RGC Ref. No.:
UGC/IDS(C)25/E02/19
(please insert ref. above)

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

INSTITUTIONAL DEVELOPMENT SCHEME (IDS)
COLLABORATIVE RESEARACH GRANT

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

The Design and Development of a Vertical Remote Sensing System for Tailpipe Emissions (VRSE) System in Single-lane Applications

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

Research Team	Name / Post	Unit / Department / Institution	Average Number of Hours Per Week Spent on this Project
Project Coordinator	Dr LIU Yaohui, Keane/Assistant Professor	Department of Construction Technology and Engineering / Technological and Higher Education Institute of Hong Kong	8
Co-Investigator(s)	Dr LIU Chun-ho / Associate Professor	Faculty of Engineering / Department of Mechanical Engineering / The University of Hong Kong	3
Co-Investigator(s)	Prof John ZHOU	School of Civil and Environmental	3

		Engineering / University of Technology Sydney	

(Please add row(s) as necessary.)

Please highlight the approved changes in project team composition and quote the date of RGC approval for such changes.

3. Project Duration

	Original	**Revised**	**Date of RGC / Institution Approval** *(must be quoted)*
Project Start Date	1 January 2020	1 February 2020	3 January 2020
Project Completion Date	31 December 2022	31 January 2023	3 January 2020
Duration *(in month)*	36	36	3 January 2020
Deadline for Submission of Completion Report	31 December 2023	31 January 2024	3 January 2020

4.4 Please attach photo(s) of acknowledgement of RGC-funded facilities / equipment.

Nil

<u>Part B: The Final Report</u>

5. Project Objectives

5.1 Objectives as per original application

1. Analyze by CFD the plume dispersion of diesel vehicles in a multi-lane road and verify the findings by smoke visualization or other methods at a test site to be set up at a two-lane private road in the THEi Tsing Yi Campus;

2. Design a multi-sensor system to detect the exhaust plume with minimum interference from the vehicles in the neighboring lanes, based on the outcomes of the CFD analysis;

3. Develop an appropriate algorithm for processing and analyzing the data collected by multi-sensor data; and

4. Test-run the prototype MFRSE system developed above in the test site and refine the design of the system as necessary.

5.2 Revised objectives

Date of approval from the RGC:	22 April 2022
Reasons for the change:	Because to carry out smoke visualization at the THEi Tsing Yi site was not feasible, the team need to find alternative method to verify the dispersion models.

1. Analyze by CFD the plume dispersion of diesel vehicles in a single-lane road and verify the findings by suitable experimental data;

2. Develop an appropriate algorithm for processing and analyzing the data collected by the single-sensor system; and

3. Test-run the prototype VRSE system developed above in the test site and refine the design of the system as necessary.

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)

a) CFD Modeling

LES approach was adopted in this project for visualising the emission dispersion process of diesel vehicles. The sub-grid scale flows are simulated using the Wall-Adapting Local Eddy-Viscosity (WALE) model. Mass, energy and momentum conservation, heat transfer, and species transfer equations are numerically solved. Diesel vehicles are relatively clean in CO and HC emissions but are the major source of NO pollution in cities. Therefore, only five gaseous species including N_2, O_2, H_2O, CO_2 and NO are considered. The pressure-velocity coupling scheme is the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) method (reference). The spatial discretization methods are Least Squares Cell Based for gradient, Second Order for pressure, Bounded Central Differencing for momentum and Second Order Upwind for energy and species transport. Transient simulations are carried out with a time step size of 0.01 s. 500 steps are simulated to obtain reliable and developed exhaust plumes. The convergence criteria are residual values of 10^{-3} for continuity, velocity and species, and 10^{-6} for energy. The maximum number of iterations is 30 per time step. Table 1 gives the boundary and initial conditions used in the simulation.

Table 1. Initial and boundary conditions.

Parameter	**Value**
Ambient air temperature	300 K
Ambient air composition (vol.)	79% N_2, 20.95% O_2, 0.05% CO_2, 0% H_2O, 0 ppm NO
Side wind speed	0 m/s
Vehicle speed	60 km/h
Acceleration	0 km/h/s
Exhaust flow rate	71.9 L/s
Exhaust temperature	595 K
Exhaust gas composition (vol.)	74.5% N_2, 11.3% O_2, 7.1% CO_2, 7.1% H_2O, 355 ppm NO

b) Field Experiments

Figure 1(a) shows the layout of the test site which is the coach depot of Eternal East Group (E&E) in San Tin. It has a 60 m paved road connecting to the main access road of the depot.

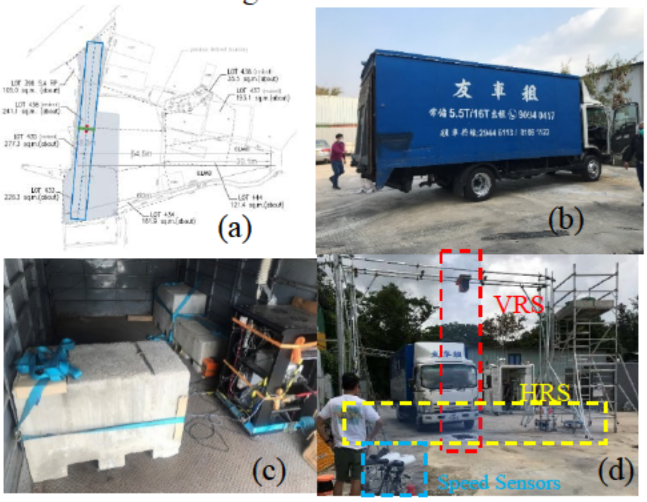

Figure 1. (a) Layout of the test site; (b) The test vehicle; (c) PEMS and loadings on the vehicle; (d) Setup of HRS, VRS and speed sensors.

The portable emission measurement system (PEMS) provided by the EPD was installed to the test vehicles to collect data related to the site conditions (i.e., ambient temperature, humidity), vehicle speed, engine load, and real-time emissions (i.e., air flowrate and emission concentrations) during the testing. The Vertical Remote Sensing (VRS) system was set up to investigate the detection efficiency and calibrate the algorithm of the sensing system. The Horizontal Remote Sensing (HRS) system currently used by the EPD for high-emitter detection was installed to compare the performance of

VRS. The vehicle run with various loadings, speeds and VRS set up (up-down and diagonal) were tested during the field study to accomplish the objectives of the project.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
1. Analyze by CFD the plume dispersion of diesel vehicles in a single-lane road and verify the findings by suitable experimental data;	√	100%
2. Develop an appropriate algorithm for processing and analyzing the data collected by the single-sensor system; and	√	100%
3. Test-run the prototype VRSE system developed above in the test site and refine the design of the system as necessary.	√	100%

6. Research Outcome

6.1 Major findings and research outcome
(Maximum 1 page; please make reference to Part C where necessary.)

Vertical remote sensing (VRS) of on-road vehicle emissions is a promising technology that can greatly improve the measurement efficiency compared to horizontal remote sensing (HRS) that is currently being used by the Hong Kong Environmental Protection Department for enforcement of high-emitting vehicles. Therefore, this project was carried to design and develop a prototype VRS system whose performance was evaluated by CFD modelling, PEMS tests and the current HRS. The major conclusions and recommendations are summarised as follows:

First, the dispersion process of vehicle emissions in the near wake region was simulated by three different turbulence models, including Steady RANS, Unsteady RANS and LES. Compared with RANS based models, LES was able to capture the unsteady eddies in the flow flied, leading a longer plume length and more turbulent distribution of the emission ratios. Therefore, LES approach could capture more details of the flow structures than RNAS based models and should be more accurate for simulating the effect of vehicle emission dispersion on remote sensing measurement. The LES results showed that CO_2 and NO emissions dispersed very quickly in the vehicle near-wake region, leading to unmeasurable concentrations (<0.1% for CO_2 and <10 ppm for NO) in less than 4.0 and1.5 m after the tailpipe exit, respectively. The LES results further revealed that the emission ratio of NO/CO_2 was not constant

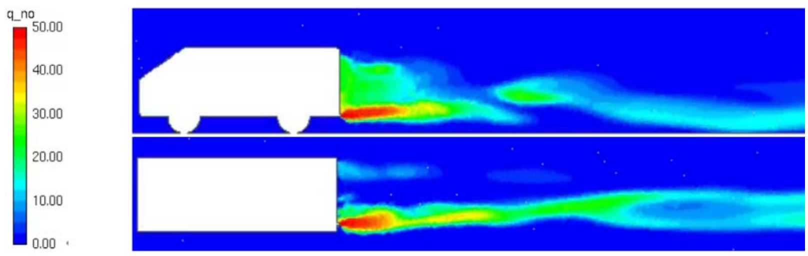

Figure 2. The modelled relative concentration ratio of NO/CO_2 (ppm/%) in the vehicle near-wake region.

in a given exhaust plume (Figure 2). Due to the faster diffusion coefficient of NO in air, NO/CO_2 ratio gradually decreased from tailpipe exit to downstream. If choosing ±10% error relative the raw emission ratio as the threshold for valid measurements, valid remote sensing measurements could only be achieved within 1.0 m after the tailpipe exit, which was even shorter than the measurable exhaust plume. These results all suggested that adopting a shorter remote sensing sampling duration (0.1-0.2 s) with a higher sampling frequency (>200 Hz) could help improve the accuracy of both VRS and HRS systems.

Second, the performance of VRS was evaluated against HRS under real driving conditions. The experimental results showed that NO/CO_2 ratios measured by VRS were obviously lower those measured by HRS (Figure 3). This was mainly because HRS was better aligned with the tailpipe than VRS did. So, the exhaust plume captured by VRS was more dispersed than HRS, leading to lower NO/CO_2 ratios, as observed in the CFD results above. Further, 50% vehicle load was more favourable for VRS measurements than 25% and 0% loads due to the more exhaust plume produced under higher vehicle loads. Generally, the emission ratios measured by VRS and HRS demonstrated reasonable linearity, implying that VRS also had the capability to be used for screening high-emitting vehicles if proper re-calibration was carried out or the high-emitter cut-points developed for HRS were adjusted for VRS.

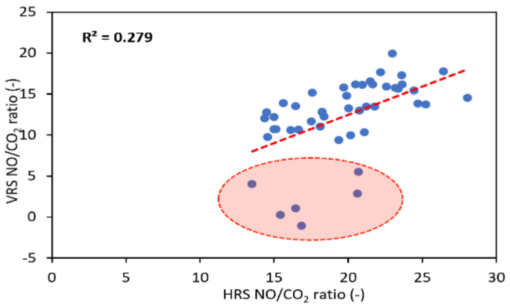

Figure 3. Comparison of NO/CO_2 ratios measured by VRS and HRS under 50% vehicle load.

Third, the performance of VRS, as well as HRS, was examined against PEMS measurements. In comparison to HRS, the correlation between PEMS and VRS was relatively low (Figure 4). This was mainly caused by a few outliners (VRS NO/CO_2 readings lower than 5) due to the fact that VRS was more likely to be affected by side winds and the alignment between VRS beam and tailpipe was more variable between individual tests. Excluding these VRS outliners was able to improve the VRS-PEMS correlation greatly to even higher than that between PEMS and HRS. These results suggested that future VRS development should address the issue of exhaust plume capture and side wind effect, e.g., excluding readings with insufficient CO_2 plumes and using a sweeping broom optical scanning method to replace the current point-to-point optical method.

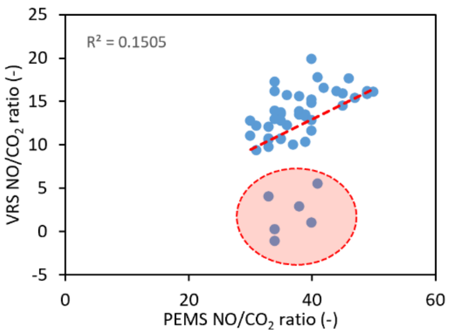

Figure 4. Comparison of NO/CO_2 ratios measured by VRS and PEMS under 50% vehicle load.

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

The study investigated the performance of the VRS and the comparison with HRS and PEMS. The findings show the feasibility of the application of VRS in the monitoring of vehicle emissions. Due to the limitations and conditions of the experimental site, the experiment of this project was set up to investigate the performance of the VRS system in single-lane conditions. To expand the application of the VRS system, it is necessary to prove the performance of the VRS system in dual-lane and multi-lane conditions. The dual-lane and multi-lane studies would enable the investigation of the interference from other vehicles on the road under a range of relative speeds and distances from the test vehicle. In addition, in the real environment, the wind speeds, temperature and solar radiation also affect the detection results of the VRS. In this study, the up-to-down and diagonal setups of VRS were investigated. The up-to-down setup was found to have a more stable performance. However, in the real application, it is necessary to investigate the durability and sustainability of the system. Therefore, further studies are expected to be carried out to promote the application of the VRS in the real environment.

6.3 Research collaboration achieved

(Please give details on the achievement and its relevant impact.)

1) Collaboration on CFD studies were carried out with efforts from HKU and UTS. The collaboration encourages the cross institutes research activities and combine the advantages of research teams from different institutes. The research collaboration also encourage the communication among researchers.
2) Collaboration on technical supports from EPD regarding the emission monitoring equipment. The equipment used in the project was at the same parameter as the one adopted by EPD in the application in HRS system. The PEMS was rented from EPD collaborated research lab. Therefore, the study results from this project could directly make reference with the technologies which are being used by EPD to reveal the feasibility of the VRS in the future application.
3) Collaboration on field experiments with supports form industry. The testing vehicle and driver was provided by Eternal East Group with friendly price. The experiment site was free for use. The collaboration shows good relationship with industry and institutes.

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)

The Horizontal Remote Sensing (HRS) system is adopted as the vehicle emission monitoring technology in HK to identify vehicles with high emissions to protect the outdoor air quality. However, the HRS is only able to monitor one vehicle at a time in single-lane conditions. The Vertical Remote Sensing (VRS) system has the potential to measure the emissions from multiple vehicles simultaneously on multi-lane roads. As the first filed test of VRS in Hong Kong, this project aims to investigate the performance of a VRS system on a single-lane road referring to the findings from the Computational Fluid Dynamics study of this project and compare the performance of the VRS with the HRS and Portal Emission Monitoring System (PEMS) to confirm the feasibility of deploying the VRS system in on-road emission detection applications. The CFD studies were carried out with researchers from UTS and HKU and the results show the patterns of dispersion of the exhaust plume when a typical Medium Goods Vehicle (MGV) is travelling at various speeds and loadings. Field experiments were then carried out to test the prototype of the VRS system with a MGV running at selected speeds and loadings that match the conditions of urban travel. The results of field experiments showed that the VRS system exhibits lower readings mainly due to the effect of side wind on the road. Further study is needed to calibrate the effects of environmental conditions. Nevertheless, the field data confirmed that VRS is a promising technology to monitor emissions from vehicles on multiple-lane roads.

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										
Year of Publication	**Year of Acceptance** *(For paper accepted but not yet published)*	**Under Review**	**Under Preparation** *(optional)*	**Author(s)** *(denote the corresponding 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)*	**This is a Collaborative Work** *(Yes or No)*
2022	December 2021	--	--	Y. Huang*, C.K.C. Lee, Y.S. Yam, W.C. Mok, J.L. Zhou*, Y. Zhuang, N.C. Surawski, B. Organ, E.F.C. Chan	Rapid detection of high-emitting vehicles by on-road remote sensing technology improves urban air quality. Science Advances	2021	NoI	Yes	Yes	Yes
N/A	N/A	N/A	2024	Y.H. LIU, Y. Huang*, C.K.C. Lee, Y.S. Yam, W.C. Mok, J.L. Zhou*, Y. Zhuang, N.C. Surawski, B. Organ, E.F.C. Chan	Study of Performance of Vertical Remote Sensing for Tailpipe Emissions (VRSE) System in Single-lane Road	2023	Yes	Yes	Yes	Yes

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)*	**This is a Collaborative Work** *(Yes or No)*
January / 2023 / Changsha, China	Investigation on Performance of a Converted Remote Sensing System for Diesel Tailpipe Emissions Monitoring	The 7th International Conference on Energy and Environmental Science (ICEES 2023)	2024	Yes	Yes	Yes	Yes
March / 2023 / Lisbon, Portugal	Development of a Cost-Effective Vertical Remote Sensing System for Detecting Emissions from Diesel Medium Good Vehicles	8th World Congress on Civil, Structural, and Environmental Engineering (CSEE'23)	2024	Yes	Yes	Yes	Yes

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

Nil

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]	Bachelor of Engineering (Honours) Civil Engineering	2018	2022
[redacted]	Bachelor of Engineering (Honours) Environmental Engineering and Management	2018	2022
[redacted]	Bachelor of Engineering (Honours) Environmental Engineering and Management	2018	2022

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

N/A

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	2	2	0	0	Type	No.

arising directly from this research project						

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	

15. Technology Transfer Plan (Optional) *(Please write on separate page)*

For project coordinator who may wish to apply for funding support from the Government's Innovation and Technology Fund at a later stage, he / she may provide a technology transfer plan or an update of the technology transfer plan previously submitted in the proposal in a separate page. The plan / update will be passed to the Innovation and Technology Commission for advance information. This update will not be assessed by the RGC. The update should include information such as:

1. Are there any applications that can be spawned from the new ideas evolved? If yes, what are these potential applications?
2. Are there any potential users identified for the new ideas evolved?
3. Are the new ideas evolved patentable or capable of protection by IP laws?
4. Details of the technology transfer activities conducted during the report period.

The vertical remote sensing system was established with the algorithm to estimate the emissions contents of the diesel MGVs. However, the performance of the VRS is relatively lower than the HRS and PEMS due to the environmental conditions interference. The technology is expected to be further optimize and studied in multi-land road. When the interferences have been eliminated, the technlolgy is expected to be made available to the public including the EPD of the HKSAR government and maybe other governments. Such information will help to set up VRSE systems to identify "Dirty MGVs" running around which are polluting our air. EPD and various EPA like government agencies all over the world could benefit from the low-cost, high-speed, and non-invasive system. The single-lane system developed in this project can be further developed into systems that are suitable for multiple-lane applications. The team will continue to explore opportunities to evolve the knowledge gained from this project into patent or IP protected inventions and will report to RGC if identified. The information will be shared with UTS and HKU and in fact other research organizations who are interested in this area aside from the patentable item which we will have different approach.