, air-handling systems, etc. Among these in-cylinder engine control technologies, EGR systems are widely applied. Thus it is introduced in this research. Exhaust after-treatment technologies remove emissions from the exhaust gas stream, including DOC, selective catalytic reduction systems (SCR), DPF, etc.

5.2.1 In-cylinder Engine Control Technologies

(1) EGR systems

An EGR system reduces NOx by recirculating a portion of engine exhaust gas back to the engine's cylinders (CDCH, 2021; Dallmann, 2018; DTF, 2003). The temperature of the recirculated gases is reduced by exhaust gas recirculation coolers (DTF, 2003). The oxygen content of the recirculated engine exhaust gas is diluted, which has a higher heat capacity and less oxygen than air (DTF, 2003). As a result, the cylinder's combustion temperature is lowered, protecting NOx from formation (CDCH, 2021; MECA, 2014). There are high-pressure and low-pressure EGR systems. Because low-pressure EGR systems require minor engine modifications, it is more widely used for retrofitting applications. Low-pressure EGR systems are usually combined with a catalyst-based DPF (CDCH, 2021). High-pressure EGR systems are currently used in new engine applications (CDCH, 2021). CDCH (2021) reported that more than 3,000 EGR systems combined with DPF systems have been installed in Europe and the United States. This study by CDCH (2021) reported that EGR systems would cause a 1% to 4% fuel economy penalty, depending on the particular engine and test cycle used.

As far as the emission reduction by using EGR systems, different research draws different results. CDCH (2021) found that EGR systems are usually combined with DPFs on off-road engines in retrofit applications, which can achieve NOx reductions of over 40%, PM reductions of greater than 90%, and CO and HC reductions of up to 90%. This study also suggested that low-pressure EGR systems can achieve NOx emission reductions of 25% to over 50%, depending on EGR system design, the engine application, engine calibration, and the operating duty-cycle.

5.2.2 Exhaust After-treatment Technologies

(1) DOCs

DOCs are one of the most common technologies for reducing diesel engine emissions due to their straightforward installation requirements, no engine modifications, and almost no maintenance

(Valentini & Cerio, 2014; CDCH, 2021). A DOC is a catalytic converter containing a honeycomb-structure substrate coated with oxidation catalysts such as platinum or palladium (Dallmann & Menon, 2016; DTF, 2003; MassDEP, 2008). The catalysts could oxidize CO, HCs, and liquid hydrocarbons, which are adsorbed on carbon particles to convert into CO2 and water (MECA, 2014). According to a report issued by the Manufactures of Emission Controls Association, over the past 30 years, oxidation catalysts have been applied to retrofit off-road diesel vehicles, with over 300,000 installations having been completed in the United States as of 2014 (CDCH, 2021; MECA, 2014). In off-road applications, DOCs were widely equipped on mining equipment, construction equipment, marine vessels, and other types of off-road engines (DTF, 2003). Previous operating experiences reveal that DOCs typically could work trouble-free, do not need maintenance for thousands of hours, and usually are replaced only when an engine is rebuilt (CDCH, 2021; MECA, 2014). DOCs could work well on a wide range of applications as long as the exhaust emission temperatures are larger than 150 ℃ (MassDEP, 2008). DOCs could work well with conventional diesel fuel and other cleaner fuels such as biodiesel (DTF, 2003). However, the use of ultra-low sulfur diesel fuel could increase PM emission reductions (MassDEP, 2008).

The ability of DOCs to reduce diesel engine emissions depends on the engine exhaust temperature, the sulfur level in the fuel, and other factors. Different research shows different percentages of emission reduction by installing DOCs on engines. For example, CDCH (2021) and DTF (2003) suggested that DOCs could reduce PM emissions by 20% to 50% and reduce HC and CO up to 90%. MECA (2014) indicated that DOCs could reduce approximately 50% to 90% of HC, 70% to 90% of CO, and 20% to 30% of PM. MassDEP (2008) estimated that a DOC costs from $800 to $3,500, including installation.

(2) DPFs

DPFs remove particles from diesel engine exhaust streams by filtering exhaust from engines (DTF, 2003; Janea et al., 2005; MECA, 2014). There are two modes of particle filtration from engine exhaust, including wall-flow filters and mental flow-through filters (MECA, 2014). Wall-flow filters could enforce exhaust gases through cell walls, causing the particles contained in exhaust gases to be filtered and deposited on the inside wall of the channel and the cleaned exhaust exiting (MECA, 2014). Wall-flow filters have a higher level of filtration efficiency, with more than 90% of particles being filtered (MECA, 2014). Mental flow-through filters employ the corrugated foil channels, which contain perturbations, force a portion of the exhaust upwards through metal mesh, and then effectively trap the particles (MECA, 2000). The filtration efficiencies of mental flow-through filters range from 50% to 80% (MECA, 2000). With use, particulate matters would accumulate in filters, which would be filled up over operating time. The trapped particulate matter should be burned off to clean or regenerate the filter (DTF, 2003). According to the methods of regenerating filters, DPFs can be typically grouped into active and passive DPFs (MassDEP, 2008a). Passive DPFs utilize catalysts costed the filters surfaces to lower the necessary ignition temperature at which soot combustion is facilitated so that regeneration occurs as frequently as required (MassDEP, 2008a). Active DPFs rely on external heat sources such as onboard or offboard burners or electrical heaters to supply the necessary energy to regenerate and burn off the accumulated particulate matter (MassDEP, 2008a). The reliability, durability, and emissions performance effectiveness of passive DPFs can be significantly affected by the sulfur in diesel fuel (Hammer-Barulich, 2013). Because sulfur can inhibit catalytic activity, compete with other exhaust constituents desired chemical reactions, and create PM through catalytic sulfate formation (MassDEP, 2008a; MECA, 2000). Passive DPFs can work best when fuel sulfur levels are less than 15 ppm (MassDEP, 2008). Thus, ultra-low sulfur diesel fuel with a sulfur content not more than 15 ppm can be used with passive DPFs (Janea et al., 2005; MassDEP, 2008). The performance of active DPFs is not affected by fuel sulfur. MECA (2014) suggested that although installations of DPFs may cause some fuel economy penalties, but these penalties for filters are very slight and are about zero or less than one percent. MECA (2014) also maintained that DPFs do not appear to cause any additional engine wear or affect vehicle or equipment maintenance.

DPFs can reduce PM2.5, PM10, HC, and CO emissions by up to 90% and significantly reduce emissions of other toxics, including aldehydes (EPA, 2004; DTF, 2003; MassDEP, 2008). However, DPFs do not remove NOx. DPFs can be combined with EGR, NOx absorber catalysts, or SCR to achieve significant NOx and PM reductions. Engines retrofit with low-pressure EGR and DPFs can achieve NOx reductions of over 40% and PM reductions of greater than 90%. Engines equipped with SCR and a filter can achieve NOx reductions of 70% to 90% and PM reductions greater than 90% (MassDEP, 2008). MECA (2014) reported that the costs of DPFs vary according to the size of the engine, the amount of particular matter emitted by the engine, the emission reduction targets, and other factors. Janea et al. (2005) stated that the costs of DPFs are between $7,000 and $12,000, excluding installation. MassDEP (2008) estimated that for a typical construction equipment engine with horsepower under 250 hp, a passive DPF costs from $8,500 to $10,000, and an active DPF costs from $14,000 to $20,000, including installation.

(3) SCR systems

SCR systems are oxidation catalyst-based technologies, which introduce a chemical reductant like ammonia to NOx over a wash-coated catalyzed substrate or a homogeneously extruded catalyst, converting nitrogen oxides into nitrogen and oxygen (CDCH, 2021; Dallmann, 2018; DTF, 2003; MECA, 2014).

Similarly, the emission reduction abilities of SCR systems are different in different studies, which may be caused by the differences in SCR system design, the engine application, and the operating duty cycle in various studies. MECA (2014) and DTF (2003) stated that open-loop SCR systems could reduce NOx emissions from 70% to 90%, while closed-loop ones can achieve more than 95%

NOx reductions. SCR systems reduce HC emissions by up to 80% and PM emissions by 20% to 30%. CDCH (2020) suggested that SCR technologies could reduce NOx emission from 25% to 90%, PM emissions from 15% to 50%, and HC and CO from 30% to 90%. The study by CDCH (2020) also suggested that NOx control efficiency is a function of 1) the SCR catalyst design; 2) the effectiveness of the reductant delivery system to match the proper dosage to the amount of NOx in the exhaust; 3) the engine application; 4) the operating temperatures; 5) the duty cycle (e.g., steady-state or transient); and 6) the sulfur level in the fuel. Although low sulfur fuel is not required for many SCR catalyst formulations, SCR performance can be enhanced by using low sulfur fuel. SCR catalysts may also be combined with DOCs or DPFs to reduce PM, HC, and CO emissions (CDCH, 2020). Combinations of DPFs and SCR generally require the use of ultra-low sulfur diesel to achieve the highest combined reductions of both PM and NOx. SCRs combined with DOCs can achieve emission reductions of 60% to 80% NOx, 25% PM, 50% to 70% HC and CO (Janea et al., 2005). The cost range for an SCR system varies greatly depending on the engine horsepower and the application (Hammer-Barulich, 2013).

Diesel retrofit technologies have demonstrated their ability to significantly reduce unwanted emissions at a reasonable cost without jeopardizing vehicle or equipment performance (MECA, 2014). This has been echoed by Janea et al. (2005), who insisted that available diesel emission reduction technologies are a cost-effective response to the challenge of mitigating CEE.

5.3 Cost of Technologies for Reducing CEE

It is difficult to estimate the cost of technologies for reducing CEE precisely. Dallmann (2018) stated that the costs of diesel emission reduction technologies are not available, which are known only to their manufacturers. Due to competitiveness concerns, manufacturers are understandably unwilling to share this information (Dallmann, 2018). On the other hand, the complex design of diesel engines in non-road equipment also increases the difficulty of estimating the cost of technologies for reducing CEE. The costs of technologies used to retrofit diesel engines are affected by several factors, including the engine model year, the size of engine, and the amount of emissions, and the installation and the regeneration method of technologies.

Several studies are available on examining the current price of retrofit technologies. US EPA (2007) estimated that the average cost per DOC and per passive DPF are $1,000 and $5,000, respectively, depending on the horsepower and average engine displacement. The estimation by US EPA (2007) is based on two reports. The *Nonroad Tier 4 Regulatory Impact Analysis (RIA)* by US EPA (2004) suggested that the passive DPF costs ranged from $178 to $6,405 and DOC from $105 to $734 depending on the horsepower and average engine displacement. This cost estimated by US EPA (2004) did not include the cost for additional exhaust tubing, data logging and installation. The other *Diesel Retrofit Technology Report* by EPA (2006) contained the additional cost for exhaust tubing, data logging and installation, which is $593 for a passive DPF and $280 for a DOC. Then, based on the estimates from the two reports and experience with nonroad retrofit technology, US EPA (2007) obtained the cost of passive DPF and DOC.

MECA (2014) reported that the cost of retrofitting a low-pressure EGR system on a typical bus or truck engine is about $18,000 to $20,000, which includes the DPF. According to the report by MECA (2014), the cost of DOCs varies from $500 to $2,000 per catalyst and the DPFs from $5,000 to $7,000, depending on engine size, the number of diesel oxidation catalysts purchased, and whether the installation is a muffler replacement or an in-line installation. MECA (2014) stated that the costs of SCR systems are from about $18,000 with a DOC to $30,000 with a DPF per vehicle. In the study by MECA (2014), the cost of various retrofitting technologies is directly given, without providing any more information.

The international council on clean transportation (ICCT) published the cost assessment of manufacturers' non-road emission control technologies to meet the emission control standards promulgated by the EPA and EU at each regulatory tier or stage (Dallmann, 2018). ICCT defined a single representative technology package for each power class and regulatory emission standard tier that contractors commonly adopt, and estimated the cost of the defined technology package. Then, the study estimates the total incremental cost of adopting emission reduction technologies to meet each emission standard tier for each power class, by matching the required technologies and their costs. For example, it is said that the cost of DOC for a 224–447 kW, 10.8 L engine to meet Tier 4f is $470 (Dallmann et al., 2018).

CARB in 2000 estimated the cost of emission reduction technologies, which is available in a web-based database named Clean Diesel Clearing House (CDCH) (CDCH, 2021). The costs of DOC and DPF are summarized in Table 4.1.

Table 5.2 The costs of DOC and DPF estimated by CARB (2000)

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

CDCH (2021) suggested that the costs for DOCs in retrofit applications are decreasing slightly and range from less than $500 to $1,250 for engines in the 100-200 horsepower category and from less than $1,000 to $1,750 for engines in the 200-500 horsepower category. Meanwhile, DOC installation typically takes one to two hours, and if provided by the technology supplier or its agent, the cost is in the range of less than $100 to about $200. Since DOC installation is relatively straightforward, fleet technicians, sometimes after receiving training from the DOC supplier, install the DOCs themselves, thereby avoiding external installation costs. Finally, since DOCs are virtually maintenance-free except for periodic checks of the DOC and exhaust system for mechanical integrity, no maintenance costs are typically incurred.

According to CDCH (2021), the installation cost of DPF is sometimes included in the purchase price but is often billed as a separate item. The time needed to install a retrofit can range from as little as two hours to over 10 hours. At an estimated rate of $65 per hour, retrofit installation costs would typically range from $130 to $650. These costs, however, could be substantially higher in situations in which complex or time-consuming DPF installations are involved.

As for the cost of SCR, CDCH (2021) pointed out that the technology costs vary greatly depending on the engine size, the vehicle application, and whether engine mapping is needed or is already available. They estimated the cost of an SCR system to be in the range of $50 to $60 per horsepower. Besides, CARB (2000) also estimated the installation costs at anywhere from $500 to $5,000 depending on the application and whether engine mapping was required.

5.4 Chapter Summary

This section introduces the main technologies used for reducing CEE, including in-cylinder engine control technology of EGR and exhaust after-treatment technologies of DOC, DPF and SCR. Moreover, the costs of these technologies available are reviewed.

CHAPTER 6 A Novel Quantitative Model for Determining Subsidy Levels to Accelerate the Replacement of Construction Equipment for Emissions Reduction

6.1 Introduction

Subsidy incentive programs for accelerating the replacement of construction equipment are widely considered effective for reducing emissions from construction equipment. However, there are no known effective models for determining the optimal subsidy levels for voluntary early replacement of in-use high-emission construction equipment. In this section, a novel quantitative model is developed to address this problem by integrating emission reduction targets and life cycle cost of construction equipment to calculate the reduced service life of an item of construction for early replacement. The economic life of construction equipment and its corresponding EUAC can be determined by using a traditional LCC analysis model introduced in Section 3.3.4. Optimal subsidy levels are obtained on the basis that the subsidized EUAC of a piece of construction equipment over its shortened service life is not more than that over its normal economic life. The applicability of the proposed model is demonstrated through a case study of a crawler crane used in Hong Kong, whereby the subsidy levels for accelerating its replacement are determined. An interview with the contractor's equipment manager responsible for the crawler crane is conducted to validate the findings of the model. It is found that the optimal subsidy levels determined by the model can accelerate the replacement of construction equipment and achieve the goal of reducing emissions from construction equipment. Replacing construction equipment earlier than its economic life is a plausible strategy for emissions reduction but places a heavy financial burden on contractors if there is no financial compensation. This study shows that the subsidy levels determined by the proposed model can adequately compensate for the extra costs incurred from early replacement and would therefore not financially discourage contractors. This model also shows that the cost-effectiveness of subsidies increases as emission reduction targets are set at higher levels.

6.2 The Framework of Developing the Quantitative Model for Determining Subsidy Levels

The research framework of this section is shown in Fig. 6.1, which demonstrates the mechanism for finding the optimal subsidy level. The methodology starts by setting emission reduction targets for subsidy incentive programs. By using a traditional LCC analysis model, the economic life of construction equipment is then identified when there are no available subsidy incentives. According to emission reduction targets, the reduced service life of the equipment is determined, by which the replacement of construction equipment is made earlier. Two constraints are then applied to make the subsidy levels optimal. One constraint is to ensure the reduction in the service life of the equipment, and the other is to ensure that the EUAC of equipment does not increase compared with that of no subsidies. Satisfying the two constraints can accelerate the replacement of in-use construction equipment without placing financial burdens on owners of construction equipment and ensure the achievement of emission reduction targets. In the final step, the optimal subsidy level can be obtained.

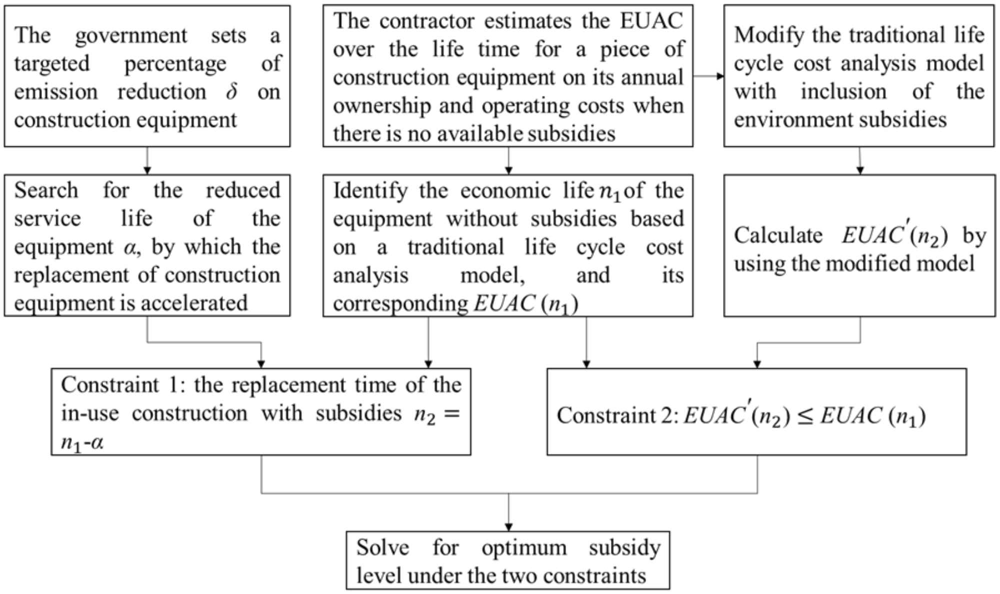

Fig.6.1 The Framework of development of the quantitative model for determining subsidy levels

The proposed methodology can meet the demands of both owners of construction equipment and governments, which is crucial to the success of construction equipment replacement programs. The subsidy levels determined by the proposed model fully consider the willingness of construction equipment owners to replace their equipment earlier. Minimizing cost is always an uppermost goal for many owners of construction equipment and various costs over the equipment's life cycle are the main things to consider when making equipment replacement decisions(Chen & Keys, 2009; Gransberg et al., 2006). Thus, this study employs a traditional LCC analysis model to analyze the annual average costs of normal equipment replacement and early equipment replacement with available subsidies. The subsidy levels must be able to trade off the costs incurred from early replacement, so as not to create a financial burden on construction equipment owners. Since achieving emission reduction targets is the main concern of governments, the methodology is designed to help achieve such targets by determining an appropriate replacement time.

6.3 Model Development

6.3.1 Setting Emission Reduction Targets

Emission reduction targets do have an impact on the optimal subsidy level (Zaman and Zaccour 2021). Therefore, to determine optimal subsidy levels, this study first set the intended emission reduction targets. The common emission reduction targets set by governments in subsidy incentive programs include reducing emissions by certain percentages or maximizing environmental benefits. Cohen et al. (2016) suggested that these targets are equivalent and yield the same results. This study assumes that governments initiate subsidy incentive programs for accelerating the replacement of construction equipment with a target of reducing emissions equivalent by a percentage of δ. The calculating method of emissions equivalent is detailed as follows.

Accelerating the replacement of construction equipment can achieve reductions in multiple types of emissions simultaneously by different amounts across them. Reduction of all main emissions should be considered and awarded in subsidy incentive programs. Otherwise, the health problem caused by emissions cannot be effectively addressed. This is because only awarding the reduction of one type of emission cannot motivate owners of equipment to reduce other harmful emissions, which may not possible to mitigate. Thus, to consider all main emissions, this study translates these emissions into emissions equivalent (abbreviated as E_{eq}). The emissions are assigned appropriate weightings according to their health effects. Referring to the study of Wong et al. (2013), the equivalent coefficient for emissions is determined by the relative risks of emergency hospital admissions for respiratory and cardiovascular diseases associated with the emission. Then, by adding the equivalent of every emission, E_{eq} is calculated using Equation (6.1):

$$E_{eq} = \sum_{k=1}^{K} \beta_k e_k \tag{6.1}$$

where E_{eq} is the emissions equivalent; e_k is the amount of emission k; and β_k is the equivalent coefficient of emission k which can be calculated by the method described in the study of Wong et al. (2013).

6.3.2 Identifying the Economic Life of Construction Equipment without Subsidies

The traditional LCC analysis model previously introduced in Section 3.3.4 is employed by this study to first find the economic life of construction equipment without subsidies.

Data for the parameters in the LCC analysis model can be obtained or estimated from the historical records of costs incurred from a piece of equipment provided by the equipment manufacturer and the owner. The following assumptions are made for conducting an economic analysis from a life cycle perspective.

1) It is not often easy to separate annual equipment profit from the entire project but various costs of equipment are clear (Gransberg et al., 2006; Hartman & Murphy, 2006). The revenue generated by construction equipment is stable due to the high utilization rate of construction equipment. In the LCC analysis conducted in this study, the widely applied minimum cost method rather than the maximum profit method is used as the analysis approach.

2) This study uses economic life as the analysis point. Owners of construction equipment can replace their equipment at any time. However, when they replace their equipment at the economic life of the equipment, the average annual cost of the equipment over its life cycle is the minimum.

3) To find the economic life, EUAC of construction equipment over its service life should be calculated and analyzed. Thus, the physical life of construction equipment is the analysis period in this economic analysis.

4) Cost discounting is considered in this economic analysis. All costs that occurred at any time over the life span of construction equipment are converted into present values at the beginning of the planning horizon using the prevailing interest rate. Inflation is not considered in this LCC analysis.

5) Ownership costs include depreciation, investment cost, insurance cost, tax, and storage cost. Among these costs, the amount of depreciation is significantly larger than others. For simplicity, only depreciation cost is considered. This study assumes that depreciation cost can be calculated by deducting salvage cost from initial cost at the decision point.

6.3.3 Searching for the Reduced Service Life to Accelerate Replacement

The model searches for the reduced service life of equipment by which the replacement of construction equipment is accelerated, denoted by α, based on the emission reduction targets set by the government in the subsidy incentive program. The relevant equations, Equations (6.2) to (6.4) are as follows.

$$\delta = \frac{E^{0}_{eq} - E^{'}_{eq}}{E^{0}_{eq}} \tag{6.2}$$

$$E^{0}_{eq} = \sum_{n=1}^{n_1} \sum_{k=1}^{K} \beta_k \, e_{k,n} \tag{6.3}$$

$$E^{'}_{eq} = \sum_{n=1}^{n_1\text{-}\alpha} \sum_{k=1}^{K} \beta_k \, e_{k,n} + \alpha \beta_k e_{k,0} \tag{6.4}$$

where E^{0}_{eq} is the amount of emissions equivalent generated by one piece of in-use construction equipment from year 1 to year n_1. $E^{'}_{eq}$ is the sum of emissions equivalent generated by one piece of in-use construction equipment from year 1 to year n_1-α and emissions equivalent generated by a new one from year n_1-α to year n_1. $e_{k,n}$ is the amount of emission k generated by one piece of in-use construction equipment in the nth year (g). $e_{k,0}$ is the amount of emission k generated by a new one each year.

This study employs the NONROAD2008a emission model (US EPA, 2018) developed by US EPA to calculate emissions from construction equipment including HC, CO, NOx and PM2.5, which is introduced in Section 3.3.6. According to this model, $e_{k,n}$ can be calculated by Equations (3.6)-(3.11).

In this study, $e_{k,0}$ is assumed to be constant every year, which can be calculated as shown by Equation (6.5) below:

$$e_{k,0}=EF_k\times C_n \tag{6.5}$$

where EF_k is the emission factor of emission k of the new construction equipment, which equals the latest emission standard implemented in the area where the construction equipment is used.

Based on Equations (6.2)-(6.5), the optimal value for α can be calculated by Equation (6.6).

$$\alpha=\frac{(1\text{-}\delta)\sum_{n=1}^{n_1}\sum_{k=1}^{K}\beta_{\mathrm{k}}e_{k,n}-\sum_{n=1}^{n_1\text{-}\alpha}\sum_{k=1}^{K}\beta_k e_{k,n}}{\beta_k e_{k,0}} \tag{6.6}$$

6.3.4 Optimizing the Subsidy Levels with Application of Two Constraints

To make the subsidy levels determined by the quantitative model optimal, two key constraints should be applied. The first constraint is that the replacement of the in-use construction equipment with subsidies dispensed in year n_2 should take place earlier than the one without subsidies by α years. This means subsidies could cause the in-use construction equipment to be replaced before the time point at which it would be replaced economically, and consequently the target of reducing emissions equivalent by a percentage of δ can be achieved. This criterion is satisfied by replacing the in-use construction equipment with subsidies in the year n_1-α. The second constraint is that the EUAC of in-use construction equipment with subsidies replaced in the year of n_1-α is lower than or equal to that without subsidies replaced in the year n_1, which are denoted by $EUAC'(n_1\text{-}\alpha)$ and $EUAC\ (n_1)$ respectively. The second criterion is to ensure that the subsidy levels can offset the cost incurred from earlier replacement of in-use construction equipment and do not put a heavy financial burden on contractors. The two constraints can be described as Inequality (6.7) and Equation (6.8).

$$EUAC'(n_1\text{-}\alpha) \leq EUAC\ (n_1) \tag{6.7}$$

$$n_2 = n_1\text{-}\alpha \tag{6.8}$$

$EUAC'(n_1\text{-}\alpha)$ and $EUAC\ (n_1)$ can be expressed in Equations (6.9) and (6.10). In Equation (6.9), subsidies are taken as revenues and added into the cash flow of construction equipment.

$$EUAC'(n_1\text{-}\alpha)=I(A/P,\ i,\ n_1\text{-}\alpha)\text{-}S_n(A/F,\ i,\ n_1\text{-}\alpha)+\sum_{j=1}^{n_1\text{-}\alpha} OC_j\ (P/F,\ i,j)(A/P,\ i,\ n_1\text{-}\alpha)$$

$$\text{-}r\ (P/F,\ i,\ \varepsilon\ )(A/P,\ i,n_1\text{-}\alpha) \tag{6.9}$$

$$EUAC(n_1)=I(A/P,\ i,\ n_1)\text{-}S_n(A/F,\ i,\ n_1)+\textstyle\sum_{j=1}^{n_1} OC_j\ (P/F,\ i,j)(A/P,\ i,\ n_1) \tag{6.10}$$

where, ε is the time (year) when the construction equipment is granted with subsidies, which is assumed to be shorter than N and r is the number of subsidies granted to the owner of the construction equipment.

6.3.5 Obtaining the Optimal Subsidy Levels

This study replaces the two sides of Inequality (6.7) with the right sides of Equations (6.9) and (6.10). Then, the corresponding subsidy level can be obtained as shown in Equation (6.11).

$$r \geq \Big\{ I\,(A/P,\, i,\, n_1\text{-}\alpha)\text{-}S_N(A/F,\, i,\, n_1\text{-}\alpha)+ \textstyle\sum_{j=1}^{n_1\text{-}\alpha} OC_j(P/F,\, i,\, j)(A/P,\, i,\, n_1\text{-}\alpha) - I\,(A/P,\, i,\, n_1)+ S_N(A/F,\, i,\, n_1)\text{-} \textstyle\sum_{j=1}^{n_1} OC_j(P/F,\, i,\, j)(A/P,\, i,\, n_1) \Big\} /(P/F,\, i,\, \varepsilon)(A/P,\, i,\, n_1\text{-}\alpha) \tag{6.11}$$

When the subsidy incentive programs require recipients of subsidies to replace their equipment on receiving the subsidy, the value of ε equals to n_1-α and the corresponding subsidy level can be determined by Equation (6.12).

$$r \geq \Big\{ I\,(A/P,\, i,\, n_1\text{-}\alpha)\text{-}S_N(A/F,\, i,\, n_1\text{-}\alpha)+ \textstyle\sum_{j=1}^{n_1\text{-}\alpha} OC_j(P/F,\, i,\, j)(A/P,\, i,\, n_1\text{-}\alpha) - I\,(A/P,\, i,\, n_1)+ S_N(A/F,\, i,\, n_1)\text{-} \textstyle\sum_{j=1}^{n_1} OC_j(P/F,\, i,\, j)(A/P,\, i,\, n_1) \Big\} /(A/F,\, i,\, n_1\text{-}\alpha) \tag{6.12}$$

6.4 Case Study

This section conducts a case study in Hong Kong to illustrate the application of the proposed model for determining optimal subsidy levels for accelerated replacement of a crawler crane.

6.4.1 Description of the Selected Construction Equipment

Crawler cranes are common construction equipment widely used for heavy lifting work and large assemblies in building construction. In this study, a Liebherr HS883HD crawler crane is employed to demonstrate the application of the proposed model. The performance data for the crawler crane is derived from Chun Wo Engineering (H.K) limited, which is a large general contractor in Hong Kong, as shown in Table 6.1.

Table 6.1 Performance data of the crawler crane

Parameters	Values
Horsepower (hp)	810
Engine Tier	Tier 2
Physical life (years)	25
Average operating hours per year (hr)	1,500
Initial cost (HK$)	6,000,000
Salvage value (HK$)	85% of its residual value of last year
Interest rate	2.50%
Repair and maintenance cost in *n*th year (HK$)	8600+*n**17,000
Fuel cost per year (HK$)	540,000

6.4.2 Emission Reduction Targets

Policy measures implemented by the Hong Kong government for reducing emissions from construction equipment or non-road mobile machines, do not include proposed targets for reducing emissions from construction equipment (Huang et al., 2021). Due to the lack of emission reduction targets on non-road mobile machines in Hong Kong, this study sets a series of emission reduction targets for reducing emissions equivalent ranging from 1% to 20%.

6.4.3 Economic Life of the Crawler Crane without Subsidies

According to Equation (6.1), when there are no available subsidies, $EUAC$ (n) of the crawler crane can be calculated, as illustrated in Fig. 6.2. When n equals 17, $EUAC$ (n) is minimum with a value of HK$ 1,317,417.31. Therefore, the economic life of the crawler crane without subsidies is n_1=17.

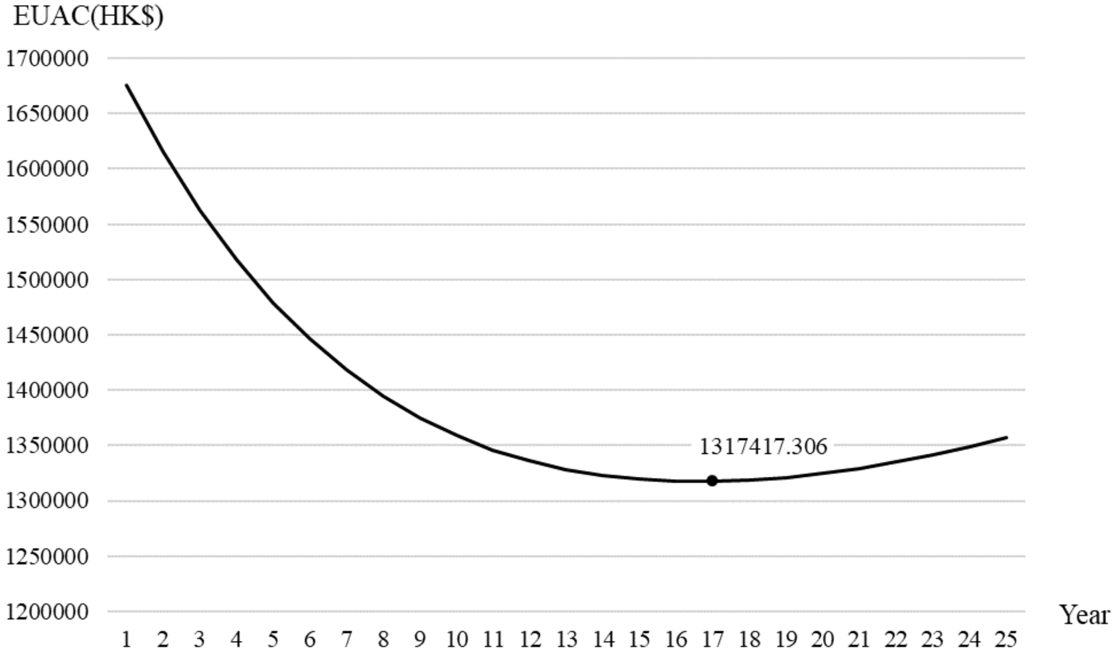

Fig.6.2 EUAC of the crawler crane over its physical life

6.4.4 Reduced Service Life of Equipment

Emissions of PM and NOx are considered in the case study because they are the main types of emissions in Hong Kong among the four types of emissions generated by construction equipment (Legislative Council of HK, 2018). According to Equations (6.6)-(6.11), the amount of PM and NOx ($e_{PM,n}$ and $e_{NOx,n}$) emissions generated by the crawler crane over n_1 years can be obtained, as shown in the first two columns of Table 6.2. By referring to the study by Wong et al.(2013), in which the relative risks of hospital admissions for respiratory and cardiovascular diseases associated with PM and NOx in Hong Kong are calculated, the values of β_{PM} and β_{NOx} are 1.0028 and 1.0045 respectively. By applying these figures to Equation (6.1), the amount of emissions equivalent generated by the crawler crane over n_1 years is calculated to be that shown in the last column of Table 6.2.

Table 6.2 Emissions and emissions equivalent generated by crawler crane over n_1 years (kg)

Year (n)	$e_{NOx,n}$	$e_{PM,n}$	E_{eq}
1	4,989.94	62.31	5,074.87
2	4,994.07	69.28	5,086.02
3	4,998.21	76.25	5,097.17
4	5,002.34	83.23	5,108.32
5	5,006.48	90.20	5,119.46
6	5,010.61	97.18	5,130.61
7	5,014.75	104.15	5,141.76
8	5,018.88	111.13	5,152.91
9	5,023.02	118.10	5,164.05
10	5,027.15	125.08	5,175.20
11	5,031.29	132.05	5,186.35
12	5,035.42	139.03	5,197.50
13	5,039.56	146.00	5,208.65
14	5,043.69	152.98	5,219.79
15	5,047.83	159.95	5,230.94
16	5,051.96	166.93	5,242.09
17	5,056.09	173.90	5,253.24

In Hong Kong, new construction equipment with a rated engine power output of 810 hp are required to meet US Tier 3 emission standards by the *Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation* issued by the government (HK EPA, 2015). Accordingly, the emission factors of PM and NOx emissions for a new crawler crane are 0.3 and 2.6 g/hp-hr respectively, which replaces the old crawler crane from n_1-α year. By applying Equation (6.6), the reduced service life of equipment corresponding to emissions equivalent reduction targets (EERTs) are calculated, by which the replacement of the case crawler crane is accelerated, as shown in Fig. 6.3. In Equation (6.6), the decimal values of α are rounded up to the nearest whole number in the result. Thus, there are some different EERTs with the same values of α. Overall, the value of α increases with EERTs being raised. Moreover, the actual percentages of emissions equivalent reduction (EER), when the crawler crane is replaced by α years ahead, are calculated by Equations (6.2)-(6.4). As can be seen from Fig. 6.4, when the crawler crane is replaced one year earlier, the actual percentage of EER is 2.32%. Therefore, when EERTs are 1% and 2%, the corresponding values of α are 1.

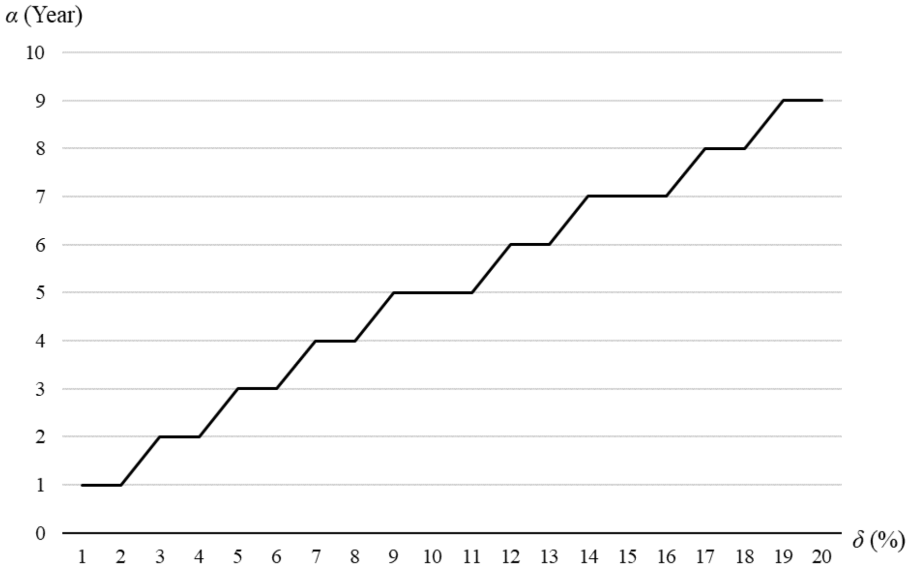

Fig.6.3 Reduced service life versus emissions equivalent reduction targets

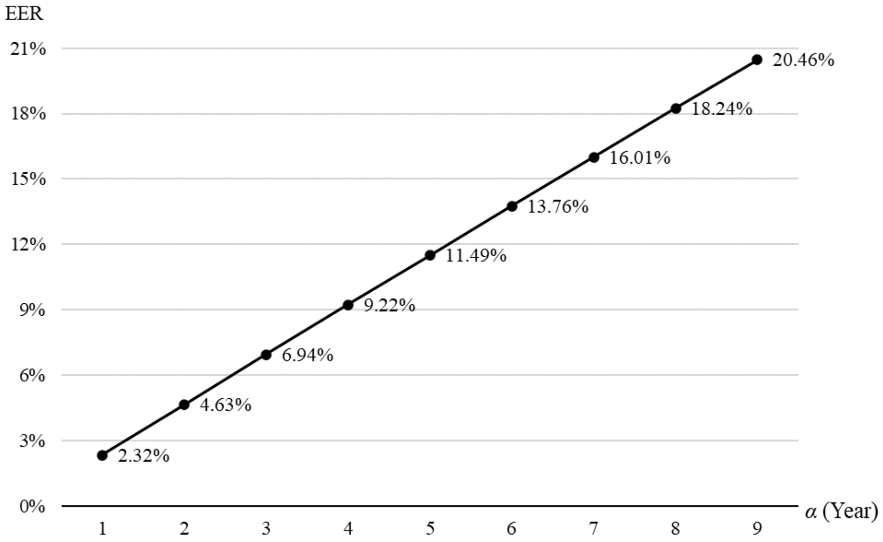

Fig.6.4 Actual percentages of emissions equivalent reduction (EER)

6.4.5 Optimal Subsidy Level for the Crawler Crane

The subsidy levels under different EERTs can be calculated by using Equation (6.12), as shown in Fig. 6.5. The subsidy levels versus reduced service life of equipment are shown in Fig. 6.6.

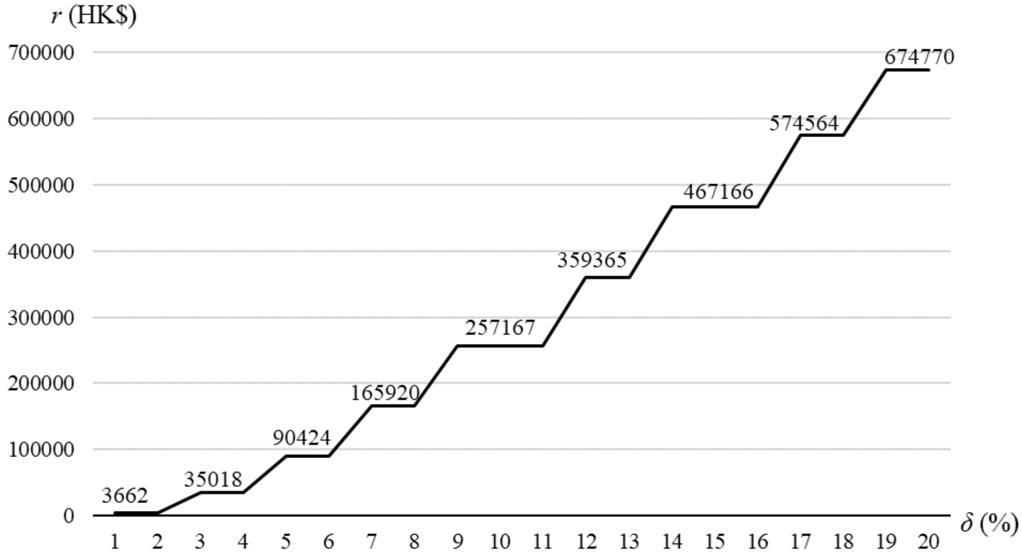

Fig.6.5 Subsidy levels versus different emissions equivalent reduction targets (EERTs)

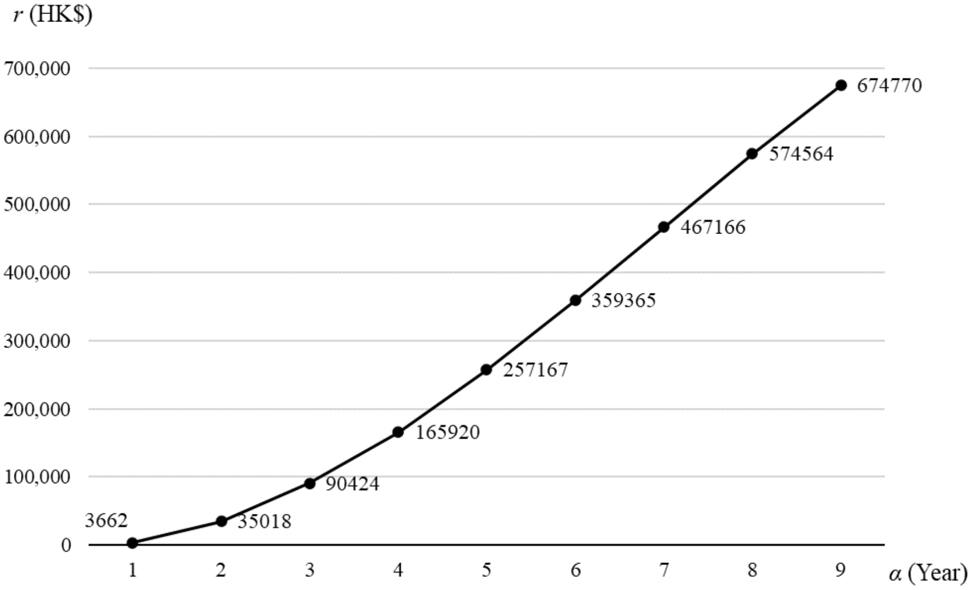

Fig.6.6 Subsidy levels versus reduced service life of equipment

According to Fig. 6.5, the subsidy levels increase with the pre-determined EERTs being raised. This is because when EERTs are raised, the crawler crane needs to be replaced earlier. Consequently, the annual costs of contractors owning and operating the crawler crane also increase when there are no subsidies. The principle of the proposed model for determining the optimal subsidy levels is to offset this additional cost and not generate a financial burden for contractors if the equipment is required to be replaced earlier, so subsidy levels increase with higher EERTs.

It can be inferred from Fig. 6.5 and Fig. 6.6 that the subsidy levels determined by the proposed model will not impose a financial burden on contractors. For example, when the government implements a subsidy incentive program with a target of reducing emissions equivalent generated by this type of crawler crane by 4%, Fig. 6.5 shows that the government will compensate the contractor HK$35,018 for each crawler crane. According to Fig. 6.6, when the owner of the crawler crane receives a subsidy of HK$35,018, the reduced service life of the crawler crane is 2 years and it will be replaced in the 15th year. $EUAC^{'}(15)$ of the crawler crane can be calculated by Equation (6.6), which is HK$1,317,417.10. The value of $EUAC^{'}(15)$ is almost equal to that of $EUAC$ (17) with a value of HK$1,317,417.306. This indicates that the subsidy level of $35,018 per unit of the crawler crane would relieve the contractor from financial burdens.

Fig. 6.7 illustrates that the subsidy levels determined by employing the proposed model can not only accelerate the replacement of construction equipment but also achieve the goal of emission reductions. The economic life of the case crawler crane with subsidies is always less than 17 years which is the economic life without subsidies. This suggests that the subsidy levels determined by the proposed model can accelerate the replacement of construction equipment. Since the EER line is shown as always above the EERT line, the subsidy levels can always achieve the EERTs.

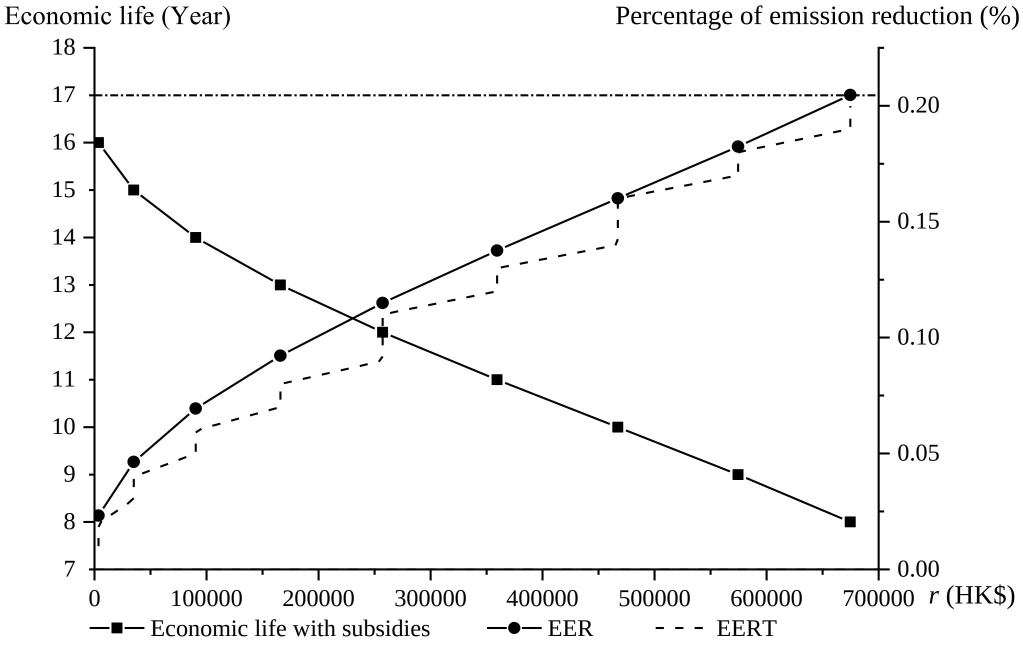

Fig.6.7 Subsidy levels versus economic life and percentages of emission reduction

After obtaining the subsidy levels by applying the proposed model for accelerating the replacement of the case crawler crane, an interview was conducted with the contractor's equipment manager responsible for the crawler crane, to validate the findings. The equipment manager was asked to answer the following question in his capacity as an expert in the field: in this case, would the contractor be willing to replace the crawler crane earlier according to the subsidy levels and the corresponding reduced service life determined by the model?

The equipment manager opined that subsidy levels determined by this study are reasonable, and that the contractor would be willing to replace the crawler crane in question according to the subsidy levels and the corresponding reduced service life. However, he said that in practice the contractor may look at other options in the market, such as leasing rather than purchasing or replacing. He also suggested that other conditions, such as equipment reliability, should be considered and pointed out that some construction sites in Hong Kong will not allow crawler cranes over 10 years old to be used.

6.5 Discussion

The main findings are summarized and discussed in this section. Parameter settings in the proposed model are first discussed, followed by a cost-effectiveness analysis of the subsidy awarded to the owner of the crawler crane in the case study.

6.5.1 Discussion of the Parameters in the Proposed Model

When the EUAC of construction equipment with subsidies from governments ($EUAC'(n_1\text{-}\alpha)$) is equal to or smaller than that of construction equipment without subsidies ($EUAC\,(n_1)$), that is, the value of *r* makes Inequality (6.7) constraint satisfied, contractors have enough financial motivation to replace their equipment earlier. However, for small contractors, subsidy incentives can bring them revenues and at the same time require them to spend a lot of money on replacing in-use equipment with a new model. Large upfront payment for buying new construction equipment may be difficult for small contractors and discourage them from participating subsidy incentives programs. However, earlier replacement of deteriorated in-use construction equipment with new models means less downtime during operations, and a more reliable and efficient construction equipment fleet can help contractors to gain a competitive edge in the market. This may encourage some contractors to join subsidy incentive programs to replace their equipment earlier even when the amount of subsidy is not lucrative, such as where it can barely balance the $EUAC'(n_1\text{-}\alpha)$ and $EUAC\,(n_1)$. Therefore, when applying this model to determine the subsidy levels for earlier replacement of in-use construction equipment, the government can consider the difference among contractors and enact some supplementary measures to attract smaller contractors to join such programs. Therefore, through initiating policy instruments, the government can raise the awareness and consciousness of contractors to environmental protection by encouraging more contractors to get involved in the subsidy incentive programs for earlier replacement of construction equipment.

This is extremely important in jurisdictions where most contractors are of small to medium size and where there are only a limited number of large general contractors in the market, such as Hong Kong.

By referring to Equation (6.10), it can be seen that subsidy levels are determined by the reduced service life by which the replacement of construction equipment is accelerated (the value of α), which depend on the emission reduction targets set by the government. Thus, the setting of emission reduction targets influences the subsidy levels. This study sets emission reduction targets as reducing emissions equivalent by a percentage. Users of the proposed model can set different emission reduction targets according to their needs. For example, when the government's aim is to initiate a subsidy incentive program to reduce PM emission, they can set the emission reduction targets as reducing PM emission by a certain percentage to calculate the subsidy levels. When the government intends to reduce several types of emissions simultaneously by different percentages, it can set different emission reduction targets for different emissions. Namely, governments can use different values of δ for different emission types to calculate the corresponding values of α and then apply the maximum α into Equation (6.12) to calculate the subsidy levels.

In the process of translating various emissions into emissions equivalent, the method for setting equivalent coefficients for emissions is based on health effects. This study determines the equivalent coefficients for emissions by the relative risk of emergency hospital admissions for respiratory and cardiovascular diseases associated with the emissions. Users of the proposed model can determine equivalent coefficients for emissions from other perspectives, such as chemical, physical, or biological effects of emissions.

6.5.2 Cost-effectiveness Analysis of Subsidies for Accelerating Replacement of Crawler Crane

Although subsidy incentive programs for accelerating the replacement of in-use construction equipment can bring environmental benefits to the public, they are costly for governments. An effective model for determining optimal subsidy levels can help governments design subsidy incentive programs to achieve their emissions reduction targets by the best use of public resources. Therefore, it is beneficial to conduct a cost-effectiveness analysis to assess the effectiveness of the proposed model for the reference of governments.

The cost-effectiveness of subsidies for reducing emissions from the crawler crane can be measured by the ratio of the amount of subsidies to the amount of emissions equivalent reduced. The cost-effectiveness of the subsidies given to the crawler crane in the case study is demonstrated in Fig. 6.8 and Fig. 6.9.

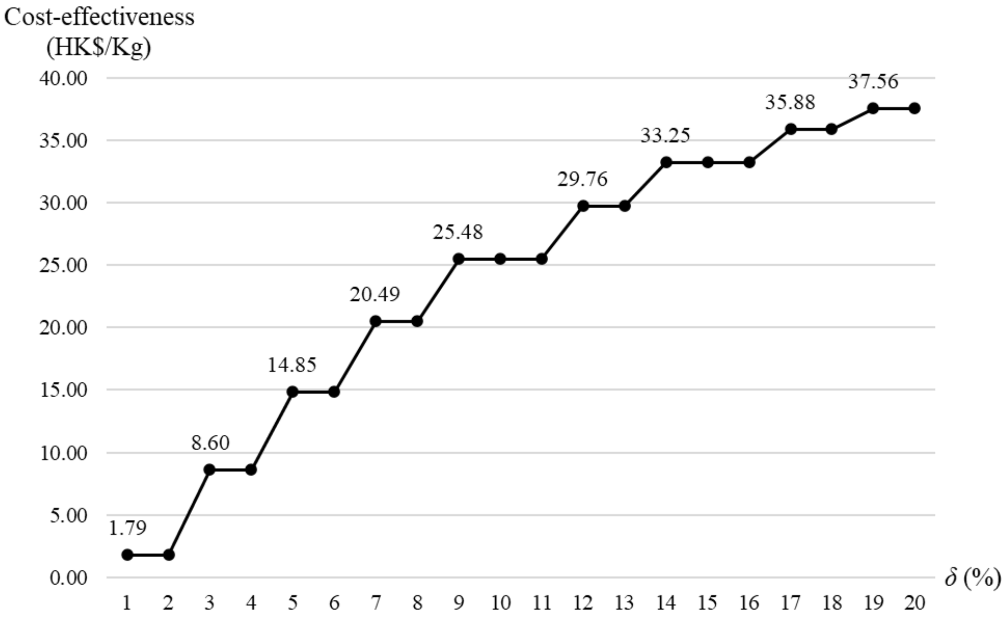

Fig.6.8 Cost-effectiveness versus emissions equivalent reduction targets

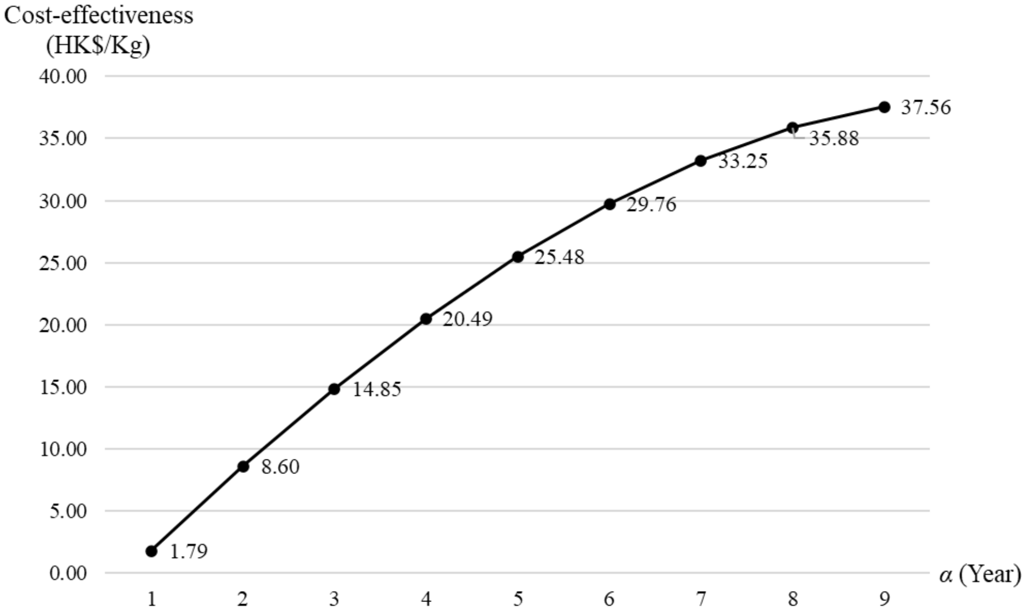

Fig.6.9 Cost-effectiveness versus reduced service life of the crawler crane

The cost-effectiveness of subsidies for reducing emissions from the crawler increases when the EERTs and the reduced service life are increased. It can be seen from Fig. 6.5 and Fig. 6.8 that when EERTs are raised from 1% to 20%, the subsidy level increases from HK$3,662 to HK$674,770, and the cost-effectiveness increases from HK$1.79 to HK $37.56 per kg of emissions equivalent reduced. The cost-effectiveness of subsidies has an upward trend, as the cost of reducing emission is increasing as the EERTs are raised. This is because when EERTs are raised, the crawler crane should be replaced even earlier. The reduced service life of equipment also increases faster as EERTs become higher, with the escalating amounts of emissions generated by the crawler crane due to aging effects. The owning and operating costs of newer construction equipment are higher with more subsidies required to offset the additional costs caused by the early equipment replacement. Thus, the cost-effectiveness increases accordingly. For example, when EERT is set at 2%, an amount of HK$3,662 is subsidized to the crawler crane owner for the equipment replacement in the 16th year with a reduction of about 2,040.69 kg emissions equivalent. When EERT is raised to 5%, the crawler crane owner receives HK$90,424, for equipment replacement in the 14th year, with a total reduction of about 6,088.64 kg emissions equivalent. The average annual emissions reduction is 2,040.69 kg emissions equivalent when the equipment is replaced in the16th year, which is larger than the average annual emission reduction of 2,029.54 kg when the equipment is replaced in the 14th year. The amounts of average annual emissions equivalent reduced increase steadily for replacement options at the 14th to the 16th year. Moreover, the average annual subsidy of the crawler crane replaced in the 14th year is HK$ 30,141, which is greater than HK$2,040.69 if the crawler crane is replaced in the 16th year. This is because more annual subsidies are needed when the crawler crane is replaced earlier to offset the additional cost induced by early replacement. Thus, the cost-effectiveness of the subsidy is increasing as EERT is raised.

6.6 Chapter Summary

Although subsidy incentive programs for accelerating the replacement of in-use construction equipment can bring environmental benefits to the public, they are costly for governments. An effective model for determining optimal subsidy levels can help governments design subsidy incentive programs to achieve their emissions reduction targets by the best use of public resources. Therefore, it is beneficial to conduct a cost-effectiveness analysis to assess the effectiveness of the proposed model for the reference of governments.

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CHAPTER 7 Responsibility-sharing Subsidy Policy for Reducing Emissions from in-use Construction Equipment

7.1 Introduction

Making subsidy policies to encourage contractors to replace or retrofit their in-use construction equipment has been accepted as an effective way to mitigate emissions generated by construction equipment. However, the existing subsidy policies do not consider the emission reduction responsibility of contractors as emitters, which would cause inequity problems and fails to motivate contractors to innovative more cost-effective emission reduction strategies. Thus, this study proposes a responsibility-sharing subsidy policy. In the proposed subsidy policy, the subsidy level and the responsibility of contractors assigned in proportion for emission reduction are determined with the attaining of minimum overall cost per ton of emissions equivalent reduced. A construction equipment fleet of excavators in Hong Kong is employed to demonstrate the application of the proposed subsidy policy. In the excavator fleet case, subsidy levels in the range of 14,800 HK$ to 2,402 HK$ per ton of emissions equivalent reduced are recommended, with the responsibility of emission reduction borne by the government from 92% to 100% and the contractor from 0% to 8%. The corresponding cost-effectiveness of the designed subsidy policy is about 16,096 HK$ per ton of emissions equivalent reduced, which is reasonable and acceptable. This study also finds that by assigning proper emission reduction responsibility to contractors, governments can lead contractors to adopt optimal strategies of replacing and retrofitting construction equipment to reduce emissions with minimum overall cost per ton of emissions equivalent reduced.

7.2 The Framework of Development of Responsibility-sharing Subsidy Policy

In this section, the responsibility-sharing subsidy policy to encourage replacement and retrofit of in-use construction equipment fleets for emission reduction is developed, which are designed at two levels. At the government level, the fleet average emission limit is set, which requires the average emission level of construction equipment fleets does not exceed a certain value. Governments also provide subsidies to contractors for offsetting partial costs of reducing emissions from construction equipment fleets. At the contractor level, an optimization model is proposed to help contractors to make optimal construction equipment replacement and retrofitting strategies with the financial subsidies and the constraint of meeting fleet average emission limit set by the government. The optimization model can help contractors become smarter regarding emission control options and costs. Under the optimal replacement and retrofitting strategy, the amount of emission reduced and the cost of reducing emissions can be obtained. Then, the cost per ton of emission reduced incurred by contractors (CE_{con}) for replacing or retrofitting construction equipment to reduce emissions can be calculated. The cost per ton of emission reduced incurred by the government (CE_{gov}) is equal to the subsidy level. Accordingly, the overall cost per ton of emission reduced incurred by the government and the contractor ($CE_{con+gov}$) can be obtained. By changing the subsidy level, the range of $CE_{con+gov}$ could be obtained. This study recommends reducing construction equipment emissions with the minimum $CE_{con+gov}$, which can ensure the greatest emission reduction per dollar from the overall social perspective. Under the minimum $CE_{con+gov}$, the responsibility for emission reduction between the government and contractor can be allocated and the optimal subsidy is derived. The framework of the responsibility-sharing subsidy policy development is demonstrated in Fig.7.1.

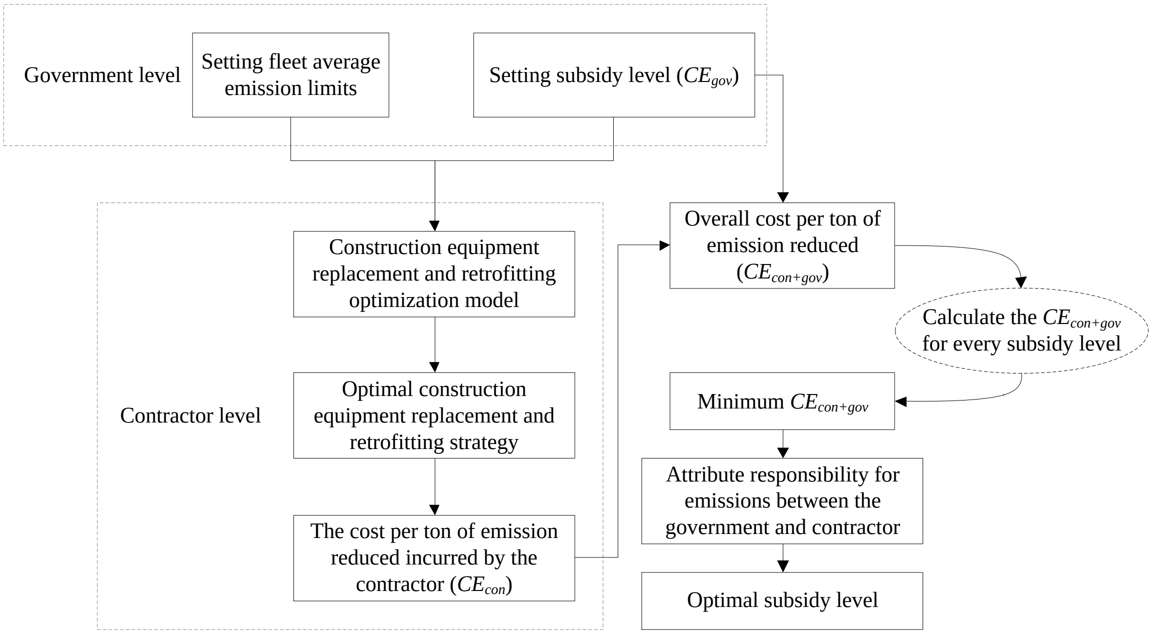

Fig.7.1 The development framework of the responsibility-sharing subsidy policy

7.3 Model Development

7.3.1 Subsidy Policy Designing at the Government Level

When a government implements subsidy policies, its primary concern is to control emission levels of construction equipment under a certain level. To this end, two main issues should be addressed. One is setting emission limits and the other is to set a subsidy level.

Only when contractors control emission levels of construction equipment fleets under the set emission limits, contractors can be awarded monetary subsidies. In this study, emission limits are set as follows.

$$FAEL_{mt} \geq FAEL_{mt}^{'} \tag{7.1}$$

$$FAEL_{mt} = (\textstyle\sum_{i=1}^{I} hp_i \times el_{imt}) / \sum_{i=1}^{I} hp_i \tag{7.2}$$

$$FAEL'_{mt}=\left(\sum_{i=1}^{I} hp_i \times el'_{imt}\right)/\sum_{i=1}^{I} hp_i \qquad (7.3)$$

where $FAEL_{mt}$ is the fleet average emission limit of emission m at the beginning of period t (g/KW-hr); $FAEL'_{mt}$ is the fleet average emission level of emission m at the beginning of period t (g/KW-hr); hp_i is the rated horsepower of the ith construction equipment in the fleet (KW); el_{imt} is the emission limit for emission m of the i th construction equipment at the beginning of period t (g/KW-hr); el'_{imt} is the emission level for emission m of the i th construction equipment at the beginning of period t (g/KW-hr); I is the number of construction equipment in a fleet.

In this study, emission limits are set from the perspective of a construction equipment fleet not from the perspective of a single piece of equipment. In other words, it is not necessary to replace or retrofit every piece of construction equipment to meet emission limits. The contractor just needs to ensure that the average emission level of the fleet is under the required limits. This can not only motivate the contractor to incorporate emissions reduction into their construction equipment management, but also provides some flexibility to contractors and help them innovate a cost-minimization equipment replacement and retrofitting strategy from a fleet perspective.

The other key issue for the government is to set a subsidy level, which is the cost of per ton of emissions reduced incurred by the government implementing this subsidy policy. A proper subsidy level should maximize environmental and social benefits with limited resources. In this study, contractors would be awarded a certain amount of money per ton of emissions equivalent reduced. The reason why the amount of emissions equivalent is considered rather than emissions is that early replacement and retrofitting of construction equipment can contribute reductions in multiple types of emissions simultaneously, including HC, CO, NOx and PM2.5. To consider all harmful emissions, this study converts emissions into emissions equivalent, through assigning appropriate weightings according to their health effects. Referring to the study of Wong et al. (2013), the equivalent coefficient for emissions is determined by the relative risks of emergency hospital admissions for respiratory and cardiovascular diseases associated with the emission. Emission equivalent of a certain emission can be calculated by using Equation (7.4):

$$EE_m = \zeta_m e_m \tag{7.4}$$

where EE_m is the emission equivalent of emission m; e_m is the amount of emission m; and ζ_m is the equivalent coefficient of emission m which can be calculated by the method described in the study of Wong et al. (2013).

7.3.2 Subsidy Policy Designing at the Contractor Level

At the contractor level, the subsidy policy designing requires deriving the fleet replacement and retrofitting strategies of contractors with the emissions reduction limits set by the government and the reward of subsidies. Accordingly, CE_{con} can be calculated, which is the ratio of costs of reducing emissions through early replacing and retrofitting equipment by the contractor to the amount of emissions equivalent reduced.

Thus, a mathematical optimization model in this section is introduced by employing the theory of integer programming, in which the contractor can incorporate the costs of meeting the emission reduction limits and subsequent subsidies into their construction equipment cost models. The mathematical model can help contractors make optimal decisions on the fleet of construction equipment which may remain in service, be retrofitted, salvaged, and replaced in each period, with the aim of minimizing expected costs.

Decision variables and parameters of the model are as follows:

Sets

- ES set of emission standards, with $ES = \{s \mid \text{T1, T2, T3, T4i, T4f}\}$;
- ESS set of emission standards switching through retrofitting, with $ESS = \{\alpha\text{-}\beta \mid \text{T1-T2, T1-T3, T1-T4i, T1-T4f, T2-T3, T2-T4i, Tier 2-T4f, T3-T4i, T3-T4f, T4i-T4f}\}$;
- CET set of construction equipment types, with $CET = \{k \mid 1,2, \ldots, K'\}$;
- T set of time periods, with $T = \{t \mid 1, 2, \ldots, T'\}$;
- CEA set of ages of construction equipment, with $CEA = \{a \mid 0, 1, 2, \ldots, A'\}$;
- M set of emission types, with $M = \{m \mid \text{HC, CO, NOx, PM}\}$.

Decision variables:

- $NR_{kat,\, \alpha\text{-}\beta}$ number of k-type and a-period-old construction equipment retrofitted from US Tier α emission standards to Tier β at the beginning of period t;
- NU_{kat} number of k-type and a-period-old construction equipment used in period t;
- $NU_{kat,\, s}$ number of k-type and a-period-old construction equipment meeting US Tier s emission standards, used in period t;
- $NP_{kt,\, s}$ number of k-type construction equipment meeting US Tier s emission standards, purchased at the beginning of period t;
- $NS_{kat,\, s}$ number of k-type and a-period-old construction equipment meeting US Tier s emission standards, salvaged at the beginning of period t;
- CE_{gov} subsidy level.

Parameters:

- B_t budget available for purchasing new construction equipment in period t;
- PC_{kt} purchase cost of a new piece of k-type construction equipment at the beginning of period t;

- OC_{ka} cost per period of operating a piece of *k*-type and *a*-period-old construction equipment;
- RS_{ka} revenue from salvaging a piece of *k*-type and *a*-period-old construction equipment;
- hp_k engine power of *k*-type construction equipment;
- $RC_{k,\alpha\text{-}\beta}$ cost of retrofitting a piece of *k*-type construction equipment from meeting US Tier α emission standards to Tier β;
- ND_{kt} number of *k*-type construction equipment demanded in period *t*;
- OT_{kat} operating time of a piece of *k*-type and *a*-period-old construction equipment in period *t*;
- $N0_{ka1,s}$ number of *k*-type and *a*-period-old construction equipment meeting US Tier *s* emission standards at the beginning of period 1;
- $el_{km,s}$ emission level of a piece of *k*-type construction equipment meeting US Tier *s* emission standards in regard of emission *m*;
- el_{km}^{0} emission level of a piece of *k*-type construction equipment meeting the emission limit of governments in regard of emission *m*.

The objective function is to minimize the sum of the economic and environmental costs associated with purchasing new construction equipment, salvaging and retrofitting old in-use construction equipment, subsidies from governments, and operating construction equipment throughout the planning periods:

The goal is to minimize:

$$\sum_{k\in CET}\sum_{t\in T}\sum_{s\in ES} NP_{kt,\,s}\ PC_{kt}$$

$$-\sum_{k\in CET}\sum_{t\in T}\sum_{a\in CEA}\sum_{s\in ES} NS_{kat,\,s} RS_{ka} + \sum_{k\in CET}\sum_{t\in T}\sum_{a\in CEA}\sum_{(\alpha\text{-}\beta)\in ESS} RC_{k,\alpha\text{-}\beta} NR_{kat,\,\alpha\text{-}\beta}$$

$$-\, CE_{gov}\Big\{\sum_{k\in CET}\sum_{t\in T}\sum_{a\in CEA}\sum_{(\alpha\text{-}\beta)\in ESS}\sum_{m\in M}\sum_{s\in ES}\big[\zeta_m \times hp_k \times OT_{kat} \times (T' + 1$$

$$-\, t) \times \big(el_{km,s} NS_{kat,\,s} + (el_{km,\,\alpha} - el_{km,\,\beta}) NR_{kat,\,\alpha\text{-}\beta}\,\big)\big]\Big\} + \sum_{k\in CET}\sum_{a\in CEA}\sum_{t\in T} NU_{kat}\, OC_{ka} \qquad (7.5)$$

This objective function is subject to the following constraints:

The number of in-service construction equipment of each type should be equal to or greater than the required number in every period (Eq. (7.6)).

$$\sum_{a\in CEA} N_{kat} \geq ND_{kt},\ \forall\ k\in CET;\ \forall\ t\in T \qquad (7.6)$$

Cost of purchasing new equipment cannot exceed the annual budget available for buying new equipment (Eq. (7.7)).

$$\sum_{k\in CET}\sum_{s\in ES} N_{kt,\,s} PC_{kt} \leq B_t,\ \forall\ t\in T \qquad (7.7)$$

The average emission level of the construction equipment fleet should not exceed the specific environmental cap (Eq. (7.8)).

$$\frac{\sum_{k\in CET}\sum_{a\in CEA}\sum_{m\in M} el^{0}_{km}\, \zeta_m hp_k NU_{kat}}{\sum_{k\in CET}\sum_{a\in CEA} hp_k N_{kat}} \geq$$

$$\frac{\sum_{k\in CET}\sum_{a\in CEA}\sum_{m\in M}\sum_{s\in ES} el_{km,s} \zeta_m hp_k\ NU_{kat,\,s}}{\sum_{k\in CET}\sum_{a\in CEA} hp_k N_{kat}},\ \forall\ t\in T \qquad (7.8)$$

This study supposed that retrofitting and salvaging equipment occurs at the beginning of each period. Therefore, at the beginning of each period except period 1, the number of retrofitted and salvaged equipment should not exceed the number of in-service equipment within the last period (Eqs. (7.9)-(7.10)).

$$\sum\nolimits_{(\alpha\text{-}\beta)\in ESS} NR_{kat,\,\alpha\text{-}\beta} + NS_{kat,\,s} \le NU_{k(a-1)(t-1),\,s},\ \forall\ k\in CET;\ \forall\ t=2,\ ...,\ T';\ \forall\ a=1,...,$$

$$A';\ \forall\ s=\mathrm{T1,\ T2,\ T3,\ T4i};\ \alpha=s \tag{7.9}$$

$$NS_{kat,T4f} \le NU_{k(a-1)(t-1),T4f},\ \forall\ k\in CET;\ \forall\ t=2,\ ...,T';\ \forall\ a=1,...,\ A' \tag{7.10}$$

At the beginning of period 1, the number of retrofitted and salvaged construction equipment should not exceed the number of initial equipment at the beginning of the planning horizon (Eqs. (7.11)-(7.12)).

$$\sum\nolimits_{(\alpha\text{-}\beta)\in ESS} NR_{ka1,\,\alpha\text{-}\beta} + NS_{ka1,\,s} \le N0_{ka1,s},\ \forall\ k\in CET;\ \forall\ a\in CEA;\ \forall\ s=\mathrm{T1,\ T2,\ T3,\ T4i};\ \alpha=s \tag{7.11}$$

$$NS_{ka1,\,T4f} \le N0_{ka1,T4f},\ \forall\ k\in CET;\ \forall\ a\in CEA \tag{7.12}$$

Eq. (7.13) can ensure that newly purchased age-0 construction equipment can not be retrofitted or salvaged immediately.

$$\sum\nolimits_{(\alpha\text{-}\beta)\in ESS} NR_{k0t,\,\alpha\text{-}\beta} + \sum\nolimits_{s\in ES} NS_{k0t,\,s} = 0,\ \forall\ k\in CET;\ \forall\ t=2,\ ...,\ T'; \tag{7.13}$$

The number of in-service equipment within any period except period 1 equals the number of in-service equipment in the last period subtracting the number of equipment retrofitted and salvaged at the beginning of this period (Eq. (7.14)).

$$
\begin{aligned}
&NU_{kat,\,s}=NU_{k(a\text{-}1)(t\text{-}1),\,s}-NS_{kat,\,s}\\
&-\sum\nolimits_{(\alpha\text{-}\beta)\in ESS}NR_{kat,\,\alpha\text{-}\beta}+\sum\nolimits_{(\alpha\text{-}\beta)\in ESS}NR_{kat,\,\alpha\text{-}\mathrm{s}}\ ,\ \forall\ k\in CET;\ \forall\ t=2,\ \ldots,\ T';\ \forall\ a=1,\ldots,\\
&A';\ \forall\ s\in ES \qquad (7.14)
\end{aligned}
$$

The number of in-service equipment within period 1 equals the number of initial equipment at the beginning of the planning horizon subtracting the number of equipment retrofitted and salvaged at the beginning of period 1 (Eq. (7.15)).

$$
\begin{aligned}
&NU_{ka1,\,s}=N0_{ka1,s}-NS_{ka1,\,s}\\
&-\sum\nolimits_{(\alpha\text{-}\beta)\in ESS}NR_{ka1,\,s\text{-}\beta}+\sum\nolimits_{(\alpha\text{-}\beta)\in ESS}NR_{kat,\,\alpha\text{-}s}\ ,\ \forall\ k\in CET;\ \forall\ a=1,\ldots,\ A' \qquad (7.15)
\end{aligned}
$$

The number of in-service construction equipment of age 0 within period 1 equals that of the initial age-0 equipment adding the newly purchased age-0 equipment and subtracting the retrofitted and salvaged age-0 equipment at the beginning of period 1 (Eq. (7.16)).

$$
\begin{aligned}
&NU_{k01,\,s}=N0_{k01,s}-NS_{k01,\,s}+NP_{k1,\,s}\\
&-\sum\nolimits_{(\alpha\text{-}\beta)\in ESS}NR_{k01,\,s\text{-}\beta}+\sum\nolimits_{(\alpha\text{-}\beta)\in ESS}NR_{k01,\,\alpha\text{-}s}\ ,\ \forall\ k\in CET;\ \forall\ s\in ES \qquad (7.16)
\end{aligned}
$$

In each period except period 1, the number of in-service age-0 equipment equals that of new purchased age-0 equipment (Eq. (7.17)).

$$
NU_{k0t,\,s}=NP_{kt,\,s},\ \forall\ t=2,\ \ldots,\ T';\ \forall\ s\in ES \qquad (7.17)
$$

Every construction equipment in the fleet must meet a certain emission standard (Eq. (7.18)).

$$NU_{kat}=\sum_{s\in ES} NU_{kat,\, s}\,,\ \forall\ k\in CET;\ a\in CEA;\ \forall\ t\in T \tag{7.18}$$

It is assumed that any equipment that reaches its maximum age will be salvaged (Eq. (7.19)).

$$NU_{kA't,\, s}=0,\ \forall\ k\in CET;\ \forall\ s\in ES;\ \forall\ t\in T \tag{7.19}$$

CE_{con} can be calculated by dividing the cost incurred from compliance with the government emission reduction limits (CC_{con}) by the amount of emissions equivalent reduced ($\sum_{m\in M} EE_m$), as showed in Eq. (7.20).

$$CE_{con}=\frac{CC_{con}}{\sum_{m\in M} EE_m}=\frac{C1_{con,CE_{gov}}-C2_{con}}{\sum_{m\in M} EE_m} \tag{7.20}$$

$$\sum_{m\in M} EE_m = \sum_{k\in CET}\sum_{t\in T}\sum_{a\in CEA}\sum_{(\alpha\text{-}\beta)\in ESS}\sum_{m\in M}\sum_{s\in ES}\Big[\zeta_m\times hp_k\times OT_{kat}\times(T'+1\text{-}t)\times\big(el_{km,s}NS_{kat,\, s}+(el_{km,\,\alpha}\text{-}el_{km,\,\beta})NR_{kat,\,\alpha\text{-}\beta}\big)\Big] \tag{7.21}$$

where $C1_{con,CE_{gov}}$ is the minimum cost of purchasing, salvaging, retrofitting and operating construction equipment fleet with government emission reduction limits and at subsidy level of CE_{gov} over the planning horizon, which can be calculated by using models (7.5)-(7.19); $C2_{con}$ is the cost of fleet owning and operating without any environmental requirements and subsidies. $C2_{con}$ can be obtained by employing the established optimization model with removing the retrofitting cost and subsidies from the objective function and corresponding constraints.

7.3.3 Attributing the Emission Reduction Responsibilities Between the Contractor and Government

From the established optimization model, it can be seen that governments setting different subsidy levels will lead contractors to take different strategies of purchasing, salvaging, retrofitting construction equipment. Therefore, minimized expected costs and CE_{con} vary under different subsidy levels.

In this step, a range of subsidy levels is set, from no subsidy to a certain level at which the full cost of reducing emissions is borne by the government. At each subsidy level, by applying the optimization model established in Section 7.3.2, this study obtains the CE_{con} in meeting the emission reduction limits and the corresponding $CE_{con+gov}$. Then, the relationship between the subsidy levels set by governments (CE_{gov}), CE_{con} and $CE_{con+gov}$ can be obtained. At the minimum $CE_{con+gov}$, the corresponding subsidy level is optimal. According to the optimal subsidy level (CE_{gov}) and the corresponding CE_{con}, the proper proportions of emission reduction responsibility can be assigned between the government and contractor.

7.4 Case Study

The proposed responsibility-sharing subsidy policy is generic and can be applied to various types of construction equipment. In this section, a fleet of six excavators of a large general contractor in Hong Kong is used to demonstrate the application of the proposed subsidy policy. Subsequently, fleet average emission limits are set, the optimal subsidy level is determined for the case excavator fleet, proper proportions of emission reduction responsibility between the Hong Kong government and the contractor are assigned, with the goal of minimizing the overall cost per ton of emissions equivalent reduced.

7.4.1 Data Sources

(1) Performance data of the case excavator fleet

Excavators are important and widely used equipment in the construction industry, which are mainly used for excavating, demolition, heavy lifting, cutting of trees, river dredging, etc. In this study, the planning horizon is assumed to be 10 years (T=10). The performance data for the case fleet is obtained from Chun Wo Engineering (H.K) limited, as shown in Table 7.1. The economic parameters in the optimization model are estimated for the coming year by using the historical records of the contractor. This study assumed that in this case there is no budget constraint, namely, $B_t = +\infty$.

Table 7.1 Performance data of the case excavator fleet

Equipment type	k=1	k=2	k=3	Unit
Number ($N0_{ka1,2}$)	2	2	2	
Age (a)	8,9	7,11	10,10	year
Maximum age (A')	20	20	20	year
Tier	2	2	2	
Horsepower (hp_k)	91	80	69	KW
Purchase cost (PC_{kt})	500,000	400,000	300,000	HK$
Operating cost (OC_{ka})	100,150+3,000a	91,500+2,000a	80,750+1,500a	HK$
Salvage revenue (RS_{ka})	500,000*0.85^a	400,000*0.85^a	300,000*0.85^a	HK$
Number of construction equipment demanded (ND_{kt})	2	2	2	piece
Operating Time (OT_{kat})	8 (hours/day)*250 (days/year)			hour

(2) Cost of retrofitting the case excavator fleet

The cost of retrofitting construction equipment to meet more stringent emission control levels depends on the specific emission reduction technologies selected by the contractor and the cost of these selected technologies. There is significant variability in emission reduction technology selection across different equipment types and even within a given equipment type. The cost of emission reduction technologies also varies from one manufacturer to another. Dallmann (2018) modeled the cost of retrofitting non-road engines through applying emission reduction technologies. The study by Dallmann (2018) defined a single representative technology package for each power class and regulatory emission standard tier, which is commonly adopted by contractors. The study also estimates the cost of the defined technology package. Then, the study estimates the total incremental cost of adopting emission reduction technologies to meet each emission standard tier for each power class, by matching the required technologies and their costs. By taking the study of Dallmann (2018) as a reference, the cost of retrofitting the case excavators to meet more stringent emission standards can be obtained, as shown in Table 7.2.

Table 7.2 The costs of retrofitting the case excavators to meet more stringent emission standards (HK$)

Equipment type	$RC_{k,\mathrm{T2\text{-}T3}}$	$RC_{k,\mathrm{T2\text{-}T4i}}$	$RC_{k,\mathrm{T2\text{-}T4f}}$	$RC_{k,\mathrm{T3\text{-}T4i}}$	$RC_{k,\mathrm{T3\text{-}T4f}}$	$RC_{k,\mathrm{T4i\text{-}T4f}}$
k=1	10,658	17,376	21,908	6,718	11,251	4,533
k=2	10,658	17,376	21,908	6,718	11,251	4,533
k=3	6,632	12,242	19,841	5,608	13,212	7,604

7.4.2 The Average Emission Limits of the Case Excavator Fleet

To set fleet average emission limits according to Eqs. (7.1)-(7.3), which emissions taken into consideration should be determined first. There are four main emissions generated by construction equipment, including HC, CO, NOx, and PM2.5 (Legislative Council of HK, 2018a). According to the report of *Air Quality in Hong Kong 2020 Statistical Summary* by the Air Science Group of Hong Kong Environmental Protection Department, among the four emissions, in 2020 only the annual average concentration of emissions PM and NOx exceeds the annual limit value (ASGEPD, 2021). The issue of extensive PM and NOx catches the attention of the Hong Kong government.

Thus, emissions PM and NOx is considered in the case study.

According to Eqs. (7.1)-(7.3), to set average emission limits of PM and NOx for the case excavator fleet, the PM and NOx emission limits of the six case excavators (el_{imj}) over the planning horizon should be set. The *Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation* issued by the government (HK EPD, 2015) requires that new construction equipment used in Hong Kong are required to meet US Tier 3 emission standards starting from June 2015. To harmonize the emission control level of in-use construction equipment with that of new ones, this study sets el_{imj} at the level of US Tier 3 emission standard over the planning horizon.

Then, by applying Eq (7.2), the average PM and NOx emission levels of the case excavator fleet at the beginning of period 1 is calculated, which is 0.329 and 6.859 g/KWh respectively. By applying Eq (7.3), the average PM and NOx emission limits of the case excavator fleet over the planning horizon is calculated, which is 0.329 and 4.201 g/KWh. Because the emission limits of PM regulated by US Tier 2 and Tier 3 are equal, thus the average PM emission limits and levels at period is the same. Thus, the subsidy policy designed by this study is to give subsidies to the contractor and encourage the contractor to control the average PM and NOx emission level of the case excavator fleet under 0.329 and 4.201 g/KWh, namely, $0.329 \geq FAEL'_{PM,t}$ and $4.201 \geq FAEL'_{NOx,t}$.

In this section, the excavator fleet owning and operating costs without any environmental requirements and subsidies over the planning 10 years ($C2_{con}$) are first calculated. By employing the established optimization model with excluding the retrofitting cost and subsidies from the objective function and corresponding constraints, the optimal schedule over the planning 10 years is obtained as shown in Table 7.3 and the corresponding cost ($C2_{con}$) is HK$7,348,640.

Table 7.3 The optimal schedule of the case excavator fleet without any environmental requirements and subsidies

New purchase ($N_{kt, s}$)	Salvaged excavators ($NS_{kat, s}$)
$N_{(2)(1), T3}=1$	$NS_{(2)(11)(1),T2}=1$

Then, set a series of subsidy levels of from HK$ 0, to HK$ 16,096 per ton of emissions equivalent reduced. At the subsidy level of 0 HK$/ton, the emission reduction responsibility is totally borne by the contractor. At the subsidy level of 16,096 HK$/ton, the cost of purchasing, salvaging, retrofitting and operating the excavator fleet ($C1_{con,(16{,}096)}$) is HK$7,348,642, which almost equals that of owning and operating the excavator fleet without any environmental requirements and subsidies ($C2_{con}$). Thus, at the subsidy level of 16,096 HK$/ton, the responsibility is totally borne by the government. By applying the optimization model established in section 3.2, the optimal schedules of excavator purchase, salvage, retrofitting at subsidy levels set above over the planning 10 years are obtained, which is shown in Table 7.4.

Table 7.4 The optimal schedule of the excavator fleet at different subsidy levels

Subsidy level	$0 \leq CE_{gov} < 6{,}928$	$6{,}928 \leq CE_{gov} < 14{,}800$	$14{,}800 \leq CE_{gov} < 16{,}096$
New purchase ($N_{kt, s}$)	$N_{(2)(1), \mathrm{T4f}}=1$	$N_{(2)(1), \mathrm{T4f}}=1$	$N_{(2)(1), \mathrm{T4f}}=1$
Retrofitted excavators ($NR_{kat, \alpha\text{-}\beta}$)	$NR_{(1)(8)(1), \mathrm{T2\text{-}T3}}=1$ $NR_{(1)(9)(1), \mathrm{T2\text{-}T4f}}=1$	$NR_{(1)(8)(1), \mathrm{T2\text{-}T4f}}=1$ $NR_{(3)(10)(1), \mathrm{T2\text{-}T3}}=1$	$NR_{(1)(8)(1), \mathrm{T2\text{-}T3}}=1$ $NR_{(1)(9)(1), \mathrm{T2\text{-}T4f}}=1$ $NR_{(3)(10)(1), \mathrm{T2\text{-}T3}}=1$
Salvaged excavators ($NS_{kat, s}$)	$NS_{(2)(11)(1),T2}=1$	$NS_{(2)(11)(1),T2}=1$	$NS_{(2)(11)(1),T2}=1$

The corresponding minimum cost of purchasing, salvaging, retrofitting and operating the excavator fleet at each subsidy level ($C1_{con,CE_{gov}}$) is calculated and shown in the second column of Table 7.5. By using Eqs. (7.20)-(7.21), the cost per ton of emissions equivalent reduced by the contractor (CE_{con}) at the subsidy levels set above is calculated, which is listed in the third column of Table 7.5. Accordingly, the overall cost per ton of emissions equivalent reduced incurred by the contractor and the Hong Kong government ($CE_{con+gov}$) is calculated by adding CE_{con} and CE_{gov}, as shown in the last column of Table 7.5.

Table 7.5 The cost per ton of emissions equivalent reduced incurred by the contractor, the Hong Kong government and the both

CE_{gov} (HK$/ton)	$C1_{con,CE_{gov}}$ (HK$)	CE_{con} (HK$/ton)	$CE_{con+gov}$ (HK$/ton)
0	7,381,206	19,278.95	19,278.95
800	7,379,855	18,479.16	19,279.16
1600	7,378,503	17,678.78	19,278.78
2400	7,377,152	16,879.00	19,279.00
3200	7,377,152	16,079.21	19,279.21
4000	7,374,449	15,278.83	19,278.83
4800	7,373,098	14,479.04	19,279.04
5600	7,371,746	13,678.67	19,278.67
6400	7,370,395	12,878.88	19,278.88
6920	7,369,517	12,358.88	19,278.88
6928	7,369,503	10,101.16	17,029.16
7200	7,368,941	9,829.16	17,029.16
8000	7,367,289	9,029.31	17,029.31
8800	7,365,637	8,229.46	17,029.46
9600	7,363,984	7,429.12	17,029.12
10400	7,362,332	6,629.27	17,029.27
11200	7,360,680	5,829.42	17,029.42
12000	7,359,027	5,029.09	17,029.09
12800	7,357,375	4,229.24	17,029.24
13600	7,355,723	3,429.38	17,029.38
14400	7,354,070	2,629.05	17,029.05
14792	7,353,261	2,237.05	17,029.05
14800	7,353,238	1,296.63	16,096.63
15200	7,351,819	896.48	16,096.48
16000	7,348,982	96.44	16,096.44
16096	7,348,642	0.56	16,096.56

The trend of $CE_{con+gov}$ and CE_{con} with the subsidy level (CE_{gov}) can be presented in Fig.7.2. From Fig. 7.2, it can be seen that with the increase of the subsidy level (CE_{gov}), the CE_{con} decreases and the $CE_{con+gov}$ is steady at first, then dropped slightly and keep steady and dropped slightly again. At the subsidy level of 1,050 HK$/ton, the CE_{gov} and CE_{con} are the same, which means that the government and the contractor share equal responsibility for emission reduction. Fig.7.2 also shows that the subsidy levels from 14,800 to 16,096 HK$/ton can make the $CE_{con+gov}$ lowest, and the responsibility of emission reduction borne by the government is from 92% to 100% and the contractor from 0% to 8%. The results provide significant insights and flexibility for the Hong Kong government to set a proper subsidy level by comparing effects of different options. The government can select a subsidy level between 14,800 to 16,096 HK$/ton with the constraint of its capital budget for the subsidy program. This subsidy level range can ensure the $CE_{con+gov}$ is minimum, which is 16097HK$ per ton of emissions equivalent reduced.

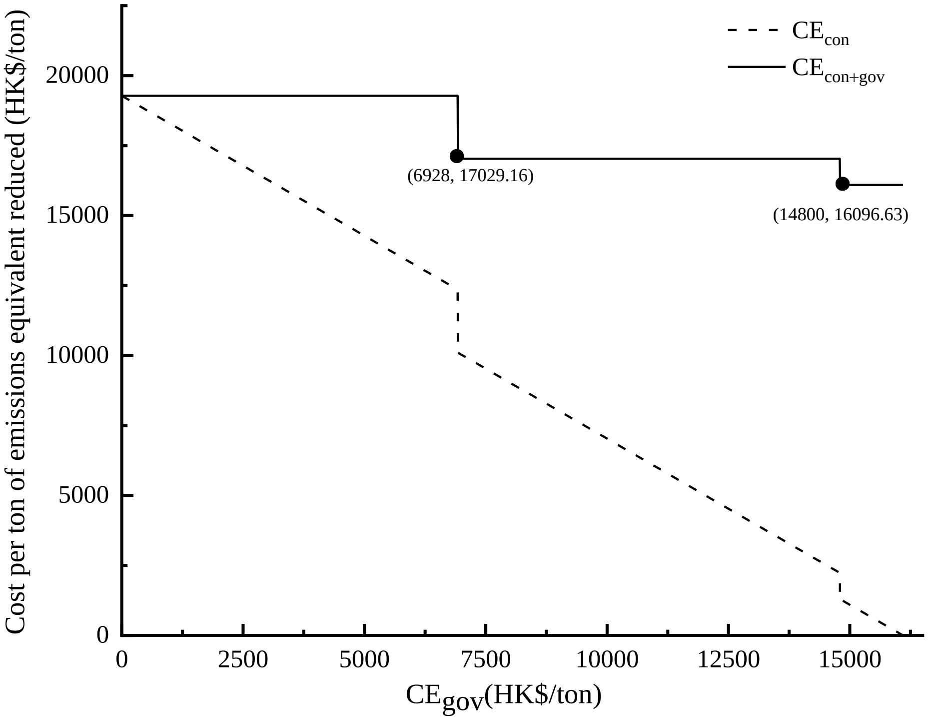

Fig.7.2 The trend of $CE_{con+gov}$ and CE_{con} with the subsidy level (CE_{gov})

7.5 Discussion

In this excavator fleet case, when the subsidy level is between 0 and 6,928 HK$/ton, the $CE_{con+gov}$ remains stable. Under this subsidy level range, the schedule of case excavator purchasing, salvaging, retrofitting is the same as shown in Table 7.5, and the cost and amount of emission reductions do not change, so that the $CE_{con+gov}$ remains stable. Similarly, when the subsidy level falls into the range of 6,928 to 14,800 HK$/ton, the $CE_{con+gov}$ is still stable but less than that of 0 to 6,928HK$/ton. This is because when the government raises the subsidy level from one range to another, to pursue more interest, the contractor switches to another more economical schedule of case excavator purchasing, salvaging, retrofitting which results in the decrease of the cost of reducing emission and the lower $CE_{con+gov}$. The above discussion indicates that the government can lead the contractor to adopt optimal strategies of replacing and retrofitting construction equipment for reducing emissions in a minimum overall social cost-effective way through setting proper subsidy levels. The results of this case suggest that the government should set subsidy levels in the range of 14,800 to 16,096 HK$/ton, which minimizes the $CE_{con+gov}$. In this range, larger subsidy levels mean that the government bears more responsibility for emission reduction, and the contractor less. Within the same $CE_{con+gov}$, assigning less emission reduction responsibility to contractors can give them more motivation to participate in the subsidy incentive program while the government needs to bear more responsibility. There is a tradeoff between the increase of motivation of the contractor and the increase of the budget for the subsidy incentive program when the government designs subsidy policy for encouraging the replacement and retrofitting construction equipment. For some countries in which contractors have good consciousness of environmental protection, governments can set a lower level of subsidy level and assign more emission reduction responsibility to contractors than those in which contractors have weaker consciousness of environmental protection when achieving the same $CE_{con+gov}$. On the other hand, governments can adopt some supplemental measures for raising the environmental protection awareness of contractors to increase the participation of such subsidy incentive programs. At the subsidy level of 16,096 HK$/ton, the $CE_{con+gov}$ is minimum, but this study does not recommend the government to set the subsidy level at 16,096 HK$/ton. It is not just because at this subsidy level the emission reduction responsibility is totally borne by the government and contractors are released of their responsibility for the reduction of emissions, not in line with the "the pullutors pay" principle. More importantly, if the emission reduction responsibility is totally born by the government, it would be difficult to stimulate the motivation of contractors to adopt innovatively the emission reduction technologies to reduce emissions in a more cost-effective manner.

Spending most cost effectively at reducing emissions is one of objectives in policy design of the governments, thus cost-effectiveness (the ratio of subsidy amount to the total emission reduced) is widely used as a critical indicator for assessing the performance of policies. The cost-effectiveness of the designed subsidy policy for the Hong Kong government reducing emissions equivalent of the case excavator fleet is 16,097 HK$/ton. To determine whether this cost-effectiveness value is reasonable and acceptable, this study compares it with the metrics set in several typical non-road emission reduction incentive programs in the United States. These incentive programs measure their cost-effectiveness in US$ per ton of NOx reduced, while the subsidy program designed by this study in HK$ per ton of emissions equivalent reduced. Before comparison, the cost-effectiveness of the designed subsidy policy is converted into 2,082 US$ per ton of NOx reduced. Some governments have set cost-effectiveness criteria before their incentive programs began, and only applicants with expected cost-effectiveness lower than criteria are granted funding. It is desirable for the government to proceed with the emissions reduction if the cost-effectiveness calculated after program implementation meets the pre-set cost-effectiveness criteria. The Carl Moyer Memorial Air Quality Standards Attainment Program (the Carl Moyer Program) implemented by California since 1998 is a successful statewide program providing funding to encourage replacement and retrofit of equipment and engines for emission reduction (CARB, 2011). Since September 2004, the Carl Moyer Program through passing new legislation sets a cost-effectiveness threshold of $13.600 per ton of NOx reduced (IFC, 2005). From 1998 to 2002, it is estimated that the Carl Moyer Program has reduced NOx emissions by more than 5,100 tons per year at an average cost-effectiveness of approximately $3,000 per ton (IFC Consulting, 2005). In 1995, Los Angeles World Airports (LAWA) implemented the Los Angeles International Airport (LAX) Master Plan Program to keep a balance between the growth of the airport and its environmental impacts (LAWA, 2004). As a part of the LAX Master Plan Program, the Community Benefits Agreement (CBA) implemented from 2004 to 2020 requires to retrofit all diesel construction equipment used at LAX Master Plan Program construction sites with best available emissions control devices to reduce diesel PM and NOx. In this program, the applied emission control devices must meet a cost-effectiveness threshold of $13,600 per ton of NOx reduced (MECA, 2006). The Texas Emissions Reduction Plan (TERP) is another successful subsidy incentive implemented by the State of Texas to reduce diesel emissions, which consists of eleven programs including the Diesel Emissions Reduction Incentive Program (DERI), Texas Clean Fleet Program (TCFP), Emissions Reduction Incentive Grants Program (ERIGP), etc. In the first three years of the TERP program, the cost-effectiveness of this program was about $5,700 per ton of NOx reduced. For the fourth year, the cost-effectiveness criterion was capped at $7,000 per ton of NOx reduced. The cost-effectiveness threshold is $13,000 per ton of NOx reduced under ERIGP and DERI, and $8500 per ton of NOx reduced under TCFP. From above discussion, it is found that the cost-effectiveness of the subsidy policy designed by this study for reducing emissions from the case excavator fleet are less than or far below the benchmarks in these typical subsidy incentives. Therefore, it can be concluded that the cost-effectiveness of the subsidy policy proposed in this study is reasonable and acceptable.

7.6 Chapter Summary

Subsidy policies have been widely considered very effective in mitigating emissions from construction equipment. However, most existing subsidy policies do not consider the responsibility of contractors for reducing emissions from construction equipment. This would cause an inequity issue when contractors as polluters do not bear any emission reduction responsibility and may be a demotivator for the contractor to reduce emissions more cost-effectively. Therefore, this study proposes a subsidy policy for reducing emissions from construction equipment fleet, in which the responsibility for reducing emissions is shared between the contractor and government. This study also quantifies the relationship of the subsidy level, the overall cost per ton of emissions equivalent reduced ($CE_{con+gov}$) and the emission reduction responsibility borne by the government and contractor. Then, through assigning responsibility for reducing emissions in proper proportions between the government and contractor, the proposed subsidy policy can minimize the overall cost per unit of emissions equivalent reduced. To demonstrate the application of the proposed responsibility-sharing subsidy policy, an excavator fleet in Hong Kong is studied.

This study finds that subsidy levels set by governments have an impact on the decision-making of contractors in terms of the number of newly purchased, replaced, retrofitted, salvaged and in-service construction equipment in each planning period. When governments change subsidy levels, contractors will adjust their equipment management strategies to minimize their costs. Therefore, governments can set proper subsidy levels and delegate the responsibility to the contractors to adopt optimal strategies of replacing and retrofitting construction equipment to reduce emissions with a minimum total cost per unit of emission reduction. This study also finds that one $CE_{con+gov}$ corresponds to many different apportionments of responsibility for emission reduction between the government and the contractor. Within the same $CE_{con+gov}$, assigning less emission reduction responsibility to the contractors can increase their motivation to participate in the subsidy incentive program while resigning the burden of the government in reducing emissions. Moreover, the subsidy level and $CE_{con+gov}$ of the proposed subsidy policy are proven reasonable and acceptable.

The proposed responsibility-sharing subsidy model has significance in enriching the theoretical development of policy instruments for reducing extensive emissions from construction equipment. In the proposed responsibility-sharing subsidy policy, the emission reduction responsibility of contractors is incorporated and the subsidy level is determined from a perspective of minimizing the total cost per unit of emissions equivalent reduced. The proposed subsidy policy could be used as an effective tool by the governments to reduce emissions from construction equipment, which can ensure emission levels of construction equipment fleet under the retargeted emission limits. Besides, by implementing the proposed subsidy policy, the decision-making burden of governments could be released since contractors themselves will determine where the emission reduction efforts are most cost-effective.

CHAPTER 8 Summary and Conclusions

8.1 Introduction

This chapter commences with reviewing the research aim and objectives of this research to check whether they have been achieved. Then, the key research findings are summarized, and the contributions of this research are highlighted. Finally, the limitations and future studies are discussed.

8.2 Review of Research Objectives

Construction equipment mainly powered by diesel engines emit considerable gaseous air pollutants, notably including NOx and PM. The increase of CEE has posed a threat to the sustainable development of human beings and communities especially in urban areas. The problem of extensive emissions from construction equipment has become an issue of growing concern. However, the effort of the Hong Kong government does not meet the challenges in reducing CEE. The policy instruments for reducing CEE are insufficient, with only newly imported construction equipment being regulated while in-use ones not. Replacing or retrofitting in-use construction equipment can dramatically reduce emissions, improve the air quality and deliver significant health benefits to those who live or work in or adjacent to construction sites. Subsidy incentives have been widely recognized as a flexible and market-based policy instrument by many businesses and entities to accelerate the replacement and retrofit of in-use construction equipment. However, in Hong Kong, any subsidy policies have not been adopted by the government to address the severe problem of extensive CEE. Therefore, this research intends to answer the following questions: (1) What CEE reduction policy instruments have been adopted worldwide? Are there any evolving trends, lessons, and accumulated experiences in developing policy instruments for reducing CEE? (2) What are emission reduction technologies available for reducing CEE, their costs and degrees of emission reduction? (3) How to make appropriate subsidy levels, which can provide contractors with enough motivation to replace their exempted construction equipment early? (4) How to assign responsibility for reducing emissions in proper proportions between contractors and the Hong Kong government?

The primary aim of this research is to reduce CEE in Hong Kong through formulating proper subsidy policies. Since the development of policy instruments for reducing CEE in Hong Kong is insufficient and any subsidy policies have not been developed in this city, this research plans to propose two quantitative models to determine appropriate subsidy levels.

Specific objectives of this research are as follows:
(1) To conduct a review on policy instruments for addressing CEE from a global perspective, and identify evolving trends, lessons, and accumulated experiences in developing policy instruments.
(2) To conduct a review on the technologies for reducing CEE and examine their costs and degrees of emission reduction.
(3) To propose a quantitative model to determine appropriate subsidy levels for accelerating the replacement of exempted construction equipment, not putting financial burdens on contractors, and ensuring the achievement of emission reduction targets set by the government.
(4) To propose a responsibility-sharing model to determine appropriate subsidy levels and assign responsibility for reducing emissions in proper proportions between governments and contractors.

To achieve Objective 1, Chapter 4 conducts a holistic review and analysis on the development of CEE reduction policy instruments from a global perspective. Three groups of policy instruments are identified, including PI-A, PI-B and PI-C. Comparative analysis of CEE reduction policy instruments is conducted between advanced and developing-economy promoters. Then, the evolving trends, lessons, and accumulated experiences in developing policy instruments are identified. To achieve Objective 2, Chapter 5 examines academic journals, doctoral theses, conference papers, government reports, and other technical guidelines to summary technologies available for reducing CEE and identify emission reduction levels achievable by these technologies. To achieve Objective 3, Chapter 6 develops an effective quantitative model for determining the optimal subsidy levels to examine the relationship between emission reduction targets, early replacement of construction equipment, and subsidy levels to the equipment owners, by employing LCC model, NONROAD2008a emission model and the method of case study. The subsidy levels determined by the proposed model can effectively enable the early replacement of construction equipment and achieve the government's goal of reducing emissions from construction equipment. The subsidy levels determined by the proposed model can also avoid creating a financial burden on contractors when they replace their equipment early for emissions reduction. To achieve Objective 4, Chapter 7 proposes a responsibility-sharing subsidy policy, based on the integer programming model, NONROAD2008a emission model and the method of case study. In the proposed subsidy policy, the subsidy level and the responsibility of contractors assigned in proportion for emission reduction are determined with the attaining of minimum overall cost per ton of emissions equivalent reduced by the government and contractor.

8.3 Summary of Research Findings

The key findings of this research are summarized below.

(1) This research finds that various CEE reduction policy instruments have been established globally in past years, and it is widely appreciated that promoting these policy instruments is essential. This study reveals the development trends, lessons and accumulated experiences of CEE

reduction policy instruments from a global perspective. The results of this study suggest that advanced and developing-economy promoters have both similarities and differences in the development of CEE reduction policy instruments. For example, both advanced and developing-economy promoters overwhelmingly prefer to adopt PI-As. Developing-economy promoters may not have sufficient resources for implementing PI-Bs and PI-Cs. Advanced-economy promoters have devoted more efforts to developing PI-Bs and PI-Cs. The study concludes that a mixture of PI-As, PI-Bs and PI-Cs can work better for reducing CEE, and policy instruments making should consider the contexts of promoters.

(2) This study finds that the subsidy levels determined by the proposed model in Chapter 5 can effectively enable the early replacement of construction equipment and achieve the government's goal of reducing emissions from construction equipment. The subsidy levels determined by the proposed model can also avoid creating a financial burden on contractors when they replace their equipment early for emissions reduction. This study also finds that setting emission reduction targets is closely related to the subsidy levels. Emission reduction targets are set as reducing emissions equivalent by a certain percentage in this study. Users of the proposed model can set different emission reduction targets according to their requirements, such as preferred orders and goals of reducing multiple types of emissions. A cost-effectiveness analysis of subsidies for accelerating the replacement of a crawler crane, suggests that the cost-effectiveness of reducing emissions from the crawler crane increases when the emission equivalent reduction targets are raised with more subsidies granted to contractors.

(3) This study finds that subsidy levels set by governments have an impact on the decision-making of contractors in regards of the number of new purchased, replaced, retrofitted, salvaged and in-service construction equipment in each planning period. When governments change subsidy levels, contractors will adjust their equipment management strategies to minimize their costs. Therefore,

governments can through setting proper subsidy levels lead contractors to adopt optimal strategies of replacing and retrofitting construction equipment to reduce emissions with a minimum overall social cost. This study also finds that one OCES corresponds to many different apportionments of responsibility for emission reduction between the government and the contractor. Within the same OCES, assigning less emission reduction responsibility to contractors can increase their motivation to participate in the subsidy incentive program while rise the burden of the government reducing emissions. Moreover, the cost-effectiveness of the proposed subsidy policy is reasonable and acceptable.

8.4 Contribution of the Research

The significance and contribution of this research are reflected in the following aspects:

1) The review on global policy instruments for reducing CEE can promote the experience-sharing between developed and developing-economy promoters, which can help improve CEE reduction by formulating more effective policy instruments. On the other hand, this research provides valuable references for those countries and cities which have not yet introduced CEE reduction policy instruments to design effective policy instruments with the understanding of the development trends, lessons and experiences of the policy instruments adopted globally. For example, the Hong Kong government can take these existing subsidy policies as references when controlling CEE. These development trends, lessons and experiences can also help practitioners understand related CEE reduction policy instruments, thus gaining comparative competitiveness in the global market. The construction market has started to favor those construction businesses who engage in green practice in operating construction equipment and generate less CEE. The policy instrument classification framework established by this study can serve as an effective tool for studying policy instruments in other fields.

2) The quantitative model proposed in Chapter 5 targeted at single construction equipment is novel in its ability to ensure the achievement of emission reduction targets with subsidies, without exerting a financial burden on contractors. The proposed quantitative model contributes to the development of research in formulating proper economic incentive policy instruments for emissions reduction. The proposed model can also be used as an effective support tool by governments to determine optimal subsidy levels to accelerate construction equipment replacement for emissions reduction. The proposed model developed in this study could not only be applied to determine optimal subsidy levels for accelerating the replacement of construction equipment, but also could be used for early replacement of other in-service vehicles or equipment for environmental benefits. The development of this model also contributes to the body of knowledge of equipment replacement, which is a specific knowledge area of engineering management.

3) The responsibility-sharing model proposed in Chapter 6 has significance in enriching the theoretical development of policy instruments for reducing extensive CEE, especially in the context of existing research mainly focusing on on-road vehicles. This model innovatively incorporates the contractor and the government's emission reduction responsibility, determines the subsidy level from a perspective of minimizing the overall cost per ton of emissions reduced, and ensures emission levels of construction equipment fleet under limited levels. The proposed model could be used as an effective tool by Hong Kong and other countries to reduce CEE. Besides, by implementing the proposed responsibility-sharing model, the governance burden of governments could be reduced since contractors themselves will determine where the emission abatement efforts are most cost-effective.

8.5 Limitations and Future Research

Firstly, although this research conducts a holistic review and analysis on the development of CEE reduction policy instruments from a global perspective, the analysis is more macroscopical, which is conducted at the level of policy instrument types. The context of specific policy instruments and the strengths and weakness of each policy instrument have not been examined. In future, a narrow analysis perspective will be adopted to examine the specific policy instrument to obtain significant insights in formulating effective policy instrument.

Secondly, this research qualitatively concluded that a mixture of PI-As, PI-Bs and PI-Cs works better. A quantitative examination on the performance of applying a mixture of PI-As, PI-Bs and PI-Cs is lack, especially compared to single policy instruments of PI-As, PI-Bs and PI-Cs. It is recommended for further study to quantitatively examine and evaluate the performance of applying a mixture of PI-As, PI-Bs and PI-Cs to reduce CEE from a group of sample cities or countries. The outcome of this study can provide practical guidance for making CEE reduction policy instruments for different types of cities or countries. It is further recommended that, in future, by considering adopting different types of subsidy policies (PI-A, PI-B and PI-C) simultaneously the optimization of subsidy level will be discussed from the perspective of market economy and the methodology of evolutionary game will be considered.

Additionally, the two proposed models presented in Chapter 5 and Chapter 6 are designed for all types of construction equipment, but in this research only two cases of a piece of crawler crane and an excavator fleet are respectively used to demonstrate the application of the two proposed models. There is a need in future to use other types of construction equipment to apply the proposed models, compare the results derived from various cases studies, and then validate and modifier the two models. This is because performance data of selected equipment have an impact on the results of subsidy levels. For other types of construction equipment or the same equipment owned by different contractors, some performance data are the same or different. Therefore, the results for different contractors may be different. How different are they should be examined on a case by case basis. To examine how different are the results among different contractors, we need to apply specific values of parameters into the proposed model.

Finally, for the responsibility-sharing model, the responsibility for emission reduction between the contractor and the government are assigned mainly based on the minimum OSCE. In the process of developing responsibility-sharing model, the willing of the contractor to participant in the subsidy incentives with the determined responsibility proportion are not considered. In future studies, the relation of motivation of contractors to participate in such subsidy incentives and their responsibility proportion have not been modeled and considered.

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Appendixes

Appendix I Identification of PI-A

Code	PI-AL
PI-AL01	Clean Air Act (US, 1977, updated in 1990)
PI-AL02	Diesel Emissions Reduction Act (US, 2010)
PI-AL03	Clean Diesel Construction Ordinance (US, 2011)
PI-AL04	New York City Local Law 77 (New York, 2004)
PI-AL05	New York City Local Law 39 (New York, 2007)
PI-AL06	Rockland County Local Law No. 3 (New York, 2007)
PI-AL07	Canadian Environmental Protection Act 1999 (Canada, 1999)
PI-AL08	Air Pollution Control Ordinance (Switzerland, 1985, updated in 2000)
PI-AL09	Law of the People's Republic of China on the prevention and control of air pollution (China, 2016)
PI-AL10	Environmental protection tax law of the People's Republic of China (China, 2018)
PI-AL11	The Clean Air Conservation Act Enforcement Rules (South Korea, 2015)
PI-AL12	Clean Air Conservation Act (South Korea, 1995, updated in 1997, 1999, 2000, 2002, 2003, 2004, 2005, 2008, 2009, 2010, 2012, 2013, 2013, 2015, and 2016)
PI-AL13	Enforcement Decree of the Clean Air Conservation Act (South Korea, 1996, updated in 1997, 1998, 1999, 2000, 2002, 2003, 2005, 2008, 2009, 2010, 2012 and 2016)
PI-AL14	Enforcement Decree of the Special Act on the Improvement of Air Quality in Seoul Metropolitan Area (South Korea, 2016)
PI-AL15	Environment Act 1995 and Air Quality Regulations (London, 2010)
PI-AL16	Provisions from the Legal Agreement that Apply to the Thames Gateway Bridge (London, 2008)
PI-AL17	Hydrocarbons Act (Mexico, 2014)
	PI-AR
PI-AR01	Final Rule Control of Emissions of Air Pollution from Nonroad Diesel Engines and Fuel (US, 2004)
PI-AR02	Control of Emissions of Air Pollution from Nonroad Diesel Engines (US, 1998）
PI-AR03	Determination of Significance for Nonroad Sources and Emission Standards for New Nonroad Compression-Ignition Engine at or above 37 Kilowatts (US, 1994)
PI-AR04	Final Rule for Nonroad Technical Amendments (US, 2014)
PI-AR05	Direct Final Rule for Heavy-Duty Engine and Vehicle, and Nonroad Technical Amendments (US, 2013)

PI-AR06	Partial Withdrawal and Final Rule for the Nonroad Diesel Technical Amendments and Tier 3 Technical Relief Provision (US, 2007)
PI-AR07	Direct Final Rule: Nonroad Diesel Technical Amendments and Tier 3 Technical Relief Provision (US, 2007)
PI-AR08	Final Rule for Test Procedures for Testing Highway and Nonroad Engines and Omnibus Technical Amendments (US, 2005)
PI-AR09	Massachusetts Department of Transportation (MassDOT)'s diesel retrofit specification (MassDOT, 2005)
PI-AR10	Notice to Contractor- Vehicle Emissions (State Contract Requirements) (Connecticut State, 2006)
PI-AR11	Notice to Contractor- Diesel vehicle emission controls (State Contract Requirements) (Connecticut State, 2006)
PI-AR12	Diesel Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles (California, 2000)
PI-AR13	MSO 07-03: New Requirement to Report Carbon Dioxide Emissions from 2008 and Subsequent Model Year California Certified Vehicles and Engines (California, 2007)
PI-AR14	New Idling limits for Owners, Operators, Renters or Lessees of In-use Off-road Diesel Vehicles (California, 2008, updated in 2015 and 2016)
PI-AR15	Updated Disclosure/Recode Retention Requirements for Dealers and Sellers of In-use Off-road Diesel Vehicles (California, 2008, updated in 2015 and 2016)
PI-AR16	Ban on Adding Tier 0 Engines (California, 2014)
PI-AR17	Ban on Adding Tier 1 Engines (California, 2014)
PI-AR18	Ban on Adding Tier 2 Engines (California, 2018)
PI-AR19	In-Use Off-Road Diesel-Fueled Fleets (California, 2008; updated in 2009, 2010, and 2011)
PI-AR20	Verification Procedure, Warranty and in-Use Compliance Requirements for in-Use Strategies to Control Emissions from Diesel Engines (California, 2003; updated in 2009 and 2013)
PI-AR21	Certification Procedures for Aftermarket Parts for off-Road Vehicles, Engines, Equipment (California, 2000)
PI-AR22	Clean Fuels Program (California, 1991, updated in 2001)
PI-AR23	Tier 4 Off-Road Compression-ignition Engines (California, 1993; updated in 2000, 2006, 2009, and 2013)
PI-AR24	Certification Procedures for Aftermarket Parts for Off-road Vehicle, Engines, Equipment (California, 2000)
PI-AR25	Directive 2002/88/EC (EU, 2002)

PI-AR26	Directive 2004/26/EC (EU, 2002)
PI-AR27	Directive 2014/26/EC (EU, 2014)
PI-AR28	Directive 2006/105/EC (EU, 2006)
PI-AR29	Directive 2010/26/EU (EU, 2010)
PI-AR30	Directive 2011/88/EU (EU, 2011)
PI-AR31	Directive 2012/46/EU (EU, 2012)
PI-AR32	Regulation (EU) 2016/1628 (EU, 2016)
PI-AR33	Regulation (EU) 2017/654 (EU, 2016)
PI-AR34	Regulation (EU) 2017/655 (EU, 2016)
PI-AR35	Regulation (EU) 2017/656 (EU, 2016)
PI-AR36	Regulation (EU) 2018/987 (EU, 2018)
PI-AR37	Regulation (EU) 2018/988 (EU, 2018)
PI-AR38	Regulation (EU) 2018/989 (EU, 2018)
PI-AR39	Off-Road Compression-Ignition Engine Emission Regulations (Canada, 2005, updated in 2011 and 2012)
PI-AR40	Off-road Compression-Ignition (Mobile and Stationary) and Large Spark-Ignition Engine Emission Regulations (Canada, 2019)
PI-AR41	The non-road Compression-Ignition Engine Emission Regulations (SOR/2005-32) （Canada, 2005）
PI-AR42	Off-road Compression-Ignition (Mobile and Stationary) and Large Spark-Ignition Engine Emission Regulations (2021 model year) (Canada, 2019)
PI-AR43	Underground Construction (SUVA) Workplace Emission Directive (Switzerland, 2001)
PI-AR44	General Construction (BUWAL) Directive (VU-5024-D) (Switzerland, 2002)
PI-AR45	VERT (Curtailing Emissions from Diesel Engines in Tunnel Construction) Program (Switzerland, 1994)
PI-AR46	Specification for Product quality supervision and spot check of diesel engine (CCGF503.12-2015) (China, 2015)
PI-AR47	Regulations on Prevention and Control of Air Pollution (Beijing, 2016)
PI-AR48	Notice on Strengthening the Emission Management of Non-Road Construction Machinery (Beijing, 2016)
PI-AR49	Clean Air Action Plan of Beijing 2013-2017 (Beijing, 2013)
PI-AR50	Regulations on the Prevention and Control of Air Pollution (Tianjin, 2015)
PI-AR51	Work Plan for Prevention and Control of Non-Road Mobile Machinery Air Pollution 2016 of Shanghai (Shanghai, 2016)
PI-AR52	Motor Vehicles and Non-Road Mobile Machinery Exhaust Pollution Prevention and Control Regulations (Foshan, 2016)

PI-AR53	Exhaust Emissions Limit and Measurement Method of In-Use Non-Road Mobile Machinery (Shenzhen, 2015)
PI-AR54	Notice on the Implementation of the Exhaust Gas Pollution Detection for Non-Road Mobile Machinery (Xi'an, 2016)
PI-AR55	Notice of the Zhengzhou Municipal People's Government on the Delimitation of the Prohibition of the Use of High-Emission Non-Road Mobile Machinery Areas (Zhengzhou, 2016)
PI-AR56	Special Plan for Management of Non-road Mobile Machinery Pollution (Zhengzhou, 2016)
PI-AR57	Notice of the Investigation on the Use of Non-Road Mobile Machinery in Factories (Zhengzhou, 2016)
PI-AR58	Notice on Doing a Good Job in Environmental Supervision of Non-road Mobile Machinery (Baoji, 2017)
PI-AR59	Notice on the Supervision of the Emission of Air Pollutants from Non-Road Transfer Machinery in Chongqing city (Chongqing, 2016)
PI-AR60	Motor Vehicle and Non-Road Mobile Machinery Exhaust Pollution Prevention Regulations (Nanning, 2017)
PI-AR61	Chongqing Air Pollution Prevention and Control Regulations (Chongqing, 2017)
PI-AR62	High-Emission Non-Road Mobile Machinery Certification Standards and Work Zone Delimitation Work Plan (Chongqing, 2017)
PI-AR63	Non-Road Mobile Machinery Pollution Prevention and Control Technology Policy (China, 2018)
PI-AR64	Three-Year Action Plan on Winning the Blue Sky Defence War (China, 2018)
PI-AR65	Notice on Accelerating the Investigation of Non-Road Mobile Machinery and Registration of Code (China, 2019)
PI-AR66	Administrative Measures for the Prevention and Control of Exhaust Pollution of Motor Vehicles and Non-Road Mobile Machinery (Changchun, 2019)
PI-AR67	Beijing Blue Sky Defence War 2018 Action Plan (Beijing, 2018)
PI-AR68	Non-Road Diesel Engine Exhaust Visible Pollutant Limit and Measurement Method (DB11/184-2003) (China, 2003)
PI-AR69	Non-Road Diesel Engine Exhaust Pollutant Limit and Measurement Method (DB11/18-2003) (China, 2005)
PI-AR70	Clean Air Action Plan (Tianjin, 2014)
PI-AR71	Motor Vehicle and Non-road Mobile Machinery Exhaust Pollution Prevention and Control Regulations of Hebei Province (Hebei, 2018)
PI-AR72	The Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation

	(“Regulation”) (Hong Kong, 2015)
PI-AR73	Special Act on the Improvement of Air Quality in Seoul Metropolitan Area (South Korea, 2010, updated in 2011, 2013 and 2015)
PI-AR74	London's ' Low Emission Zone' for Non-road Mobile Machinery (London, 2015)
PI-AR75	A supplementary planning guidance (SPG) for The Control of Dust and Emissions from Construction and Demolition (London, 2014)
PI-AR76	Non-Road Mobile Machinery (Emission of Gaseous and Particulate Pollutants) Regulations (London, 1999)
PI-AR77	The Control of Dust and Emissions during Construction and Demolition (London, 2014)
PI-AR78	The Non-Road Mobile Machinery (Type-Approval and Emission of Gaseous and Particulate Pollutants) Regulations 2018 (London, 2018)
PI-AR79	Exemptions and Retrofit Procedures for the Non-Road Mobile Machinery (NRMM) Low Emission Zone (London, 2016, updated in 2018)
PI-AR80	PROCONVE MAR-I (equivalent to US Tier III and EU Stage III A) (Brazil, phased in from 2015 to 2019)
PI-AR81	National Council on the Environment (CONAMA) Resolution #433 (Brazil, 2011)
	PI-APP
PI-APP01	Massachusetts Department of Transportation (MassDOT)’s Diesel Retrofit Program (MassDOT, 1998)
PI-APP02	(BETA) UPMC - Luna Parking Garage (US, 2013)
PI-APP03	Launching the Pilot Program on Non-road Mobile Machinery Emissions Declaration and Registration (Shanghai, 2015)
	PI-AS
PI-AES01	Statement of Principles (SOP) (US, 1996, 1998 updated)
PI-AES02	US EPA Tier 1 (US, phased in from 1996 to 2000)
PI-AES03	US EPA Tier 2 (US, phased in from 2001 to 2006)
PI-AES04	US EPA Tier 3 (US, phased in from 2006 to 2008)
PI-AES05	US EPA Tier 4i (US, phased in from 2008 to 2012)
PI-AES06	US EPA Tier 4f (US, phased in from 2008 to 2015)
PI-AES07	California Exhaust Emission Standards and Test Procedures for New 2000 and Later Tier 1, Tier 2, and Tier 3 Off-Road Compression-Ignition Engines, Part I-B (California, 2008)
PI-AES08	California Exhaust Emission Standards and Test Procedures for New 1996 and Later Tier 1, Tier 2, and Tier 3 Off-Road Compression-Ignition Engines, Part II (California, 1993, updated in 2000 and 2005)
PI-AES09	California Exhaust Emission Standards and Test Procedures for New 2008-2010 Tier 4 Off-Road Compression-Ignition Engines, Part I-C (California, 2005; updated in 2012)

PI-AES10	California Exhaust Emission Standards and Test Procedures for New 2011 and Later Tier 4 Off-Road Compression-Ignition Engines, Part I-D, (California, 2005; updated in 2012)
PI-AES11	California Exhaust Emission Standards and Test Procedures for New 2011 and Later Tier 4 Off-Road Compression-Ignition Engines, Part 1-E (California, 2012)
PI-AES12	California Exhaust Emission Standards and Test Procedures for New 2011 and Later Tier 4 Off-Road Compression-Ignition Engines, Part 1-F (California, 2005; updated in 2012)
PI-AES13	EU Stage I (EU, phased in from 1999 to 2002)
PI-AES14	EU Stage II (EU, phased in from 2002 to 2003)
PI-AES15	EU Stage IIIA (EU, phased in from 2006 to 2007)
PI-AES16	EU Stage IIIB (EU, phased in from 2011 to 2013)
PI-AES17	EU Stage IV (EU, phased in from 2011 to 2013)
PI-AES18	EU Stage V (EU, phased in 2019)
PI-AES19	Tier 2 and 3 (Canada, phased in from 2006 to 2007)
PI-AES20	Tier 4i (Canada, phased in from 2012 to 2014)
PI-AES21	Tier 4 (Canada, implemented from 2015)
PI-AES22	Limits and Measurement Methods for Exhaust Pollutants from Diesel Engines of Non-Road Mobile Machinery: Stage III/IV (GB 20981-2014) (China, 2014)
PI-AES23	Non-Road Mobile Machinery Emission Standard of Tianjin (Tianjin, 2015)
PI-AES24	Limits and Measurement Methods for Exhaust Pollutants from Diesel Engines of Non-Road Mobile Machinery: Stage I/II (GB 20891-2007) (China, 2007)
PI-AES25	Limits and Measurement Methods for Exhaust Pollutants from Diesel Engines of Non-Road Machinery (DB11/185-2013) (Beijing, 2013)
PI-AES26	Limits and Measurement Methods for Exhaust Smoke from In-Use Diesel Engines of Non-Road Mobile Machinery (DB 31/981-2016) (Shanghai, 2016)
PI-AES27	Limits and Measurement Methods for Exhaust Smoke from In-Use Diesel Engines of Non-Road Mobile Machinery (DB13/2543-2017) (Hebei, 2017)
PI-AES28	EU Stage IIIA, US Tier 2/3 or Japan MoE standards (Standards specified in Announcement No.72 Made by Japan Ministry of Environment ("MoE") in 2006) (Hong Kong, 2015)
PI-AES29	Emission Standards for Diesel Engines Rating Less than 0.8 Mw (800 Kw) for Power Plant, Generator Set Applications and Other Requirements (India, 2002)
PI-AES30	Emission Standards for Diesel Engines Rating More than 0.8 Mw (800 Kw) for Power Plant, Generator Set Applications and Other Requirements (India, 2002)
PI-AES31	Emission Limits for New Diesel Engine up to 800 kW for Generator Set (Genset) Application (India, 2014)
PI-AES32	Emission Standards for Diesel Construction Machinery (India, 2006)

PI-AES33	Diesel Construction Equipment Vehicle Bharat Stage II (BS-II(CEV)) (India, 2007)
PI-AES34	Diesel Construction Equipment Vehicle Bharat Stage III (BS-III ((CEV)) (India, 2011)
PI-AES35	Diesel Agricultural Tractor, Construction Equipment Vehicle and Combine Haevester Bharat Stage IV (BS (CEV/TREM) IV) (India, 2018)
PI-AES36	Diesel Agricultural Tractor, Construction Equipment Vehicle and Combine Haevester Bharat Stage V (BS (CEV/Trem)) V) (India, 2018)
PI-AES37	Tier 1 (South Korea, 2004)
PI-AES38	Tier 2 (South Korea, 2005)
PI-AES39	Tier 3 (South Korea, 2009)
PI-AES40	Tier 4 (South Korea, 2015)
PI-AES41	EU Stage I (Turkey, 2003)
PI-AES42	EU Stage II (Turkey, 2007)
PI-AES43	EU Stage IIIA (Turkey, 2011)
PI-AES44	EU Stage IIIB (Turkey, phased in from 2011 to 2018)
PI-AES45	EU Stage IV (Turkey, 2019)
PI-AES46	NOM-016-CRE-2016, Petroleum Quality Specifications (Mexico, 2016)
PI-AES47	NOM-086-SEMARNAT-SENER-SCFI-2005 (Mexico, 2006)
PI-AES48	NOM-086-SEMARNAT-1994 (Mexico, 1994)
PI-AES49	NOM-051-SEMARNAT-1993 (Mexico, 1993)
PI-AES50	Resolution 2063-2005 (Chile, 2006)
PI-AES51	Decree NO. 4 Stationary Engine PM Emissions Regulation 1992 (Chile, 1991)
PI-AES52	Stationary Engine SO2 and CO Emissions Regulation 2005 (Chile, 2005)

Appendix II Identification of PI-B

Code	**PI-BS**
PI-BS01	The Early Turnover Scheme (Singapore, 2013)
	PI-BT
PI-BT01	Clean Construction USA (US, 2007)
	PI-BR
PI-BR01	Clean Diesel program (US, 2012)
PI-BR02	U.S. EPA Construction Rebate Program (Chicago, 2014)
PI-BR03	Clean Construction Rebate - Retrofit (US, 2007)
PI-BR04	Clean Construction Rebate - Engine Replacement (US, 2007)
	PI-BLI
PI-BLI01	The National Clean Diesel Campaign (NCDC)-National Clean Diesel Finance Program (US, 2008-2019)

PI-BLI02	Diesel Emissions Reduction Act Grants (US, 2012-2015)
PI-BLI03	Diesel Emissions Reduction Act Grants (US, 2012-2015)
PI-BLI04	The National Clean Diesel Campaign (NCDC)-State Clean Diesel Grant Program (US, 2008-2020)
	PI-BG
PI-BG01	Clean Construction USA (US, 2007)
PI-BG02	Diesel Emissions Reduction Act Grants (US, 2012-2016)
PI-BG03	Diesel Emissions Reduction Act Grants (US, 2012-2016)
PI-BG04	Illinois Clean Diesel Grant Program (Chicago, 2014)
PI-BG05	The National Clean Diesel Campaign (NCDC)-National Clean Diesel Funding Assistance Program (US, 2008-2019)
PI-BG06	The National Clean Diesel Campaign (NCDC)-Clean Diesel Emerging Technologies Program (US, 2008-2019)
PI-BG07	The National Clean Diesel Campaign (NCDC)-State Clean Diesel Grant Program (US, 2008-2020)
PI-BG08	The Diesel Emissions Reduction National Program (DERA)(US, 2008)
PI-BG09	The Carl Moyer Memorial Air Quality Standards Attainment (Carl Moyer) Program (California, 1998)
PI-BG10	The Carl Moyer Memorial Air Quality Standards Attainment (Carl Moyer) Program (Singapore, 1998)

Appendix III Identification of PI-C

Code	**PI-CVS**
PI-CVS01	Blue Sky Series Engines (US, 2002)
	Northeast Diesel Collaborative Model Contract Specification (US, 2008, updated in 2010)
	PI-CGS
PI-GS01	A Training Event for the Contractor Community on how to Comply with the New Requirements of the Clean Diesel Construction ordinance (US, 2014)
PI-GS02	Best Practices for Clean Diesel Construction-Successful Implementation of Equipment Specifications to Minimize Diesel Pollution (Northeast Diesel Collaborative, 2012)
PI-GS03	Guide to Off-Road Vehicle & Equipment Regulations (California, 2015)
PI-GS04	California's Small Business Assistance Program (California, 2016)
PI-GS05	One-Stop Truck Events (California, 2019)
PI-GS06	Non-Road Mobile Machinery (NRMM) Practical Guide (London, 2017)
PI-GS07	The Control of Dust and Emissions from Construction and Demolition-Best Practice Guidance (London, 2006)

PI-GS08	Cleaner Machinery for London (London, 2017)
PI-GS09	Fleet Operator Recognition Scheme (FORS) (London, 2018)
PI-GS10	Best in Class' Guidance on Dust and Emission from Construction (London, 2019)
	PI-CCL
PI-CCL01	LEED Clean Construction Pilot Credit (The US Green Building Council, 2007)
	PI-CVPP
PI-VPP01	Retrofit Program for Diesel Equipment during the Construction Phase of the I-95 New Haven Harbor Crossing Improvement Program in Southern Connecticut (New York, 2002)
PI-VPP02	Portland Nonroad Pilot Clean Diesel Program (US, 2016)
	PI-CID
PI-CID01	Construction Fleet Inventory Guide (EPA, 2010)
PI-CID02	Progress Report on EPA's Nonroad Mobile Source Emissions Reduction Strategies (Office of Inspector General, 2006)
PI-CID03	Environment Protection Information Disclosure of Motor Vehicles and Non-road Mobile Machinery (China, 2016)