

# **Improving Remote Sensing of Vehicle Emissions through Monitoring Data, Vehicle Fault Analysis and Tailpipe Temperature Setting**

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## CERTIFICATE OF ORIGINAL AUTHORSHIP

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This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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## List of Publications

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Huang Y, Ng ECY, Yam Y-s, Lee CKC, Surawski NC, Mok W-C, Organ B, Zhou JL, et al. Impact of potential engine malfunctions on fuel consumption and gaseous emissions of a Euro VI diesel truck. *Energy Conversion and Management* 2019; 184: 521-529.

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Huang Y, Lee CKC, Yam YS, Mok WC, Zhou JL, Zhuang Y, Surawski NC, Organ B, Chan EFC. Rapid detection of high-emitting vehicles by on-road remote sensing technology improves urban air quality. *Science Advances* 2022; 8: eabl7575.

## **Abstract**

Air pollution is a serious public health issue around the globe that needs to be addressed. The World Health Organisation (WHO) estimates there are 7 million deaths annually resulting from air pollution, with an estimated 4.2 million of these resulting from ambient air pollution. Pollution from vehicle transport emissions is a significant component of this problem worldwide and pollution control programmes utilising ambient monitoring, annualised vehicle checks for licensing, random testing and so forth conducted by government or commercial organisations have not been able to satisfactorily control and reduce this issue. Traditional detection and testing methods alone are not sufficient to reduce vehicle emissions without the addition of non-intrusive wide spread vehicle fleet monitoring. To deliver such non-intrusive monitoring, Remote Sensing (RS) of vehicle emissions can be utilised. Since September 2014, RS has been deployed by the Hong Kong Environmental Protection Department (HKEPD) to identify Gasoline and Liquefied Petroleum Gas (LPG) fuelled vehicles excessively emitting pollutants. Analysis and assessment of the effectiveness of this HKEPD RS system application by investigating the data from the enforcement programme has been undertaken. This allowed assessment of areas of uncertainty from RS measurements or the available programme knowledge to be identified for potential improvements. Furthermore, this permitted study of RS variability under controlled experimental conditions and also the determination of common engine faults generating high emissions. The knowledge and benefits from these studies are able to be utilised to develop technology and facilitate improvements into the RS programme.

To understand how effective the emissions control programme using RS was, an investigation was undertaken to assess RS data for Gasoline and LPG vehicles collected by the HKEPD from 6<sup>th</sup> January 2012 to 30<sup>th</sup> December 2016. This encompassed a large dataset of 2,144,422 records. The analysis of the data showed the highest Emissions Factors (EFs) for the first two measurement years. This was followed by significant improvements in the LPG vehicle fleet after a maintenance programme in 2013 then followed by further improvements with the influence of RS based enforcement and subsequent effective repairs of high emitting vehicles in 2015 and 2016. The analysis allowed identification of individual vehicles, makes and models of vehicles and years of manufacture where high emitters and problematic models could be assessed and targeted for follow up maintenance and verification testing. The results showed by 2016 that there

were significant EFs reductions of 40.5% HC, 45.3% CO and 29.6% NO for gasoline vehicles. Furthermore, EF reductions of 48.4% HC, 41.1% CO and 58.7% NO were achieved for LPG vehicles. This analysis highlighted the capability this unique emissions enforcement programme utilising RS to effectively reduce vehicle emissions and in turn improve air quality.

Upon implementation of RS enforcement by the HKEPD, it was apparent that there was a significant lack of knowledge in the automotive repair industry's capability to identify various emissions problems and how to implement repairs to pass the mandatory short duration chassis dynamometer emissions test. To help address this, I undertook research for the HKEPD to develop a Toyota Crown Comfort Taxi with relevant engine hardware which could simulate 15 different faults that could impact emissions. Testing of these simulated fault conditions showed they could increase emissions by up to 317%, 782% and 282% for THC, CO and NO<sub>x</sub> respectively. The knowledge developed from this was used to educate the repair industry on the largest emissions fault sources so effective repairs could be performed on high emitting vehicles to return them to an optimum performance condition.

The analysis of the RS programme data showed the technique is mainly effective for identifying gross emitters for earlier emissions standard vehicles (Pre Euro to Euro 5). To improve this situation, testing and calibration devices were built and experiments conducted to assess potential sources of measurement variability. As the experiments with the devices were refined and control improved, they identified that the temperature of exhaust gas being measured impacted the RS measurements. A measured  $\Delta T$  of 14.6°C resulted in 2.6% variation in the RS data for the same CO<sub>2</sub> concentration. As gas temperature variation across a plume could be significantly higher, the RS percentage variation would increase in proportion to the temperature. This could impact every RS measurement, further experiments were developed and confirmed the influence of exhaust gas temperature. Utilising this information, a vehicle-based experiment was designed to determine exhaust plume temperature profiles using a chassis dynamometer with gasoline and diesel test vehicles. From the experimental data, a speed temperature profile was determined. To improve RS reliability, such measurements should occur 50 cm away from the exhaust tailpipe which helps reduce temperature related variability. Applying this will help to improve RS measurement accuracy, with an aim to make RS effective for all types of vehicles regardless of fuel or their size.

# Contents

Acknowledgements.....	ii
List of Publications .....	iii
Abstract.....	v
Definitions and Abbreviations .....	xiv
1. Introduction.....	1
1.1 Research background and motivation.....	1
1.2 Research methodology and objectives.....	6
1.3 Thesis outline.....	7
2. Literature Review.....	9
2.1 Air pollution from vehicle emissions.....	9
2.2 Vehicle emissions testing – the journey begins .....	10
2.3 Vehicle emissions laboratory testing and techniques.....	13
2.3.1 Calculation of vehicle emissions factors.....	23
2.3.2 Real driving emissions.....	33
2.3.3 Comparison of different emissions measurement techniques .....	35
2.4 Optical spectrometry and RS .....	37
2.4.1 The development of optical spectrometry and RS .....	37
2.4.2 Photographic (optical) and satellite RS.....	40
2.4.3 Near field emissions development for RS.....	41
2.5 RS of vehicle emissions.....	42
2.5.1 CO optical measurement development .....	42
2.5.2 HC optical measurement development .....	48
2.5.3 NO optical measurement development .....	50
2.5.4 Further RS developments, inventories and research outcomes.....	52
3. Methodology.....	61
3.1 Remote sensing.....	62
3.1.1 Data collection .....	62



3.1.2	Data analysis .....	66
3.2	Fault simulation in an LPG taxi .....	67
3.2.1	Simulation of malfunctions .....	71
3.2.2	Intake system .....	72
3.1.3	Fuel system .....	73
3.1.4	Ignition system.....	75
3.2.5	Exhaust system.....	76
3.3	Factors affecting RS sensitivity .....	79
3.3.1	Calibration device for improved RS measurement .....	79
3.3.2	Open path measurement technique for improved RS measurement. ....	86
3.3.3	Determination of vehicle exhaust plume temperature profile.....	90
4.	Analysis of RS emissions monitoring data .....	94
4.1	Introduction.....	94
4.2	Results and discussion .....	99
4.2.1	Survey data characteristics.....	99
4.2.2	Overall emissions trends .....	101
4.2.3	Emissions trends of dominant gasoline vehicle models.....	109
4.3	Conclusions.....	114
5	Analysis of simulated engine faults and their impact .....	115
5.1	Introduction.....	115
5.2	Results and discussion .....	120
5.2.1	Regulated gaseous emissions .....	120
5.2.2	Fuel consumption and CO <sub>2</sub> emissions.....	126
5.2.3	Impact on drivability .....	128
5.2.4	Impact on industry training and knowledge.....	129
5.3	Conclusions.....	131
6.	Factors affecting RS sensitivity .....	133
6.1	RS instrumentation calibration.....	134
6.1.1	Initial version of calibration device.....	136

6.2 Refined RS calibration device.....	137
6.2.1. Identification of temperature influence in open path RS measurements.....	145
6.3 Exhaust plume temperature measurements.....	152
6.3.1 Design of experimental measurements .....	153
6.3.2 Vehicle testing .....	154
6.3.3 Assessment of Exhaust Plume measurements.....	167
6.4 Conclusions.....	172
7. Conclusions and future work .....	174
7.1 Conclusions.....	174
7.2 Suggestions for future work.....	177
References.....	179
Appendix A – RS measurement locations .....	190
Appendix B – Signal emissions analyser.....	194
Appendix C – Exhaust emission temperature - drive cycles.....	195

# Figures

Figure 1.1: Thesis structure and inter-connections between chapters.....	8
Figure 2.1: US Emissions testing drive cycles. a) 7 Mode warm up cycle, b) 11 Mode hot cycle, c) EPA Urban Dynamometer Driving Schedule FTP-72 and d) EPA Federal Test Procedure 75 FTP-75/EPA75.....	17
Figure 2.2: European emissions testing drive cycles. a) UNECE Regulation 15 - Urban Drive Cycle, b) UNECE Regulation 83 - New European Drive Cycle and c) WLTC for Class 3b vehicles .....	21
Figure 2.3: Emissions testing laboratory setup. ....	22
Figure 2.4: Kirchhoff and Bunsen’s first spectroscope (Kirchhoff and Bunsen, 1860).....	39
Figure 2.5: CO RS instrument detector schematic (Bishop et al., 1989). ....	43
Figure 2.6: CO RS system schematic (Stedman and Bishop, 1991). ....	44
Figure 2.7: CH <sub>2</sub> combustion characteristics for CO and CO <sub>2</sub> (Stedman and Bishop, 1991).....	45
Figure 2.8: Concept of GMRL RS system configuration for CO measurement (Stephens and Cadle, 1991).....	47
Figure 2.9: Concept of DU 2 <sup>nd</sup> generation RS configuration for CO and HC measurement (Guenther et al., 1991). ....	49
Figure 2.10: Concept of DU 3 <sup>rd</sup> generation RS configuration for CO, HC and NO measurement (Zhang et al., 1996b).....	51
Figure 2.11: Concept of EDAR measurement configuration (Dallmann, 2018). ....	57
Figure 3.1: The ETC-S420 RS system.....	62
Figure 3.2: The locations of RS measurement sites in Hong Kong. ....	63
Figure 3.3: Setup of a typical RS measurement site in Hong Kong, China. ....	65
Figure 3.4: The study vehicle (a) and its HKTET speed chart (b). ....	70
Figure 3.5: Modified Intake system hardware for experimental testing (a – c). ....	73
Figure 3.6: Modified Fuel system hardware for experimental testing (a – b).....	75
Figure 3.7: Worn Ignition system hardware for experimental testing. ....	76
Figure 3.8: Modified Exhaust system hardware for experimental testing (a – c). ....	78
Figure 3.9: Initial trial calibration device schematic.....	80
Figure 3.10: Concept for the refined calibration device for testing. ....	82
Figure 3.11: The concept of gas plunger system for calibration device .....	82
Figure 3.12: Refined calibration device drawing model.....	83
Figure 3.13: Thermocouple setup for exhaust gas monitoring .....	84
Figure 3.14: RS testing with resistance load bank connected.....	86
Figure 3.15: Proposed open path RS testing schematic .....	88

Figure 3.16: Vehicle exhaust plume temperature test experimental layout. Minivan art (SmartDraw, 2021) .....	91
Figure 3.17: EET drive cycle 7 – 15 km/h steps.....	93
Figure 4.1: Emission factors of HC (a), CO (b) and NO (c) for gasoline and LPG vehicles during 2012-2016.....	103
Figure 4.2: Emission factors for all LPG vehicle and taxi measurements.....	106
Figure 4.3: Gasoline emission factors by survey year and vehicle year of manufacture .....	108
Figure 4.4: Gasoline emission factors for dominant measured vehicle models during 2012-2016. The error bars represent the 95% confidence interval over the mean.....	110
Figure 5.1: THC emissions results for malfunctions. Error bars indicate standard deviations and the dotted black line indicates Euro 3 THC emissions limit. (For Euro 2 standard, THC emissions are combined with NO <sub>x</sub> ).....	121
Figure 5.2: CO emissions results for malfunctions. Error bars indicate standard deviations and the dashed orange line indicates Euro 2 CO emissions limit. Dotted black line indicates Euro 3 CO emissions limit.....	122
Figure 5.3: THC+NO <sub>x</sub> emissions results for malfunctions. Error bars indicate standard deviations, and the dashed orange line indicates Euro 2 THC+NO <sub>x</sub> emissions standard. ....	124
Figure 5.4: NO <sub>x</sub> emissions results for malfunctions. Error bars indicate standard deviations and the dotted black line indicates Euro 3 NO <sub>x</sub> emissions limit.....	124
Figure 5.5: Fuel economy results for malfunctions. Error bars indicate standard deviations and the black dashed line represents the baseline fuel economy.....	127
Figure 5.6: CO <sub>2</sub> emissions results for malfunctions.....	128
Figure 6.1: Refined RS calibration device – schematic (a) and test equipment setup (b). ....	138
Figure 6.2: Refined calibration device emissions measurements from EMS 5003 gas analyser (a and b) and from RS device (c and d). ....	139
Figure 6.3: Comparison of EMS 5003 gas analyser (a and b) and RS (c and d) data with exhaust gas temperatures.....	140
Figure 6.4: Resistor load bank test for revised calibration device. ....	143
Figure 6.5: Equipment layout for open path experiment testing.....	146
Figure 6.6: Diesel open path experiment test results. ....	147
Figure 6.7: Gasoline open path experiment test results. ....	150
Figure 6.8: Experimental setup of vehicle and thermocouples for exhaust plume temperature logging. ....	155
Figure 6.9: First vehicle exhaust plume temperatures at discrete measurement points from tailpipe. ....	156
Figure 6.10: Second vehicle - exhaust plume temperatures at discrete measurement points from tailpipe. ....	158

Figure 6.11: Second vehicle exhaust plume temperature profile.....	160
Figure 6.12: EET drive cycle 6 exhaust plume temperature profile from Nissan Lafesta testing. .....	161
Figure 6.13: Third vehicle exhaust plume temperature profile - test 1.....	162
Figure 6.15: Fourth vehicle - sample result for revised thermocouple array spacing for exhaust plume temperature test.....	165
Figure 6.16: Fourth vehicle final consolidation measurements with revised thermocouple array spacing for exhaust plume temperature tests. ....	166
Figure 6.17: Combined gasoline exhaust plume temperature profile measurements with 50 cm cut point indication. ....	170
Figure C1: Original drive cycle - 5 kph steps, 20 - 45 kph, 180s duration .....	197
Figure C2: Drive cycle 1 - 15 kph steps, 15 - 90 kph, 100s duration .....	197
Figure C3: Drive cycle 2 - 15 kph steps, 15 - 90 kph, 60s duration .....	198
Figure C4: Drive cycle 3 – 5 kph steps, 15 - 90 kph, 60s duration.....	198
Figure C5: Drive cycle 4 – 10 kph steps, 10 - 90 kph, 60s duration.....	199
Figure C6: Drive cycle 5 – 5 kph steps, 10 - 90 kph, 60s duration.....	199
Figure C7: Drive cycle 6 – 15 kph steps, 15 - 90 kph, 200s duration.....	200
Figure C8: Drive cycle 7 – 15 kph steps, 15 - 90 kph, 240s duration.....	200

## Tables

Table 2.1: Summary of WLTC test cycles.....	20
Table 2.2: CVS Volume flow parameters.....	24
Table 2.3: Standardised density values of different gases. ....	25
Table 2.4: Mass emissions calculation parameters. ....	25
Table 2.5: Corrected emissions calculations parameters .....	26
Table 2.6: Dilution factor regulation parameters. ....	27
Table 2.7: Comparison of different emissions measurement testing techniques .....	36
Table 2.8: Timeline of major RS testing developments.....	52
Table 3.1: European emissions standards and durability requirements. ....	64
Table 3.2: Specification of the vehicle used in this study.....	68
Table 3.3: Experimental test setup and sequence.....	85
Table 3.4: Resistance load bank setting and thermocouple locations used for testing. ....	87
Table 3.5: Resistance load bank setting of gasoline open path RS experiment. ....	89
Table 3.6: Thermocouple array configurations used for exhaust plume measurement.....	92
Table 4.1: RS emissions limit cut points for identification of high emitting vehicles.....	98
Table 4.2: Number of valid vehicle emission measurements by RS during 2012-2016. ....	99

Table 4.3: Most frequently measured gasoline vehicles in the RS database.....	100
Table 4.4: Number of LPG vehicles and associated RS measurements.....	101
Table 4.5: Statistics on number of ETNs issued (1/9/2014 to 31/12/2016) .....	101
Table 4.6: Average vehicle age (years) for main LPG and dominant gasoline models during RS survey.....	112
Table 5.1: Summary of relative change from baseline test of emissions factors of simulated malfunctions.....	121
Table 5.2: Summary of relative change from baseline test of CO <sub>2</sub> emissions factors and fuel economy (l/100km) of simulated malfunctions .....	126
Table 6.1: RS and temperature data comparison .....	141
Table 6.2: Diesel open path testing operational loading and individual test variables .....	146
Table 6.3: Diesel CO <sub>2</sub> RS and temperature values .....	148
Table 6.4: Gasoline open path testing operational loading and individual test variables .....	149
Table 6.5: Gasoline CO <sub>2</sub> RS and temperature values .....	151
Table 6.6: EET drive cycle description and parameters .....	161
Table A1. RS measurement location data .....	190
Table B1. Signal Maxsys900 emissions analyser system accuracy.....	194
Table C1. EET drive cycles numerical data tables .....	195

## Definitions and Abbreviations

### Acronyms

AFR	Air Fuel Ratio
AQO	Air Quality Objectives
BAR	California Bureau of Automotive Repair
BC	Black Carbon
CARB	California Air Resources Board
CFR	Code of Federal Regulations (US)
CN <sub>x</sub>	China National Emission Regulation (x = UNECE regulation level)
CO	Carbon monoxide
CLA	Chemiluminescence Analyser
CO <sub>2</sub>	Carbon dioxide
conc.	Concentration
CVS	Constant Volume Sampler
DU	University of Denver
ECU	Engine Control Unit
EET	Exhaust Emission Temperature
EF	Emission Factor
EGR	Exhaust Gas Recirculation
EMS	Engine Management System
ETN	Emissions Test Notice
FEAT	Fuel Efficiency Automobile Test

FID	Flame Ionisation Detector
FSP	Fine Suspended Particles
GDI	Gasoline Direct Injection
GEEC	Green Environmental Emission Consultant Ltd.
GMRL	General Motors Research Laboratories
HC	Hydrocarbons
HKEPD	Hong Kong Environmental Protection Department
HKTET	Hong Kong Transient Emissions Test
HP	Horsepower
IDI	Indirect Injection
I/M	Inspection Maintenance
IM240	Inspection Maintenance 240 second chassis dynamometer emissions test
IVE	Institute of Vocational Education
JCEC	Jockey Club Emissions Centre
kW	Kilowatts
LPG	Liquified Petroleum Gas
MPV	Multi-Purpose Vehicle
Nd:YAG	Neodymium-doped yttrium aluminium garnet
NDIR	Non-Dispersive Infra-Red
NEDC	New European Drive Cycle
NMHC	Non-Methane Hydrocarbons
NG	Natural Gas (Methane – CH <sub>4</sub> )
Nm	Newton metres



NO	Nitrogen monoxide
NO <sub>2</sub>	Nitrogen dioxide
NO <sub>x</sub>	Total Oxides of Nitrogen
O <sub>3</sub>	Ozone
OBD	On Board Diagnostics
PEMS	Portable Emissions Measurement System
PLB	Public Light Bus (minibus)
PMR	Power to Mass Ratio
PM <sub>2.5</sub>	Particulate Matter of 2.5 micrometer or less
Q <sub>P</sub>	Concentration ratio of pollutant P over CO <sub>2</sub>
rpm	Revolutions per minute
RDE	Real Driving Emissions
RS	Remote Sensing
RSP	Respirable Suspended Particles
TC	Particulate Carbon
THC	Total Hydrocarbons
TWC	Three Way Catalytic converter
UFP	Ultra-Fine Particles
UNECE	United Nations Economic Commission for Europe
USEPA	United States Environmental Protection Department
UV	Ultra Violet
VW	Volkswagen

## Symbols

$Vol_{CVS}$	CVS Test volume of dilute gas
$K_V$	Venturi Calibration co-efficient
$Temp_{CVS}$	CVS Test Ambient Temperature
$Press_{CVS}$	CVS Barometric Pressure
$P_R$	Barometric Pressure
$V_R$	Volume of dilute gas for test
$T_R$	Ambient Temperature for test
$P_C$	Regulation Barometric Pressure
$V_C$	Corrected volume of dilute gas for test
$T_C$	Regulation Ambient Temperature
$M_i$	Pollutant mass emission $i$
$V_C$	Corrected volume of diluted exhaust gas
$Q_i$	Pollutant density 'i'
$K_H$	Humidity correction factor for oxides of nitrogen only
$C_i$	Corrected concentration of pollutant in diluted exhaust gas (in ppm)
$d$	Test cycle distance
$C_i$	Corrected concentration of pollutant $i$ in diluted exhaust gas
$C_e$	Measured pollutant concentration $i$ in exhaust sample
$C_d$	Pollutant concentration $i$ in air
DF	Dilution Factor
$C_{CO}$	Gas concentration of CO in sample bag
$C_{H_2O}$	Gas concentration of H <sub>2</sub> O in sample bag

$C_{H_2O-DA}$	Concentration of H <sub>2</sub> O in dilution air
$C_{H_2}$	Concentration of H <sub>2</sub> in sampling bag
$C_{NMHC}$	Corrected concentration of NMHC (carbon equivalent)
$C_{THC}$	Corrected concentration of THC (carbon equivalent)
$C_{CH_4}$	Corrected concentration of CH <sub>4</sub> (carbon equivalent)
$R_{fCH_4}$	FID response factor to CH <sub>4</sub>
H	Absolute Humidity
$R_a$	Relative Humidity
$P_d$	Saturation Vapour Pressure at Ambient Temperature
$P_B$	Barometric Pressure
T	Test Temperature
$\int_{t_1}^{t_2} C_{HC} \cdot dt$	integral of recording for heated FID for test.
$C_e$	HC concentration of C <sub>i</sub> is substituted for CHC in equations.
$M_p$	Particulate emission
$V_{mix}$	Corrected volume of diluted exhaust gas
$V_{ep}$	Volume of exhaust flow through particulate filter
$P_e$	Particulate mass on filter(s)
$P_R$	Barometric Pressure
$V_R$	Gas volume flow through filters
$T_R$	Test Ambient Temperature
$P_C$	Regulation Barometric Pressure
$V_C$	Corrected gas volume flow through filters
$T_C$	Regulation Ambient Temperature

$m_{\text{corr}}$	Corrected PM mass for buoyancy
$m_{\text{uncorr}}$	Uncorrected PM mass for buoyancy
$\rho_{\text{air}}$	Air density
$\rho_{\text{weight}}$	Calibration weight density for span balance
$\rho_{\text{media}}$	PM sample medium density (filter)
$P_{\text{abs}}$	Absolute pressure in balance chamber
$M_{\text{mix}}$	Molar mass of air in balance chamber (28.836 g/mol)
$R$	Molar gas constant (8.314 g/mol)
$T_{\text{amb}}$	Absolute ambient temperature in balance chamber.
$\Delta T$	Temperature difference
$N$	particulate number emissions
$V$	Corrected volume of the diluted exhaust gas
$K$	calibration factor for correction of particulate number counter measurements.
$\bar{C}_s$	Corrected concentration of particulates of diluted exhaust gas.
$\bar{f}_r$	mean particulate concentration reduction factor