0 RGC Ref. No.: UGC/FDS/25/E01/18
(please insert ref. above)

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

Investigation on effects of biodiesel blends on gas- and particulate-phase light duty diesel vehicle exhaust emissions

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

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	Dr. Wang Bei / Assistant Professor	Faulty of Science and Technology/ Technological and Higher Education Institute of Hong Kong (THEi)
Co-Investigator(s)	Prof. LEE Shun-cheng / Professor	Department of Civil and Environmental Engineering / The Hong Kong Polytechnic University
Co-Investigator	Prof. LEUNG Yiu-cheong / Professor	Department of Mechanical Engineering / Hong Kong University of Hong Kong
Co-Investigator	Mr. ORGAN Bruce/ Centre Manager	Jockey Club Heavy Vehicle Emissions Testing and Research Centre / The Institute of Vocational Education

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval

			(must be quoted)
Project Start Date	1 January 2019	NA	NA
Project Completion Date	31 December 2020	30 June 2021	7 September 2020
Duration *(in month)*	24	30	7 September 2020
Deadline for Submission of Completion Report	31 December 2021	30 June 2022	7 September 2020

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

The main aim of this proposed project is to evaluate and characterize the effect of biodiesel blends (i.e. B0 and B5) on the gaseous and particulate matter emissions from light duty diesel vehicles in different driving conditions on a chassis dynamometer.

1. To monitor the real-time vehicular emissions including volatile organic compounds (VOCs), oxygenated volatile organic compounds (OVOCs), and particulate matter (PM) number concentrations in different driving conditions including transient cycle, steady state, and idling;
2. To quantify the chemical composition including polycyclic aromatic hydrocarbons (PAHs), oxygenated polycyclic aromatic hydrocarbons (oxy-PAHs), and carbonaceous species (i.e. organic carbon (OC) and elemental carbon (EC)) of PM emitted from the tested vehicles;
3. To compare the carbonyl emissions measured by Proton Transfer Reaction – Quadrupole ion Time of Flight Mass Spectrometer (PTR-QiTOF) and 2,4-Dinitrophenylhydrazine (DNPH) cartridge techniques; and
4. To evaluate the pros and cons of using biodiesel blend (B5) as motor fuel in Hong Kong

5.2 Revised objectives

Date of approval from the RGC: 31 October 2018

It was originally planned to conduct vehicle testing on four light duty diesel vehicles, while the revised vehicle testing was conducted on one light duty diesel vehicle according to the funding condition "Rental of one light duty diesel vehicle is allowed under 'Equipment Expenses'".

Reasons for the change: The main reason of cutting the objective "*To compare the carbonyl emissions measured by PTR-QiTOF and DNPH cartridge techniques"* from this project is that the total fund awarded for this project is HKD780,174, which is much lower than the request amount of HKD1,144,695. Besides, this objective is mainly to compare the results of carbonyl emissions by two different sampling and

analyzing techniques; while it will not contribute a lot to the main aim of this project.

The revised objectives are as follows:

The main aim of this proposed project is to evaluate and characterize the effect of biodiesel blends (i.e. B0 and B5) on the gaseous and particulate matter emissions from a light duty diesel vehicle in different driving conditions on a chassis dynamometer.

1. To monitor the real-time vehicular emissions including VOCs, OVOCs, and PM number concentrations in different driving conditions including transient cycle, steady state, and idling;
2. To quantify the chemical composition including PAHs, oxy-PAHs, and carbonaceous species (i.e. OC and EC) of particulate matters emitted from the tested vehicles; and
3. To evaluate the pros and cons of using biodiesel blend (B5) as motor fuel in Hong Kong

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 analyses of particulate emission samples, calculation of pollutant emission factors (EFs), and statistical analysis. The realisation of the three specific objectives is summarized as follows:

Testing vehicle, fuel blends and driving cycles (Objective 1, 2 and 3)

A Euro-VI light duty diesel vehicle (Euro VI-LDV, H1, Hyundai) was tested on a chassis dynamometer in Jockey Club Heavy Vehicle Emissions Testing and Research Centre (JCEC). The vehicle was tested with two types of fuels (i.e., B0 and B5). B0 is the ultralow sulphur content diesel (ULSD) and B5 is 5% waste cooking oil (WCO) derived biodiesel blended with 95% ULSD by volume. Three types of driving conditions, namely transient, steady-state, and idling were carried out for the vehicle testing. For each combination of fuel blend and driving condition, three trials were performed. New European Driving Cycle (NEDC) test was adopted representing the transient condition. The vehicle speed at steady-state test was set at 50 km/h since it is the speed limit for the majority of roads in urban areas of Hong Kong. For idling test, the tested vehicle was parked on the chassis dynamometer with engine on.

Online measurement of exhaust emissions and collection of particulate matters (Objective 1 and 2)

The gaseous emission measuring systems, the particle number (PN) counting system, and the PTR-QMS were connected to the constant volume sampler (CVS) coupled with a dilution tunnel. The real-time vehicular emissions of VOCs and OVOCs were monitored by the PTR-QMS (IONICON Analytik GmbH), while real-time particle number concentration was monitored by the particle number counting system. Calibrations of the PTR-QMS with zero air generated by a gas calibration unit (Ionicon Analytik GmbH) and Ionimed mixed-VOC standard gases (Ionicon Analytik GmbH) were carried out prior to the testing campaign. In addition, the real-time emissions of commonly regulated gases including CO_2, CO, THC and NO, were also recorded by the emission measuring system. During each driving test, PM was collected on a pre-baked 47 mm Whatman quartz filter

and a 46.2 mm Whatman Teflon filter simultaneously using two parallel filter holders.

Chemical analyses of collected PM samples (Objective 2)
The analyses of OC, EC, PAHs, and oxy-PAHs were conducted from the PM samples collected on the quartz filters. A specially designed chopper cut each quartz filter exactly in half. The contents of OC and EC were determined by the IMPROVE thermal/optical reflectance method (DRI Model 2001 Thermal/ Optical Carbon Analyzer). The PM samples on another half portion of each quartz filter were analyzed for PAHs and oxy-PAHs determinations. The samples were quantified by the thermal desorption-gas chromatography/mass spectrometer (TD-GC/MS) method.

Data analysis (Objective 1, 2 and 3)
The gaseous and particulate emissions from vehicle exhaust, expressed in fuel based emission factors, were reported and discussed. Furthermore, VOC-related ozone formation potential (OFP) and secondary organic aerosol potential (SOAP), as well as PAHs-related toxic equivalent factors (TEFs) PAHs with reference to benzo[a]pyrene (BaP), were calculated to reflect the potential impacts of B5 to atmospheric and health.

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 monitor the real-time vehicular emissions including VOCs, OVOCs, and PM number concentrations over different driving conditions including transient cycle, steady state, and idling;	✓	100%
2. To quantify the chemical composition including PAHs, oxy-PAHs, and carbonaceous species (i.e. OC and EC) of PM emitted from the tested vehicles;	✓	100%
3. To evaluate the pros and cons of using biodiesel blend (B5) as motor fuel in Hong Kong.	✓	100%

6. Research Outcome

6.1 Major findings and research outcome

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

Generally, low levels of gaseous and particulate emissions were detected from the tested light duty diesel vehicle with the use of both fuel blends. For CO, the fuel-based emission factor (*EF*) was increased by 13.0% and 15.4% under steady-state test and idling, respectively, while reduced by 8.2% under transient cycle (NEDC). For THC, the change in *EF*s was 20.9%, 31.9%, and -9.0%, for steady-state test, idling, and NEDC, respectively. The use of B5 improved NO_x emissions under all driving cycles. Replacing B0 with B5 reduced NO_x emissions by a range between 27.0% and 32.2% under different driving cycles. The *EF*s of PN was reduced at idling by 15.7%, but it was increased at transient and steady test by 37.4% and 102.6%, respectively. On the contrary, total VOCs, as well as OFPs and SOAPs, were increased in all tests. The emissions of total VOCs were increased by a range between 47.7% and 135.8% under different driving cycles. The total OFPs were increased by a range between 48.6% and 212.6%, while the total SOAPs were increased by a range between 28.8% and 123.4%. Individual VOC/ OVOC species experienced different changes in emissions, and the changes vary across different driving cycles. Real-time emission profiles showed that gaseous and particulate emissions were affected by the initiation and the acceleration of the driving cycle.

Generally, this study observed low *EF*s of OC and EC from the exhaust particulate samples, suggesting that the DPF has a high effectiveness to remove particulate exhaust emissions. The OC *EF*s of B0 across the driving cycles were between 2.86 ± 0.33 and 7.19 ± 1.51 mg/kg, and those of B5 were between 4.31 ± 0.64 and 15.36 ± 3.77 mg/kg. It was found that the average EC *EF*s for B0 ranged from 0.01 ± 0.00 to 0.11 ± 0.10 mg/kg, while the average EC *EF*s for B5 ranged from 0.02 ± 0.02 to 0.25 ± 0.39 mg/kg. Both B0 and B5 generated the highest OC *EFs* under idling and the lowest *EFs* at NEDC. Under idling state, B5 raised OC *EF*s by 114% compared to B0. The rise in OC *EF*s was 50.6% in NEDC and 39.5% in steady-state cycle, respectively. It was found that EC *EFs* varied significantly across driving cycles (i.e., from - 80% to + 816%) by the use of B5. As the EC content detected for each trail was very small and some samples were even below the detection limit, the changes in percentage were apparent.

The results revealed that with the use of B5 the *EF*s of total particle-phase PAHs and oxy-PAHs were reduced by 50.2%, 30.7%, and 15.2% over NEDC, steady-state, and idling, respectively, compared to when using B0. The *EF*s of total PAHs were dominantly attributed to low molecular weight (LMW-, 2 to 3ring) PAHs including Acenaphthylene (ACY), Acenaphthene (ACE), Fluorene (FL), and Naphthalene (NAP). Together, they contributed to around 70% of the total particle-phase PAHs when B0 was used. It was found that there was a reduction in total *EF*s of these dominant LMW-PAHs by 61.1% in NEDC, 47.7% in steady-state, and 28.4% in idling, respectively, when replacing B0 by B5. However, the emissions of high molecular weight (HMW-, 5- to 7-ring) and medium molecular weight (MMW-, 4-ring) PAHs did not show a reduction trend with the use of B5. The oxy-PAHs *EF*s ranged from 2.2 ± 0.6 to 4.3 ± 2.5 μg/kg with B5 which only contributed to a small fraction of the total PAHs.

The toxicity of particulate phase PAHs emissions was evaluated by the toxicity equivalent factors (TEFs) of individual PAH with reference to benzo[*a*]pyrene (BaP), expressed in BaP equivalent (BaP_{eq}). With B5, the BaP_{eq} *EF*s were 3.10 ± 0.76 (NEDC), 3.34 ± 2.17 (steady-state), and 5.89 ± 2.55 μg/kg (idling), respectively. Since the use of B5 switched the compositions of PAHs to more HMW-PAHs with higher TEFs in compared with using B0, the BaP_{eq} *EF*s were increased by 11.3%, 53.8%, and 117.0% over NEDC, steady-state and idling tests, respectively.

To conclude, our study shows a mixed effect of B5 application. CO, THC and PN emissions were generally increased but stay within the emission standards. On the other hand, there was a rise in VOC and OC emissions, as well as VOC related OFP and SOAP. While the total PAHs were reduced, the composition of PAHs profile changed and the toxicity increased. The findings raise concern of biodiesel blend application on environmental and health impacts. Our study contributes to a comprehensive understanding of the feasibility of using B5 biodiesel blend in Hong Kong.

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

Potential for further development of the research is multifold. Firstly, this project examined the effects of biodiesel blends on exhaust emissions. A life cycle assessment (LCA) could show a complete picture of overall impact of replacement of motor fuel. The tested biodiesel blend, originated from waste cooking oil, may appear to be more stainable than conventional diesel and other biodiesel originated from cash crops through a LCA. Secondly, the testing was performed on a light duty diesel vehicle. An increase in coverage of fleet in terms of vehicle type and other parameters such as emission standard, age, distance travelled and aftertreatment system could increase the reliability of the research and it would better represent the city's vehicle mix. Thirdly, this study examined the effect of B5 blend, further research may attempt to increase the biodiesel content and identify the ratio that achieve the optimal compromise of engine performance, fuel consumption and air quality. While B5 is currently the specification of motor vehicle biodiesel by regulation in Hong Kong, the findings may assist in further amendment of the Air Pollution Control (Motor Vehicle Fuel) regulation.
For further action, the investigators will seek to acquire further research funding to conduct subsequent research as mentioned above.

7. Layman's Summary

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

Biodiesel is considered as a viable transport fuel alternative for diesel vehicles. The use of biodiesel as vehicle fuels in lieu of petroleum-based diesel can help to reduce greenhouse gas emissions and therefore arrest global climate changes. However, Petroleum-based fuels still serve as the major motor fuels in Hong Kong nowadays. There are currently three local biodiesel manufacturers in Hong Kong, but the usage of biodiesel lags behind many other countries. The most updated study investigating the feasibility of biodiesel usage as transport fuel in Hong Kong was conducted more than ten years ago (Leung, 2003). Therefore, there is an urgent need to comprehensively investigate the exhaust from vehicles using biodiesel blends in Hong Kong.

This project utilizes the chassis dynamometer at Jockey Club Heavy Vehicle Emissions Testing and Research Center in Hong Kong to investigate the effect of a biodiesel blend (5%, locally-produced waste cooking oil) on the gaseous and particulate matter emissions from a light duty diesel vehicle in different driving conditions. This study provides valuable information about the effects of biodiesel blends on exhaust emissions and potential effects to air quality. The findings are expected to contribute to motor fuel application and policy discussion.

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)*	Acknowl-edged 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)*						
2021	N.A.	N.A.	N.A.	Bei Wang*, Wing-Hong Or, Shun-Cheng Lee, Yiu-Cheong Leung, Bruce Organ, Kin-Fai Ho*	Characteristics of particle emissions from light duty diesel vehicle fueled with ultralow sulphur diesel and biodiesel blend. *Atmospheric Pollution Research* 12(2021)101169.	No	Yes	Yes	Yes
N.A.	N.A.	N.A.	Yes	Bei Wang*, Wing-Hong Or, Shun-Cheng Lee, Yiu-Cheong Leung, Bruce Organ, Kin-Fai Ho*	Online monitoring of regulated and unregulated exhaust emissions from a light duty diesel vehicle using waste cooking oil-based biodiesel blend	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)*

June, 2021/ Tokyo, Japan	Investigation of the Effects of Biodiesel Blend on Particulate-Phase Exhaust Emissions from a Light Duty Diesel Vehicle	ICEPPC 2021: International Conference on Effects of Pollution and Pollution Control	No	Yes	Yes	Yes

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

(Please elaborate)

The principal investigator has integrated the research project with her teaching of module Air Pollution and Noise Control (SEV4231), Environmental Engineering (SCE5251) and Environmental Risk Analysis (SEV5381) by a combination of theoretical principals and empirical practice. In addition, for each academic year in the project period 5 students participated in the project as their final year projects through taking part in experiment or data analysis.

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
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]

12. Other Impact

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

Nil

13. 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	1 (published) 1 (under preparation for publication)	1	Nil	Nil	Type	No.
					Nil	Nil

14. 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
N.A.	