RGC Ref. No.:
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RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR
THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report
(for completed projects only)

Submission Deadlines: *1. Auditor's report with unspent balance, if any: within **six** months of the approved project completion date.*
*2. Completion report: within **12** months of the approved project completion date.*

Part A: The Project and Investigator(s)

1. Project Title

Chemical and Toxicological Characterization of Particulate Emissions from Diesel Vehicles

2. Investigator(s) And Academic Department(s) / Unit(s) Involved

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	Dr. WANG Bei	FST/THEi
Co-Investigator(s)	Prof. LEE Kin-man Prof. LEE Shun-cheng Mr. ORGAN Bruce Dr. HO Kin-fai Dr. CHUANG Hsiao-chi	FST/THEi (retired) CEE/HKPU EM/ETRC JCSPHPC/CUHK School of Respiratory Therapy/ TMU

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval *(must be quoted)*
Project Start Date	1 January 2016	NA	NA
Project Completion Date	31 December 2017	30 June 2018	09 August 2017
Duration *(in month)*	24	30	09 August 2017
Deadline for Submission of Completion Report	December 2018	30 June 2019	09 August 2017

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. To characterize the particulate emissions from 15 diesel vehicles
2. To quantify the chemical composition including polycyclic aromatic hydrocarbons and carbonaceous species of particulate matters from diesel vehicles
3. To compare the particulate emissions and chemical compositions over different driving cycles
4. To investigate the factors including vehicle model year, vehicle type, country of vehicle manufactured, and different emission control technologies that may affect the particulate exhaust emissions
5. To conduct the toxicological assessment of the diesel vehicle particulate emissions

5.2 Revised objectives

Date of approval from the RGC: NA

Reasons for the change: NA

5.3 Realisation of the objectives
(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)

The objectives of the project have been fully accomplished through literature review, vehicle testing, chemical and toxicological analyses of particulate emission samples, calculation of pollutant emission factors (*EF*s), and statistical analysis. The realization of the five specific objectives is summarized as follows:

Testing vehicles and Driving cycles (Objective 1, 3 and 4)
Fifteen diesel vehicles were recruited to investigate the effects of vehicle factors on the exhaust emissions. The vehicle tests by chassis dynamometer were carried out at Jockey Club Heavy Vehicle Emissions Testing and Research Centre (JCEC). Two passenger cars (PCs) and five light duty vehicles (LDVs) were tested on a Mustang Dynamometer with 48" single roller, while six medium duty vehicles (MDVs) and two heavy duty vehicles (HDVs) were tested on a Mustang Dynamometer with 17.2" triple roller. The specifications of the tested vehicles spanned a range of model years, capacities and powers of engines, emission standards from Euro-II to Euro-VI. Some were equipped with different combinations of after-treatment devices including exhaust gas recirculation (EGR), diesel particulate filter (DPF), diesel oxidation catalyst (DOC) and selective catalytic reduction (SCR) systems.

The vehicles were tested over four driving conditions, including cold-start transient, hot-start transient, idling (20 minutes) and steady-state (50 km h^{-1}, 20 minutes) to simulate the real-world driving situations and quantify the respective emissions. Two type-approval testing cycles, New European Driving Cycle (NEDC) for PCs and LDVs and Forschungsinstitut für Geräusche und Erschütterungen (FIGE) Cycle (European Transient Cycle) for MDVs and HDVs, were applied for testing the transient emissions.

Online measurement of exhaust emissions and collection of particulate matters (Objective 1 and 3)
The vehicle testing and sample collections were executed between July 2016 and April 2017. For each tested vehicle, instantaneous concentrations of gaseous emissions including carbon dioxide (CO_2), carbon monoxide (CO), total hydrogen carbon (THC) and nitrogen oxides (NO_x) were measured throughout the whole driving cycle. Particulate emissions were collected simultaneously on 47 mm quartz fiber filters and 47 mm Teflon-membrane filters. The masses of total particulate matters (PM) on the filters were determined by a gravimetrical method.

Chemical analysis of carbonaceous composition of the particulate emissions (Objective 2)
The PM samples collected on the quartz fiber filters were analyzed the contents of organic carbon (OC) and elemental carbon (EC) with the Thermal/Optical Carbon Analyzer and the IMPROVE-A protocol, and the concentrations of polycyclic aromatic hydrocarbons (PAHs) with the thermal desorption-gas chromatography/mass spectrometer. 17 PAHs species categorized from three- to seven- aromatic rings were detected.

Toxicological assessment of particulate emissions (Objective 5)
The PM samples were extracted from the Teflon-membrane filters for *in vitro* exposure experiments. Human lung adenocarcinoma epithelial cells (A549 cells) were seeded for cell culture medium. After exposure to 50μg ml^{-1} of the PM extracts, three toxicological markers including (1) the level of reactive oxygen species (ROS), (2) the concentrations of antioxidant glutathione (GSH) and (3) pro-inflammatory mediator interleukin 6 (IL-6) were determined in order to assess the oxidative potential of PM, the antioxidant and the inflammation responses of the cellular activities, respectively.

Data analysis (Objective 3 and 4).
The *EF*s of NOx, CO, THC, PM, OC, EC, and PAHs, as well as the OC/EC ratio were calculated for each vehicle under different driving conditions. The effects of driving conditions and the emission standards of vehicles on the pollutant *EF*s were evaluated. The correlation analysis between the pollutant *EF*s, the driving conditions, and the vehicle parameters including emission standards, testing weights, maximum engine powers, engine capacity and mileages were performed.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
1. To characterize the particulate emissions from 15 diesel vehicles	✓	100%
2. To quantify the chemical composition including polycyclic aromatic hydrocarbons and carbonaceous species of particulate matters from diesel vehicles	✓	100%
3. To compare the particulate emissions and chemical compositions over different driving cycles	✓	100%
4. To investigate the factors including vehicle model year, vehicle type, country of vehicle manufactured, and different emission control technologies that may affect the particulate exhaust emissions	✓	100%
5. To conduct the toxicological assessment of the diesel vehicle particulate emissions	✓	100%

6. Research Outcome

6.1 Major findings and research outcome

(Maximum 1 page; please make reference to Part C where necessary)

The major research outcome was presented in two research papers as in Part C. The findings revealed that the *EF*s of NOx, CO, THC, PM, OC, EC and total PAHs, as well as the OC/EC ratios varied over different diesel vehicles under four driving conditions. The factors affecting the particulate exhaust emissions, the chemical composition of PM, and the cellular effects from exposure to the PM extracts are illustrated as follows:

Driving conditions

Elevated emissions of PM, total EC and OC, and total PAHs were predominantly detected from the tested vehicles during cold-start and hot-start transients, compared with steady or idling driving conditions. This was attributed to more fuel required to power for acceleration during transients, leading to formation of EC arisen from droplet pyrolysis, OC and PAHs derived from incomplete fuel combustion processes.

Emission standards

The emission standard of the vehicles was identified as the key determinant in controlling emissions of the targeted pollutants. The *EF*s of PM, total EC and OC, and total PAHs generally followed the tendency to decrease with the advanced emission standards of the diesel vehicles from Euro-II to Euro-VI, among the same class of vehicles.

After-treatment control devices

The vehicles equipped with combinations of EGF, DPF and/ or DOC were found with noticeable reduction of PM, total OC and EC emissions under all driving conditions, compared with the same classes of vehicles merely equipped with EGR/SCR, or without any after-treatment device. The EGR and DPF equipped vehicles (Vehicle 7, 10, 13) were noted with high OC/EC ratios under idling, indicating DPFs effectively removed PM and EC, but inefficiently controlled or altered the emission behaviors of OC and PAHs during idling. In contrast, the vehicles equipped with EGFs, DPF and DOC (Vehicle 2, 11) eliminated OC, EC and total PAHs in a satisfactory manner.

Chemical and toxicological characterization in the particulate emissions

OC was the prominent fraction of PM emissions of the tested fleet. Among the identified PAHs, four- and five- aromatic ring PAHs were the most abundant species in order of pyrene (Pyr), benz[*a*]anthracene (BaA), chrysene (CHR), benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF) and benzo[*a*]fluoranthene (BaF), in which CHR, BaA, BkF and BbF are classified as probably carcinogenic to human (Group 2B). Among the tested vehicles, the HDVs were found with relatively higher emission of heavy molecular weight PAHs that tend to be more harmful to human health, including the most potently mutagenic benzo(*a*)pyrene (BaP) (Group I).

The cellular exposure experiments revealed that the diesel vehicle PM emissions exerted potential oxidative stresses emerged from the ROS to human lung cell activities. Compared with LDVs, higher levels of antioxidant GSH and cytokine IL-6 responses were triggered by the PM emissions of MDVs and HDVs, implying that the PM emitted by the high-loading diesel vehicles induced more oxidative and inflammatory responses in human lung cells, and therefore caused cell damage and posed threat to human respiratory system when inhaled. On the other hand, the highest level of GSH was detected from the PM emitted by the most advanced Euro-VI PC under hot-start transient, indicating that exposure to the particulate emissions from the modern diesel vehicles still could induce cytotoxicity responses and in turn lead to undesirable effects on respiratory diseases. Statistical analysis showed the cellular production of IL-6 in response to the PM emissions was associated with the vehicle factors including weights, engine capacity and maximum power under hot-start transient and idling.

6.2 Potential for further development of the research and the proposed course of action *(Maximum half a page)*

Street-level photochemical smog derived from the transportation sector is very challenging in Hong Kong, despite various stringent control measures implemented to reduce roadside NOx and PM. Meanwhile, exposure to fine particulates was reported higher among the local adults than those in the other developed areas (Chen et al., 2018).

This research revealed that, both NOx emissions and cellular cytokine IL-6 production in response to PM emission were statistically correlated with the weight and the engine power of diesel vehicles, rather than the emission standards. On the other hand, the SCR-equipped Euro-V HDV was found failure to control NOx, PM and total PAHs emissions substantially. Previous studies also reported malfunctions in the after-treatment devices including EGR valves, DPF and SCR systems, as well as ageing engine significantly rocketed NOx and PM emissions from the diesel vehicles.

For further study, the effects of maintenance levels, the effectiveness and durability of the catalytic convertors and the sensors on emission control are suggested to be investigated among various diesel vehicles, as well as the retrofitted, petrol and liquefied petroleum gas vehicles using dynamometers under various driving cycles.

Besides, this study showed that the diesel particulate emission contained the carcinogenic PAHs (BaP, BaA, CHR, BbF and BkF). The chemical characterization of PM emissions; the relationship between the exhaust emission and the cytotoxic effects with respect to specific primary and secondary organic aerosols; and the risk assessments of vehicular emissions are suggested to be investigated, and incorporated into environmental mitigation measures and public health protection strategies.

Reference:
Chen, X. C., Ward, T. J., Cao, J. J., Lee, S. C., Chow, J. C., Lau, G. N., Yim, S.H., Ho, K. F. (2018). Determinants of personal exposure to fine particulate matter (PM2.5) in adult subjects in Hong Kong. *Science of the Total Environment, 628:* 1165-1177.

7. Layman's Summary

(Describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

Vehicle tailpipe emission is the key anthropogenic source to roadside air pollution. This research presented the first chemical and toxicological characterization of diesel vehicle emissions over different driving conditions, utilizing chassis dynamometers in Hong Kong. The factors affecting the diesel exhaust emissions were comprehensively evaluated.

The findings would provide the policy decision makers in formulation of measures for better roadside air quality. For example, the tests demonstrated that the diesel exhaust particulate emissions and the carbonaceous contents generally tended to decline with advanced diesel vehicles; meanwhile, the functioning emission control systems played detrimental roles in reducing harmful exhaust emissions. In addition, the cellular exposure experiments indicated that particulate emission from the advanced diesel vehicles still posed undesirable effects on human respiratory diseases.

The detailed data of pollutant emission factors can further be used for the database development of emission inventory and air modelling analysis; and for the industries to develop after-treatment devices and monitoring systems in order to halt harmful exhaust emission and emission-related faults.

Part C: Research Output

8. Peer-Reviewed Journal Publication(s) Arising Directly From This Research Project

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) *(denote the correspond-ing author with an asterisk*)*	Title and Journal / Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowledged the Support of RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of Publication	**Year of Acceptance** *(For paper accepted but not yet published)*	**Under Review**	**Under Preparation** *(optional)*						
		✓		Wang Bei*, Lau Yik Sze, Organ Bruce, Lee Shun Cheng, Ho Kin Fai*	Investigation of Factors Affecting the Gaseous Pollutants and Particulate Matter Emission from Diesel Vehicles in Hong Kong/ *Air Quality, Atmosphere & Health - Springer*	2018	Yes	Yes	No
			✓	Wang Bei*, Lau Yik Sze, Organ Bruce, Lee Shun Cheng, Ho Kin Fai*	Chemical and Toxicological Characterization of Particulate Emissions from Diesel Vehicles/ *Air Quality, Atmosphere & Health - Springer*	No	Yes	Yes	No

9. Recognized International Conference(s) In Which Paper(s) Related To This Research Project Was / Were Delivered

(Please attach a copy of each conference abstract)

Month / Year / Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowledged the Support of RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
February 2018 Osaka	Gaseous pollutants emission from diesel vehicles in Hong Kong	2018 Asian Conference on Engineering and Natural Sciences	2017	No	Yes	Yes

10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning
(Please elaborate)

The PI has been teaching the course Air Pollution and Noise Control (SEV4231) at THEi. The research experience and latest findings have contributed to the teaching and learning. The research project has also been integrated with the final year projects that were offered for the Bachelor of Engineering students as noted in section 11. They gained solid research experience and knowledge on the particular air pollutant emissions from diesel vehicles over different driving cycles.

11. Student(s) Trained
(Please attach a copy of the title page of the thesis)

Name	Degree Registered for	Date of Registration	Date of Thesis Submission / Graduation
	Management / THEi	1/9/2013	31/7/2017
	Management / THEi	1/9/2013	31/7/2017
	Environmental Engineering and Management / THEi	1/9/2015	31/7/2017
	Management / THEi	1/9/2013	31/7/2017
	Environmental Engineering and Management / THEi	1/9/2014	31/7/2018
	Environmental Engineering and Management / THEi	1/9/2016	31/7/2018
	Environmental Engineering and Management / THEi	1/9/2016	31/7/2018
	Environmental Engineering and Management / THEi	1/9/2016	31/7/2018
	Environmental Engineering and Management / THEi	1/9/2016	31/7/2018
	Environmental Engineering and Management / THEi	1/9/2015	31/7/2019
	Environmental Engineering and Management / THEi	1/9/2015	31/7/2019
	Environmental Engineering and Management / THEi	1/9/2015	31/7/2019
	Environmental Engineering and Management / THEi	1/9/2015	31/7/2019
	Environmental Engineering and Management / THEi	1/9/2015	31/7/2019
	Environmental Engineering and Management / THEi	1/9/2015	31/7/2019

12. Other Impact
(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)

The PI has been teaching the course Air Pollution and Noise Control (SEV4231) at THEi. The research experience and latest findings have contributed to the teaching and learning. The research project has also been integrated with the final year projects that were offered for the Bachelor of Engineering students as noted in section 11. They gained solid research experience and knowledge on the particular air pollutant emissions from diesel vehicles over different driving cycles. Besides, the instrumental setup installed in Jockey Club Heavy Vehicle Emissions Testing and Research Center at IVE (Tsing Yi) campus was introduced to the Bachelor of Engineering students at THEi during the laboratory section of the course Air Pollution and Noise Control (SEV4231).

13. Public Access Of Completion Report

(Please specify the information, if any, that cannot be provided for public access and give the reasons.)

Information that Cannot Be Provided for Public Access	**Reasons**
NIL	

RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR
THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report - Attachment
(for completed projects only)

RGC Ref. No.:	UGC/FDS25/E06/15
Principal Investigator:	Dr. WANG Bei
Project Title:	Chemical and Toxicological Characterization of Particulate Emissions from Diesel Vehicles

Statistics on Research Outputs

	Peer-reviewed Journal Publications	Conference Papers	Scholarly Books, Monographs and Chapters	Patents Awarded	Other Research Outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	2	1	Nil	Nil	The research experience and latest findings have contributed to the teaching and learning. 15 students have been trained through the Final Year Project.