UNIVERSITY OF TECHNOLOGY SYDNEY

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

by Bruce Douglas Organ

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University of Technology Sydney

Faculty of Engineering and Information Technology

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Bruce Douglas Organ declare that this thesis is submitted in fulfilment of the requirements for the reward of Doctor of Philosophy, in the School of Civil and Environmental Engineering / Faculty of Engineering and Information Technology at the University of Technology Sydney.

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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Signature: Production Note:
Signature removed prior to publication.

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List of Publications

Journal articles derived from this PhD:

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Organ B, Huang Y, Zhou JL, Yam Y-S, Mok W-C, Chan EFC. Simulation of engine faults and their impact on emissions and vehicle performance for a liquefied petroleum gas taxi. *Science of The Total Environment* 2020; 716: 137066.

Organ B, Huang Y, Zhou JL. Determination of exhaust plume temperature profiles for remote sensing applications. Under preparation 2022.

Conference proceedings from this PhD:

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Other related journal articles:

Huang Y, Organ B, Zhou JL, Surawski NC, Hong G, Chan EFC, et al. Emission measurement of diesel vehicles in Hong Kong through on-road RS: Performance review and identification of high-emitters. *Environmental Pollution* 2018; 237: 133-142.

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Huang Y, Mok W-C, Yam Y-S, Zhou JL, Surawski NC, Organ B, et al. Evaluating in-use vehicle emissions using air quality monitoring stations and on-road remote sensing systems. *Science of The Total Environment* 2020; 740: 139868.

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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 Liquified 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 6th January 2012 to 30th 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_x 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 ΔT of 14.6°C resulted in 2.6% variation in the RS data for the same CO_2 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

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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_x	China National Emission Regulation (x = UNECE regulation level)
CO	Carbon monoxide
CLA	Chemiluminescence Analyser
CO_2	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_4)
Nm	Newton metres

NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Total Oxides of Nitrogen
O_3	Ozone
OBD	On Board Diagnostics
PEMS	Portable Emissions Measurement System
PLB	Public Light Bus (minibus)
PMR	Power to Mass Ratio
$PM_{2.5}$	Particulate Matter of 2.5 micrometer or less
Q_P	Concentration ratio of pollutant P over CO_2
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_{H2O}	Gas concentration of H_2O in sample bag

C_{H2O-DA}	Concentration of H_2O in dilution air
C_{H2}	Concentration of H_2 in sampling bag
C_{NMHC}	Corrected concentration of NMHC (carbon equivalent)
C_{THC}	Corrected concentration of THC (carbon equivalent)
C_{CH4}	Corrected concentration of CH_4 (carbon equivalent)
Rf_{CH4}	FID response factor to CH_4
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 Ci 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_{corr}	Corrected PM mass for buoyancy
m_{uncorr}	Uncorrected PM mass for buoyancy
ρ_{air}	Air density
ρ_{weight}	Calibration weight density for span balance
ρ_{media}	PM sample medium density (filter)
P_{abs}	Absolute pressure in balance chamber
M_{mix}	Molar mass of air in balance chamber (28.836 g/mol)
R	Molar gas constant (8.314 g/mol)
T_{amb}	Absolute ambient temperature in balance chamber.
ΔT	Temperature difference
N	particulate number emissions
V	Corrected volume of the diluted exhaust gas
K	calibration factor for correction of particulate number counter measurements.
$\overline{C_s}$	Corrected concentration of particulates of diluted exhaust gas.
$\overline{f_r}$	mean particulate concentration reduction factor