UNIVERSITY OF SOUTHAMPTON

Faculty of Engineering and the Environment

Civil, Maritime and Environmental Engineering and Science Unit

Variations in Carbon Emissions from Vehicles at Signalised Intersections

by

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Thesis for the degree of Doctor of Philosophy

September 2011

ABSTRACT

University of Southampton

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Carbon emissions from road transport make up 20% of the total greenhouse gas emissions in the UK. Therefore, reducing carbon emissions from road transport is significant in reaching carbon reduction targets. In urban areas where signal controlled intersections are common, carbon emissions from vehicular traffic can be aggravated by aggressive driving and interruptions induced by traffic control. Considerable variations in speed and acceleration profiles could be observed between high carbon and low carbon driving. In view of the immediate effects that changing driving behaviour could have on carbon emissions without extra cost, this study had investigated the variations in carbon emissions at signalised intersection, which includes the scale of impacts of changing driving behaviour and flow interruption on carbon emissions. Characteristics which lead to high CO_2 emissions could then be modified by addressing the behavioural change and control strategies. High frequency real world driving data was collected using the TRG highly instrumented vehicle. The vehicle was equipped with a number of on-board systems, i.e., on-board emission measurement system, velocity box, on-board diagnostic unit, Dashdyno and video recorder. Aggressive and economical driving styles observed for two drivers during initial tests showed distinct differences in terms of speed profiles and fuel consumption. These initial tests were used to examine the nature and scale of potential impacts on fuel consumption and to design main field tests. Natural driving observed from twenty nine drivers from the main field tests also showed significantly different levels of carbon emissions at signalised intersections, which were caused by variations in both driving behaviour and traffic control. In terms of driving behaviour, changing the worst driving to the best driving during interrupted driving was found to reduce CO_2 emissions significantly. The carbon reductions were collectively contributed by 1) applying soft acceleration and keeping acceleration below $0.6m/s^2$ during the acceleration mode and 2) reducing leaving speed at intersections, 3) practising smooth deceleration and stable speed during the deceleration mode and 4) applying the idle-stop system. Carbon emission rates of different vehicles may vary from one to another. However, it was found that the amount of carbon savings demonstrated in this study could be possibly achieved by other internal combustion vehicles of the same class, and by hybrid electric vehicles to a lesser extent. In this study, changing driving behaviour is recommended as a cost effective way to achieve carbon reduction.

CONTENTS

DECLARATION OF AUTHORSHIP

I, Koh Moi Ing declare that the thesis entitled "Variations in Carbon Emissions from Vehicles at Signalised Intersections" and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- none of this work has been published before submission.

Signed: …………………………………………………………………..

Date:……………………………………………………………………….

DEDICATION

This thesis is dedicated to my beloved mother.

ACKNOWLEDGEMENTS

Foremost, I would like to express my deepest gratitude to Emeritus Professor Mike McDonald and Co-supervisor Dr. Tim Felstead for their guidance and support and for sharing their insight and expertise.

My sincere appreciation goes to Brian Mould and Doug Robinson from Transport Research Group laboratory for their assistance in the field test. Also, special thanks to all the volunteers for participating in the field test.

I extend my sincerest gratitude to Janne Ruostekoski, Valerie Sewell and Carol Edwards for their support and comments on this thesis.

I convey my special acknowledgments to the external examiner, Prof. Margaret Bell and internal examiner, Dr. Nick Hounsell for their constructive and inspiring comments during my PhD viva.

I would like to thank Universiti Teknologi PETRONAS for their financial support to complete this study.

I am truly grateful to my entire family at home and friends in the UK as well as in Malaysia for their endless support and inspiration.

Last but not least, to my special one, thank you for coming into my life.

GLOSSARY

- Driving Behaviour – describes how drivers drive the vehicle and includes decisions on stopping, speed, acceleration, deceleration, braking, etc.
- Driving Mode – represents a certain driving situation that is similar in terms of activity, e.g., acceleration mode, idle mode, deceleration mode, cruise mode, etc.
- Fuel Economy/Efficiency – is the distance travelled per unit of fuel used, or vice versa, commonly expressed as miles per gallon (mpg) or litres per 100km (l/100km).
- Driving Case – represents data on particular segments of roads or intersections that can be used to compare driving behaviour.
- Economical driving – is a driving style used in this study that aims to achieve minimum CO_2 emissions/fuel consumption (refer Section 5.2 Test Route).
- Aggressive driving – is a driving style used in this study that is more aggressive than economical driving, e.g., uses of hard acceleration, heavy braking, etc., that resulted in higher CO_2 emissions/fuel consumption (refer Section 5.2 Test Route).
- Natural driving – is the normal driving behaviour of the volunteered drivers, without following any driving instructions.
- Acceleration – is the rate of change of speed in time, in the unit of metres per square second (m/s^2).
- Fuel consumption – is the amount of fuel consumed over a period of time, in the unit of grams per second (g/s) or litre per hour (l/h).
- Cumulative/total fuel consumption is refer to the total fuel consumed under particular driving mode, e.g., acceleration, deceleration, idle, positive acceleration, negative acceleration, braking, etc.

NOMENCLATURE

1E	: Economical driving performed by driver 1
1A	: Aggressive driving performed by driver 1
2E	: Economical driving performed by driver 2
2A	: Aggressive driving performed by driver 2
Acc	: Acceleration
ANOVA	: Analysis of variance
CANBUS	: Controlled Area Network Bus
Dec	: Deceleration
EV	: Electric Vehicle
ICE	: Internal Combustion Engine
ICV	: Internal Combustion Vehicle
IV	: Instrumented Vehicle
GPS	: Global Positioning System
HEV	: Hybrid Electric Vehicle
kph	: Kilometres per hour
l/h	: Litres per hour
lowess	: Locally weighted scatterplot smoothing
mpg	: Miles per gallon (imperial)
MSE	: Mean Squared Error
OBS-2200	: On-board Emission Measurement System (Horiba model 2200)
PEMS	: Portable Emission Measurement System
rpm	: Revolutions per minute
SSE	: Sum of Squared Error
Stata	: Statistical software package (StataCorp, 1985)
TRG	: Transportation Research Group in University of Southampton
VBOX-III	: Velocity Box III
VIF	: Variance inflation factor

Chapter 1 Introduction

1.1 Background

Carbon dioxide (CO_2) is the major greenhouse gas (GHG) as a result of power generation, agriculture, industrialisation, construction, and deforestation activities (Solomon, Change et al. 2007). These activities alter the chemical composition of the atmosphere leading to climate change that is currently one of the greatest environmental concerns. In the UK and U.S., CO_2 accounted for 85% of the total GHG emissions in the year 2008 (Department of Energy & Climate Change 2010; U.S. Environmental Protection Agency 2010). Of the total UK domestic GHG emissions, 18.9% (118.4 million tonnes) were produced by road transport. Of the total carbon emissions in road transport, 61.5% were generated by passenger cars, 20% were produced by heavy goods vehicles and the rest from light duty vehicles (Department for Transport 2010).

Considering the impact of massive carbon footprints from road transport, various efforts have been made to reduce carbon emissions generated by vehicles on the road. These include improvement in fuel efficiency, clean energy development and transport demand management. Vehicles with improved engine efficiency, lower tailpipe emissions and better engine control have become increasingly common in the automobile market these days. However, these technologies take time to penetrate into existing vehicle fleets. On the other hand, transport demand management optimises the traffic movement and influences driver behaviour.

Large carbon savings from influencing driver behaviour can be better achieved at locations where carbon emissions are higher, such as at signalised intersections. Traffic interruptions at signalised intersections, which includes delay and stop-and-go events increase emissions (Pandian, Gokhale et al. 2009). For instance, fuel consumption in urban driving could be twice the fuel consumption on a ring road because of interruptions in flow (De Vlieger, De Keukeleere et al. 2000). Maximum carbon savings from improved traffic flow can be best achieved between 10 mph and 30 mph speed range (Barth and Boriboonsomsin 2008), which is similar to vehicle speed at urban intersections. As much as 45% CO_2 could be saved if traffic were to be smoothed to the steady-state (Barth and Boriboonsomsin 2008). These studies imply that a significant amount of carbon can be cut by changing the driving at signalised intersections, typically in terms of speed and acceleration. Specifically, this research has focused on the following areas as these could be the most cost effective ways of reducing carbon emissions from the road without inducing an extra cost.

- CO_2 variations at signalised intersections.
- Characteristics of Low carbon driving at signalised intersections.

1.2 Objectives

The aim of this study has been to improve the understanding of variations in carbon emissions at signalised intersections because of different driving behaviours and to recommend driving strategies that can reduce carbon emissions.

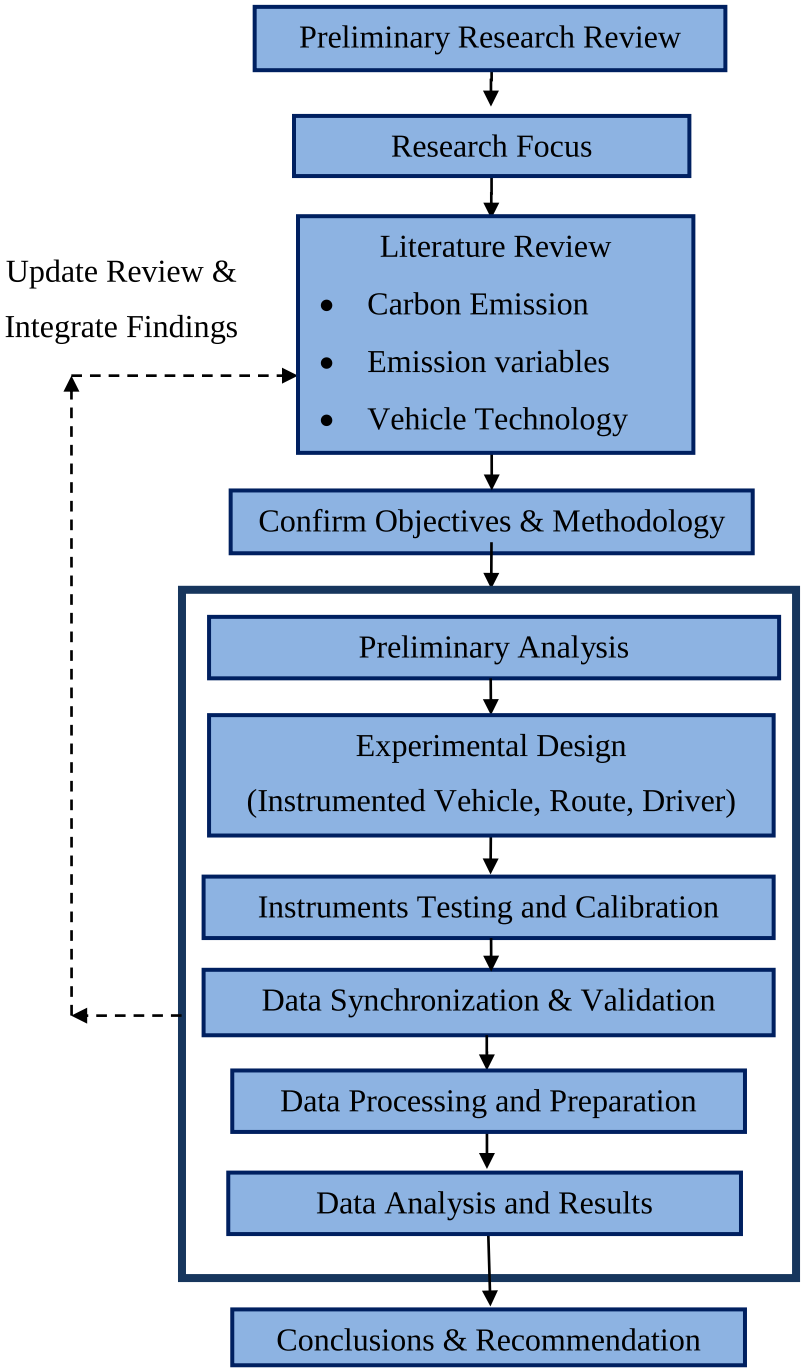
Specific objectives are:

- To find the differences in driving behaviour within and between drivers and show that changing driving behaviour can lead to significant carbon savings.
- To quantify the amount of carbon savings from changing high carbon driving to low carbon driving.
- To propose driving strategies that lower carbon emissions at signalised intersections.

1.3 Research Approach

The research approach is summarised in Figure 1-1.

Figure 1-1: Research Approach



1.4 Thesis Layout

The objectives, research approach and knowledge gaps are presented in Chapter 1.

Carbon emissions from transport, its impact and mitigation strategies adopted by the transport sector are discussed in Chapter 2. These include the propulsion technologies (hybrid and electric vehicles, biofuels, hydrogen and fuel cells) and changing driving behaviour. The latter includes reviews on vehicle operating conditions and vehicle attributes that affect carbon emissions.

The methodology is explained in Chapter 3, which is comprised of various steps, e.g., choosing the test method, designing test procedures and participant recruitment procedures, identifying and calibrating instruments, design the sampling method and choosing the test route.

The data processing approach is presented in Chapter 4, which included synchronising the datasets obtained from various instruments, validating the variables from different instruments for accuracy, extracting and labelling the data and smoothing the variable to remove potential outliers.

The preliminary analysis and findings are presented in Chapter 5 using data obtained from the initial field test. This includes planning of the test route, selection of the intersections, identifying the data and variables, validation of the variables, defining the intersection boundary and analysis of the data. Besides the preliminary findings, some design issues related to the methodology for Chapter 3 are also discussed.

The clustering of driving behaviour and results derived from the analysis are discussed in Chapter 6.

The main analysis is presented in Chapter 7, which includes exploring the relationship between carbon emissions and fuel consumption, investigating the effects of individual variables on carbon emissions and investigating driving behaviour for every driving mode.

Finally, conclusions and recommendation are presented in Chapter 8.

Chapter 2 Literature Review

2.1 Introduction

The carbon issues, i.e., the significant carbon footprint from the transport industry and strategies used to decarbonised transport are discussed in this chapter. The decarbonising strategies are explored in terms of vehicle technology, alternative fuels, transport management and changing driving behaviour. Changing driving behaviour is especially the focus of this study as it is perceived as one of the most cost effective strategies that gives immediate effect. This review also focuses on factors used in quantifying driving behaviour and its effects on carbon emissions.

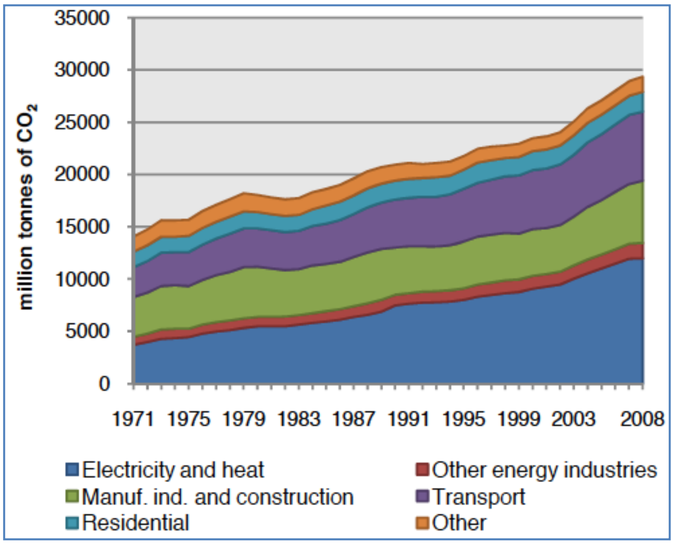
2.2 Carbon Emissions from Road Transport

The transport sector is the second largest carbon emitter after the energy sector; 22.5% of the total global CO_2 emissions in 2008 come from the transport industry (International Energy Agency 2010).CO_2 emissions from transport made up 27.1% (1886.1 Mega tonnes of CO_2) of the total U.S. greenhouse gas emissions (U.S. Environmental Protection Agency 2010) and 26% (173.9 Mega tonnes of CO_2) of the UK total greenhouse gas emissions (Department for Transport 2010). According to Metz et al, 2007, 95% of the transport energy come from oil-based fuel. Therefore, CO_2 emissions of transport are commonly estimated based on energy use, e.g., fuel combustion (Metz, Davidson et al. 2007). Of all transport modes, shares of road transport in total CO_2 emission produced by fuel combustion was 16.5% globally (4848.4 Mt CO_2), 25.7% for North America (1582.7 Mt CO_2), 17.9% in the Pacific (283.1 Mt CO_2) and 22.5% for the UK (115 Mt CO_2) (refer Appendix A: CO_2 Emissions by Sector).

The transport sector produces a significant proportion of the carbon emissions and, in addition, its total amount of carbon emissions has been growing since 1971 (Figure 2-1). By 2008, CO_2 emissions from road traffic had increased 47.5% compared with 1990's level (International Energy Agency 2010). The projected annual CO_2 emissions from transport by 2050 is double of the CO_2 emission in 2007 (IPCC 2007). However, this might change if more decarbonising technologies replaced existing vehicle fleets or travel pattern significantly changed.

Considering road transport is the largest and continuously increasing source of carbon emissions in the transportation industry, the sector has good potential to achieve the required carbon reduction in the coming decades (Department for Transport 2007).

Figure 2-1: Global CO_2 emissions by sector (International Energy Agency 2010)



2.2.1 Impacts of Carbon Emissions

Despite all the attempts to reduce the greenhouse gas (GHG) emissions, the world still experiences continuous growth of GHG emissions. It is widely speculated that the greatest impact of increasing GHG for now, and in the future, is climate change and its consequences (IPCC 2007; Pachauri and Reisinger 2007). The strongest evidence of this theory is the increase of 0.3°C-0.6°C in global temperature in the last century, where eleven out of the twelve years between 1995 and 2006 were ranked the warmest since 1850 (IPCC 2007). The report also suggested that the strong warming phenomenon in the last 50 years cannot be explained by natural climate variations alone, but by human activities. Several climate models predict an increase of 1.1°C to 6.4°C in global temperatures by the end of the 21st century, based on different emission scenarios (IPCC 2007; Solomon, Qin et al. 2007). The rise of sea levels, and the change in precipitation and local climate conditions are consequences of the increase in the average global temperature. These changes are believed to impact the world environment, economy and society through flooding, food shortage, diseases, severe water shortage and loss of tropical forests (Pachauri and Reisinger 2007).

2.2.2 Carbon Abatement Strategies in Road Transport

Due to the understanding of the potential impact of increasing carbon emissions, two intergovernmental agreements for five-year carbon abatement between 2008 and 2012 were reached, namely United Nations Framework Convention on Climate Change (1992) and Kyoto Protocol (1997). The countries signing the agreement achieved consensus to reduce the emissions of six greenhouse gases[1] by 2012 to 5.2% below 1990 level. Besides Kyoto Protocol, the UK targets to reduce 12.5% of CO_2 level from the 1990 level, and moves towards a 20% reduction of CO_2 by 2010 (DETR 2000). Beyond that, the Climate Change Act covers greenhouse gas abatement efforts up to 2050, which consisted of four legally binding carbon budgets to achieve 22%, 28%, 34% and 80% carbon reductions below the 1990 level by 2012, 2017, 2022 and 2050, respectively (Department for Transport 2010). Other than the government commitment, the car industry, i.e., European Car Manufacturer Association (ACEA) is also targeting a reduction of CO_2 emissions from an average of 169 g/km at the year 2000 to 125 g/km by year 2015 (Silva, Ross et al. 2009).

There are a number of carbon abatement strategies acknowledged by the road transport stakeholders. These include the application of new engine and fuel technologies, smaller and lighter vehicles and mobility management (Shaheen and Lipman 2007). The engine and fuel strategies can be divided into long term and short term strategies (Department for Transport 2007; Hoen, de Wilde et al. 2009). The short term strategies are 1) incremental enhancements to petrol and diesel engines, 2) existing or near market petrol-electric or diesel-electric vehicles and 3) existing or near market biofuels, which are the first generation biofuels made from sugar, starch crops, oil crops or wastes. The long term strategies are 1) plug-in hybrid, 2) full-electric vehicles, 3) second generation biofuels made from various biomasses and 4) hydrogen and fuel-cell vehicles. The long term strategies offer better reduction potential, because of substantial carbon reduction prospective and potential in completely decarbonising road transport (Department for Transport 2007). It is estimated that these strategies could reduce carbon emissions by 65%-95% when fully implemented (Hoen, de Wilde et al. 2009).

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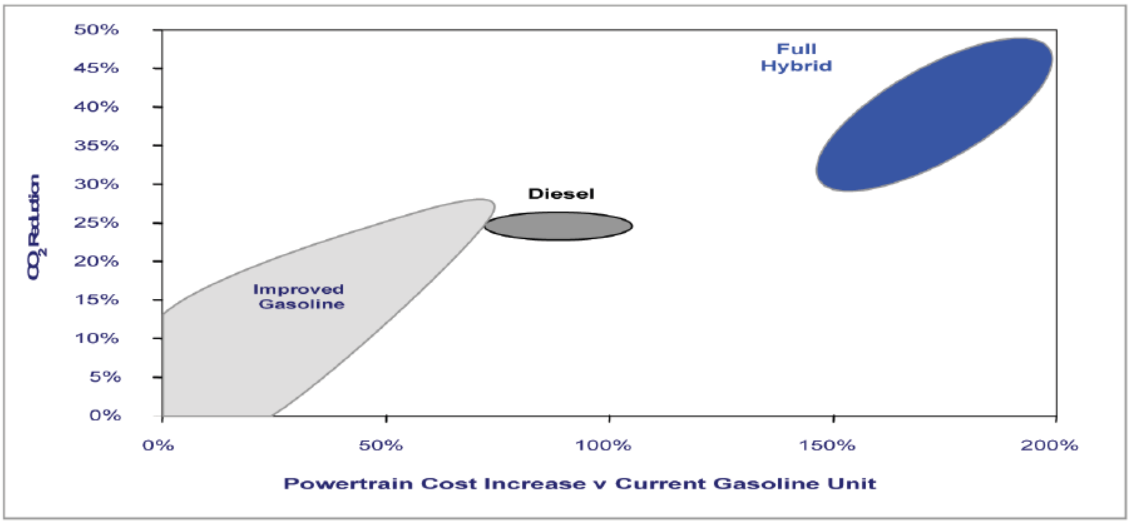
[1] Carbon dioxide, methane, nitrous oxide, hydroflurocarbons, perflurocarbons and sulphur hexafluoride.

Hybrid Electric and Battery Electric Vehicles

A hybrid electric vehicle (HEV) combines electric power from on-board batteries with power from an internal combustion engine (ICE). The main difference between a hybrid electric vehicle and a battery electric vehicle is the proportion of electric power usage. Hybrid electric vehicles have a choice of using either partial or full electric power during driving, while battery electric vehicles are solely dependent on the electric power. In order to improve fuel efficiency, hybrid electric vehicles use electric power at low vehicle speed or when ICE efficiency is low. Sometimes, additional electricity generated from regenerative-braking is used to maximise the fuel efficiency further. For a full hybrid vehicle, a maximum carbon reduction of 50% can be expected (Figure 2-2). However, carbon emissions of the hybrid electric and battery electric vehicles depend on the source of electricity. To date, a number of hybrid electric and battery electric vehicles (taxis, buses, trucks and cars) are available. Mild to full hybrid electric cars produced by the major car manufacturers include Toyota Auris Hybrid, Toyota Prius, Lexus CT, Lexus GS, Lexus LS, Lexus LX, Peugeot 3008 HYbrid4, Honda CR-Z Hybrid, Honda Insight Hybrid, Honda Jazz Hybrid, Volvo V60 Plug-in Hybrid, Porsche Panamera Hybrid, Porsche Cayenne S Hybrid and VW Touareg. The latest battery electric cars available in the market are Nissan Leaf, Mitsubishi i-MiEV, Vauxhall Ampera, Volvo C30 Electric, Peugeot iOn and Renault Z.E.

Figure 2-2: Carbon reduction from the vehicle technology improvements [page 35, (Department for Transport 2007)]



Biofuels

Biofuels, which include solid biomasses, liquid fuels and various biogases are derived from different biomasses, e.g., sugar, wheat, corn, rapeseed, soya and palm oils. Biofuels are considered carbon-neutral fuels because carbon released during power generation is equal to the amount of carbon absorbed during their growing process (Department for Transport 2007). Existing biofuels are mostly produced from food crops, and considered inferior in terms of carbon benefits because of lower fuel efficiency and extra energy required during manufacturing and transportation. A true carbon reduction could only be achieved through sustainable biofuels without jeopardizing the food supply or increasing carbon emissions during biomass production, due to changes in landuse (Department for Transport 2009).

Fuel Cell Vehicles

Fuel cell vehicles use hydrogen as the power source. This form of energy has zero carbon emissions when powering the vehicle. However, external energy is required to produce the hydrogen for the vehicle. Therefore, savings in carbon from hydrogen power largely depend on the source of energy involved in its production and transportation.

Limitations of New Engine and Fuel Technologies

To date, most decarbonisation technologies in transport are still technically and commercially immature because of a number of limitations (Department for Transport 2007). The major limitations are the lack of refuelling infrastructure, storage facilities, and insufficient energy density to match that of fossil fuels. The energy density requirement for different travel distances is shown in Figure 2-3, where hybrid plug-in vehicles are still less capable of achieving long distance travel as the conventional combustion engine vehicles. There is a need for substantial technology improvements to reduce the cost and overcome their limitations before they enter the market. These technology improvements include energy storage system, drive train technology, vehicle system integration, grid integration, integration into the transport system and safety (Meyer 2010). Most importantly, it will take some time for the clean technology vehicles to penetrate into existing vehicle fleets. The turnover may take approximately 10 years for passenger cars and light vehicles to be replaced by a new generation of vehicles (Department for Transport 2007). Fossil-based fuels will still be the dominant source of power for road transport by 2030 (European Road Transport Research

Advisory Council 2010). In view of that, suggestions were made to improve primarily petrol and diesel engines for the coming 10-15 years (Department for Transport 2007; Department for Transport 2009). Although the first generation hybrid could be available before 2030 (Figure 2-4), technologies in plug-in hybrid, electric and fuel cell vehicles will not be mature before 2050 (Figure 2-4). The improvement and innovation on internal combustion vehicles (ICV) should be continued until 2050. Therefore, improvements to reduce carbon by changing driving practice/behaviour with ICE vehicles will be important in the short to medium term.

Figure 2-3: Energy density requirement for different travel distances (European Road Transport Research Advisory Council 2010)

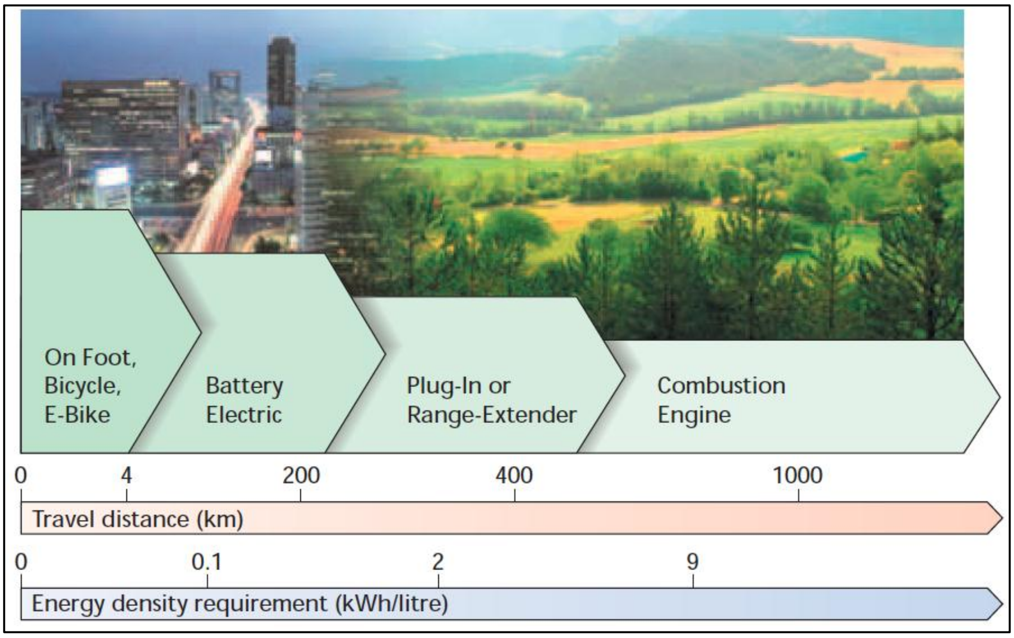
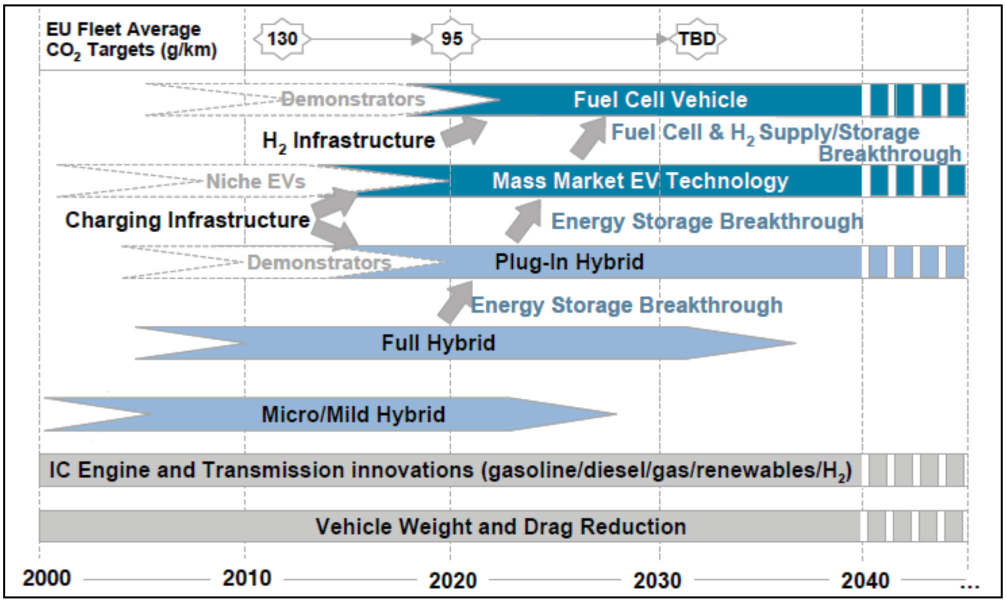


Figure 2-4: Timeline of vehicle technology progression towards 2050 (NAIGT 2009)



Mobility Management

The decarbonisation of transport by vehicle and fuel technologies is dependent on the source of power. Without real low carbon energy, carbon emissions might shift from roads to power plants, but the real carbon footprint would not be significantly different. Therefore, mobility management provides strategies that could truly cut the carbon emissions. These strategies focus on changing drivers' consciousness, and subsequently their driving behaviour and travel decisions. The options include eco-driving, ridesharing, park-and-ride, smart cards, telecommuting, road pricing, etc. Mobility management strategies can be divided into technology/infrastructure dependent or non-technology/non-infrastructure dependent. Technology/infrastructure dependent options, e.g., intelligent transportation systems (ITS) improve the traffic flow, travel time and traffic congestion by influencing drivers' decisions with the help of information technology. This is achieved by integrating vehicles, system users and infrastructure through a wireless, electronic or automated system to allow the communication of traffic information. On the other hand, non-technology/infrastructure dependent options include influencing driving behaviour by providing advice on fuel-efficient and eco-friendly driving practices. Drivers reduce carbon emissions and fuel consumption through their behavioural change (Department for Transport 2007). Depending on the level of changes, 10%-50% fuel savings can be expected from changing driving behaviour (Reichart, Friedmann et al. 1998; De Vlieger, De Keukeleere et al. 2000; Felstead, McDonald et al. 2009).

Summary

Actual energy and emission savings from new engine and fuel technologies dependent strategies are relatively small at this time because of the constraints discussed earlier. These strategies could not be successful unless the technology becomes widely available and affordable. Changing driving behaviour could provide a cost effective and immediate reduction in CO_2 emissions before the new technology completely replaces existing ICE vehicles.

2.2.3 Changing Driving Behaviour

Changing driving behaviour can bring immediate carbon savings without relying on the new infrastructure or a major technology breakthrough. Up to 50% of the fuel consumption can be saved by applying a suitable driving style (Reichart, Friedmann et al. 1998). It is claimed that by changing driver behaviour, in-vehicle feedback systems on the market could notably reduce the carbon footprint and fuel consumption (reduced by 14.7-21.1%) of the vehicle (Reichart, Friedmann et al. 1998). The in-vehicle feedback system generally consists of an on-board diagnostic unit and an online feedback system. The diagnostic unit allows drivers to assess their instantaneous fuel economy en route thus prompting a change in driving behaviour. The online feedback system analyses the driving behaviour including changes made by the drivers, and provides recommendations to optimise the driving. The feedback entails various driving parameters, such as the engine speed, vehicle speed, engine load, instantaneous and total fuel economy, instantaneous and total carbon emissions, total fuel, total distance, idle time and rapid acceleration/deceleration. These in-vehicle feedback systems are more prevalent among the corporations that possess large vehicle fleets compared with individual car owners because the savings would be more significant. Some examples of in-vehicle feedback systems include Greenroad™, Eco-Log™, EcoTrak, GreenerFleet, Logica EMO, etc. Eco-Log™ system[2] reported a variation of over 51% CO_2 emissions between the best and worst drivers within a fleet performing the same operation. Greenroad™ system[3] claimed an average of 10% savings on fuel through their analysis, feedback and incentive program on driving behaviour. As driving behaviour significantly affects carbon emissions, it is essential to investigate how it could be improved.

Driving behaviour has previously been grouped into economical, normal and aggressive types (De Vlieger, De Keukeleere et al. 2000; El-Shawarby, Ahn et al. 2005). No standard guidelines have been used to categorise driving behaviour. Economical/mild driving is generally defined by soft acceleration and anticipating traffic behaviour. Normal driving is between economical driving and aggressive driving (De Vlieger, De Keukeleere et al. 2000). The general public's perception on aggressive driving has always been confined to behaviour that failed to obey traffic rules, such as 1) running red light, 2) improper passing, turning, overtaking and changing lane, 3) failing to yield, 4) running stop signs 5) tailgating and 6) careless driving and speeding

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[2] An in-vehicle system developed by Lysanda to improve driving behaviour using in-vehicle driver aid and online reporting tools.
[3] An in-vehicle system plus online tool that gives drivers and fleet managers real-time feedback and analysis of driving patterns.

(Tasca 2000; Shinar and Compton 2004). A definition has been proposed that driving behaviour is defined as aggressive if it is deliberately and likely to increase the risk of collision and is motivated by impatience, annoyance, hostility and/or an attempt to save time (Tasca 2000).

According to Van Mierlo et al., 2004, aggressive driving, speeding and use of air-conditioning increase CO_2 emissions at both local (individual) and global (entire car fleet) levels with the greatest impact coming from the aggressive driving (Van Mierlo, Maggetto et al. 2004). Aggressive driving also reduces the fuel efficiency (Lenaers 2009; U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE) 2011). On the other hand, economic driving with proper tyre pressure and with the use of cruise control reduces CO_2 emissions (Van Mierlo, Maggetto et al. 2004).

The impacts of driving aggressiveness on carbon emissions could vary from one study to another depending on the road type, level of change in driving behaviour, criteria used for defining aggressiveness and test method. The summary of carbon reductions for a number of studies is shown in Table 2-1. It can be concluded that changing driving behaviour on urban roads (consisting of links and intersections), achieved greater savings (26%-40%) compared with rural roads (28%). For a freeway, the results were rather inconsistent varying between -10% and 21%. It has also been found that changing aggressive driving to normal driving decreased carbon emissions more than changing normal driving to economical driving. This is because aggressive driving produces a larger amount of carbon emissions compared with normal driving or economical driving. However, the test method and criteria used for defining aggressive driving should be taken into account when comparing the results from different studies.

Table 2-1: Carbon savings from changing driving behaviour

Paper	Vehicle Type	Driving Behaviour Change	Definition of Aggressive Driving	Road Type	Savings (%)	
					CO_2	Fuel
Lenaers, 2009	Peugeot 307 1.6l Petrol	Aggressive to Normal	• Aggressive: average accelerations 0.85-1.1m/s^2 • Normal: average accelerations from 0.65-0.8m/s^2	Urban	41	40
				Rural	29	29
				Motor-way	6	5
De Vlieger et al., 2000	Renault MeHgane 1.4l Petrol	Aggressive to Normal	• Aggressive: average accelerations from 0.85-1.1m/s^2 • Normal: average accelerations from 0.65-0.8m/s^2	Urban		26
				Rural		28
				Motor-way		21
El-Shawarby et al., 2005	Ford Crown Victoria 4.6l Automatic	Aggressive to Normal	• Aggressive: 100% of the max vehicle acceleration envelope • Normal: 60% of the max vehicle acceleration envelope	Free-way	-10	
Felstead et al., 2008	Chassis Dynamometer	Aggressive to Passive	Qualitative instructions (**Table 2-2**)	Urban	32	
Beusen et al., 2009	Mixed of Petrol and Diesel Vehicles	Normal to Eco	Qualitative instructions (**Table 2-2**)	General		5.8
Van Mierlo et al., 2004	Chassis Dynamometer	Normal to Eco (New Style Driving)	Qualitative instructions (**Table 2-2**)	Real World Speed Profile	4	

Table 2-2: Instructions for driving

Paper	Instructions
Felstead et al., 2008	Instructions for defensive driving: • Use moderate acceleration and braking during driving. • Obey the speed limit at all times. • Overtake on dual carriageway sections when it is appropriate. • Coasting/sitting on the clutch is not allowed.
	Instructions for aggressive driving: • Use hard acceleration and heavy braking during driving. • When behind a vehicle keep pace with the vehicle at a distance at which the driver feels safe. • Attempt to reach the speed at which they would normally travel along that road as quickly as possible. • Overtake on dual carriageway sections when it is appropriate. • Coasting/sitting on the clutch is not allowed.
Beusen, et al., 2009	Instructions for eco-driving: • Shift up as soon as possible (shift up between 2000 and 2500 rpm). • At steady speed, use the highest gear possible and drive with low engine rpm. • Try to maintain a steady speed by anticipating traffic flow. • Decelerate smoothly by releasing the accelerator in time while leaving the car in gear (this is called ‘‘coasting”).
Van Mierlo et al., 2004	Instructions for eco-driving: • Shift as soon as possible at maximum of 2500 rpm to as high a gear as possible. • Do not shift down to a lower gear too early and keep the car rolling without disengaging the clutch and stay at high gear as long as possible.

Despite different engine technologies, changing aggressive driving to normal driving on hybrid electric vehicles was not much different from the ICE vehicles, although it would be likely that the range of CO_2 savings would be different (Table 2-3).

Table 2-3: Comparison on carbon savings for hybrid and ICE vehicles

	Toyota Prius II Petrol (Hybrid)			Peugeot 307 1.6l Petrol (ICE)		
	CO_2/km		Savings* (%)	CO_2/km		Savings* (%)
	Aggressive	Normal		Aggressive	Normal	
Urban	238	150	37	429	255	41
Rural	121	103	15	213	151	29
Motorway	152	136	11	188	177	6

*Decrease in CO_2 emissions for changing from aggressive driving to normal driving.

It can be concluded from Table 2-3 that carbon emissions are strongly correlated to driving behaviour. For both ICE and hybrid electric vehicles, significant savings in carbon emissions can be achieved through changing driving behaviour, especially at urban roads. The change is possible if the driver is positively motivated (Van Mierlo, Maggetto et al. 2004), e.g., through the savings in vehicle and road taxes, reduction in the carbon footprint, improvement in fuel efficiency, cost effectiveness, etc.

2.2.4 Eco-Driving

Eco-driving has broadly embraced the concepts from fuel efficient driving to low carbon footprint driving. Some Nordic countries have started advocating the concept of eco-driving since the nineties. The potential effects of acceleration, stop, speed and driving mode, driving interruption and anticipating driving were embedded in the concept of eco-driving. The eco-driving ranges from Finnish EcoDriving to Swiss ECO-DRIVE, Dutch New Style Driving and Swedish EcoDriving. Guides for eco-driving practices given by Ecowill (Austrian Energy Agency 2011) include:

- Shift up as soon as possible. Shift up between 2,000 and 2,500 revolutions.
- Maintain a steady speed. Use the highest gear possible and drive with low engine rpm.
- Anticipate traffic flow. Look ahead as far as possible and anticipate the surrounding traffic.
- Decelerate smoothly. When you have to slow down or to stop, decelerate smoothly by releasing the accelerator in time, leaving the car in gear.
- Check the tyre pressure frequently. 25% too low tyre pressure increases rolling resistance by 10% and fuel consumption by 2%.

The UK government has launched an "Act on CO_2" campaign to bring awareness to motorists that a carbon reduction could be achieved without compromising the type of car they drive (Department for Transport 2007). This could be attained by buying a low carbon vehicle within their preference class and by driving more efficiently (Department for Transport 2007). It was estimated that the eco-driving tips from "Act on CO_2" could reduce CO_2 emissions by approximately 8%. Endeavours were also made by integrating eco-driving techniques into the new driving test (Department for Transport 2009). Eco-driving tips quoted from "Act on CO_2" include (Directgov 2011):

- Drive at an appropriate speed. Driving at 50 miles per hour (mph) instead of 70 mph can improve fuel economy by 25 percent.
- Speed up and slow down smoothly. Every time you stop and start, your engine uses more fuel and produces more emissions.
- Change gear at the right time. Changing up gears little earlier can reduce revs and reduce your fuel usage.
- Avoid leaving your engine running. If you're likely to be at a standstill for more than three minutes, switch off the engine.
- Don't use air conditioning unless you really need it.

Eco-driving will be more effective under substantial incentives (Confederation of British Industry 2009) and perhaps also investment from the government and transport stakeholders. However, benefits of reducing the carbon footprint in addition to the fuel saving could be a strong motivation for drivers to change their driving behaviour. Eco-driving can also be combined with the in-vehicle feedback system to increase carbon savings. More in-vehicle feedback systems coming to the market indicated a good public acceptance on fuel/carbon savings through changing driving behaviour.

2.2.5 Summary

Sixteen percent of the global carbon emissions are generated by road transport (International Energy Agency 2010) and growth in road traffic will increase carbon emission if no countermeasures are taken. The measures that could be adopted by the public and private sectors include introducing new engine and fuel technologies, effective mobility management, changing driving behaviour and travel choice. Considering the infancy of the vehicle decarbonisation technology and considerable amount of time required for replacing the existing fleet with cleaner energy vehicles, changing driving behaviour would be a more cost effective and quick countermeasure for this transition period.

2.3 Variables Affecting Carbon Emissions during Driving

Carbon emissions are the result of fuel burning process to propel the vehicle at the desired engine load. The engine load is affected by the combination of vehicle attributes, vehicle operating conditions (Kean, Harley et al. 2003), traffic condition and road geometry (Li, Andrews et al. 2007). Vehicle attributes include the engine, vehicle mass and transmissions, while operating conditions refer to speed and acceleration that are affected by traffic control, road conditions and the driver’s mentality (Kean, Harley et al. 2003). Traffic control and road geometry could increase fuel consumption by factors of 3.2-4 and 3.5 for stop-turn and uphill driving, respectively, compared with a 30mph steady speed driving (Li, Andrews et al. 2007).

Reviews of emission variables in this section have been based on both carbon emission and fuel consumption studies, considering a strong correlation between the two.

2.3.1 Vehicle Operating Conditions

Vehicle Speed

Speed is the most commonly used variable to estimate carbon emissions (Ericsson 2001). The average speed has been mostly used in macroscopic models (for example, MOBILE6 that was developed by U.S. Environmental Protection Agency) and the instantaneous speed is used in microscopic models (for instance, CMEM that was developed by University of California Riverside). The instantaneous speed variable could outperform the average speed variable in some emission models that required microscopic details because of its ability to capture small changes during the vehicle operation (Int Panis, Broekx et al. 2006). According to Int Panis et al., 2006, different ranges of instantaneous speeds can be observed under the same average speed in the standard driving cycle, which lead to disparity in total carbon emissions (Int Panis, Broekx et al. 2006). This infers that for the study of the relationship between carbon emissions and vehicle speed, the instantaneous speed variable might better reflect changes in CO_2 emissions caused by variations in speed. The average speed variable would be good for comparison of driving behaviour between different driving modes or road types at macroscopic level.

Fuel consumption/CO_2 emission has a nonlinear dependency on the average speed, which can be represented by a convex curve (Figure 2-5, Figure 2-6). Fuel consumption could be high when average speed is very low or very high. An optimum speed at the middle of the curve indicates the speed for the lowest fuel consumption. The optimum speed varies depending on the road type and vehicle type. On link roads, such as freeways and arterial roads, optimum speed values were reported to be 72kph[4] (El-Shawarby, Ahn et al. 2005), 80kph[5] (Rakha and Ding 2003) and between 72-80kph[6] (Barth and Boriboonsomsin 2008). However, no optimum speed has been investigated for signalised intersections. Optimum speed at a signalised intersection is speculated to be different from a freeway because of greater speed variation induced by the traffic lights.

Speed variation has a significant impact on carbon emissions (Ericsson 2000). Steady speed at the optimum value reduces CO_2 emissions but unsteady speed increases CO_2 emissions (Barth and Boriboonsomsin 2008). CO_2 emissions were high when speed was below 20kph or above 80kph (Figure 2-6). This explained the reason carbon emissions at intersections are higher than link roads.

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[4] On 1km state route using VT-Micro model.
[5] On 4.5km urbanised arterial section using VT-Micro model.
[6] On freeways using CMEM and a wide range of vehicle types.

Figure 2-5: Fuel consumption and emissions as the functions of speed (Rakha and Ding 2003)

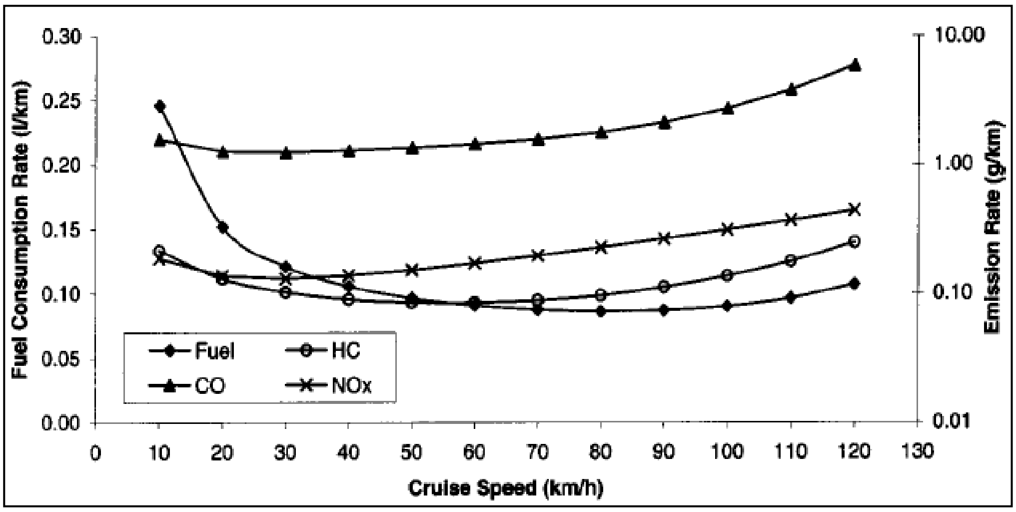
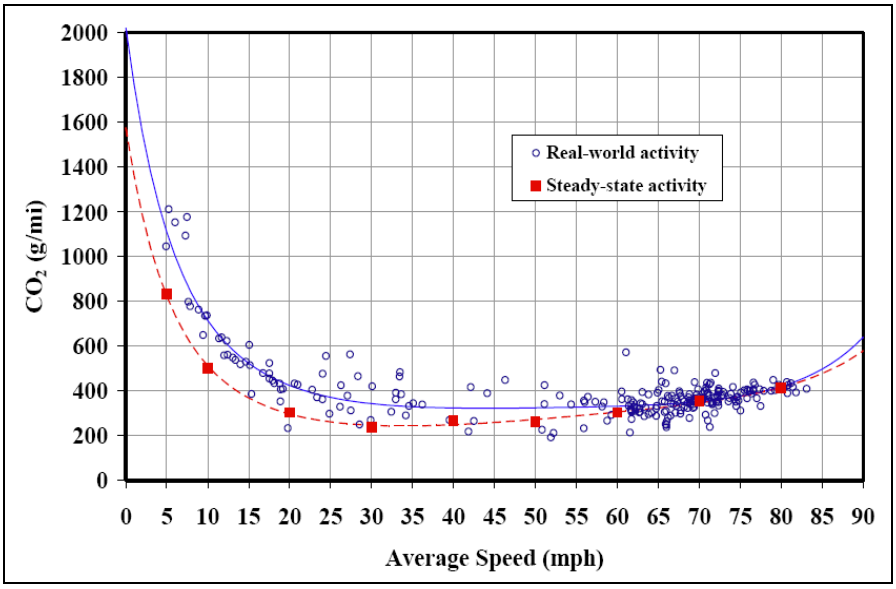


Figure 2-6: CO_2 emissions as a function of average speed (Barth and Boriboonsomsin 2008)



Note: Average speed is the mean speed of a trip.

Acceleration

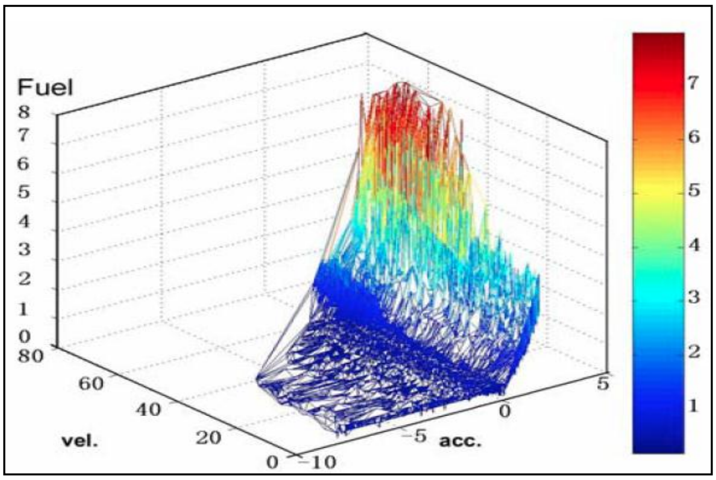
Acceleration is an important variable in carbon emission study (Ericsson 2001). The acceleration variable is often used together with the speed variable to estimate fuel consumption and emissions (Joumard, Jost et al. 1995). This is because fuel consumption and emissions are governed by the engine load, which can be explained by the product of speed and acceleration (Joumard, Jost et al. 1995). Therefore, fuel consumption and carbon emissions increase with the increase of acceleration and speed (Figure 2-7). Fuel consumption is highly sensitive to acceleration at the optimum speed range (Rakha and Ding 2003), especially when acceleration exceeds $0.6 m/s^2$ (Figure

2-8). However, fuel consumption is less susceptible to acceleration when the acceleration is negative and engine load is low (Figure 2-9).

Engaging high acceleration may sometimes shorten the duration of extreme acceleration and reduce the total carbon emissions (El-Shawarby, Ahn et al. 2005). More often, engaging high acceleration increases the total CO_2 emissions over longer distance. Therefore, both acceleration level and acceleration duration could significantly influence CO_2 emissions, i.e., percentage of time acceleration exceeds 1.5 m/s^2; percentage of time deceleration lies between -1.5m/s^2 and -2.5m/s^2; and relative positive acceleration (RPA), which is interpreted as acceleration with high power demand (Ericsson 2000).

Besides the acceleration level and duration, the engine load is also affected by the aerodynamic drag, rolling resistance, roadway grade, engine friction and use of accessories (Kean, Harley et al. 2003).

Figure 2-7: Relationship between instantaneous speed, acceleration and fuel consumption (Chen and Yu 2007)



Note: Fuel represents fuel consumption (g/s), vel. represents vehicle speed (kph) and acc. represents acceleration (m/s^2)

Figure 2-8: Fuel consumption vs. acceleration (Li, Andrews et al. 2006)

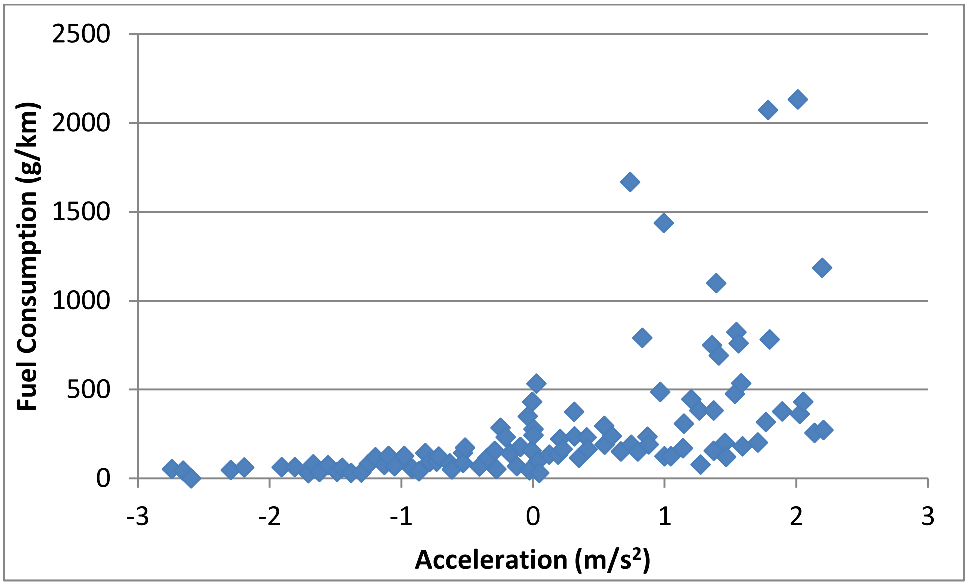
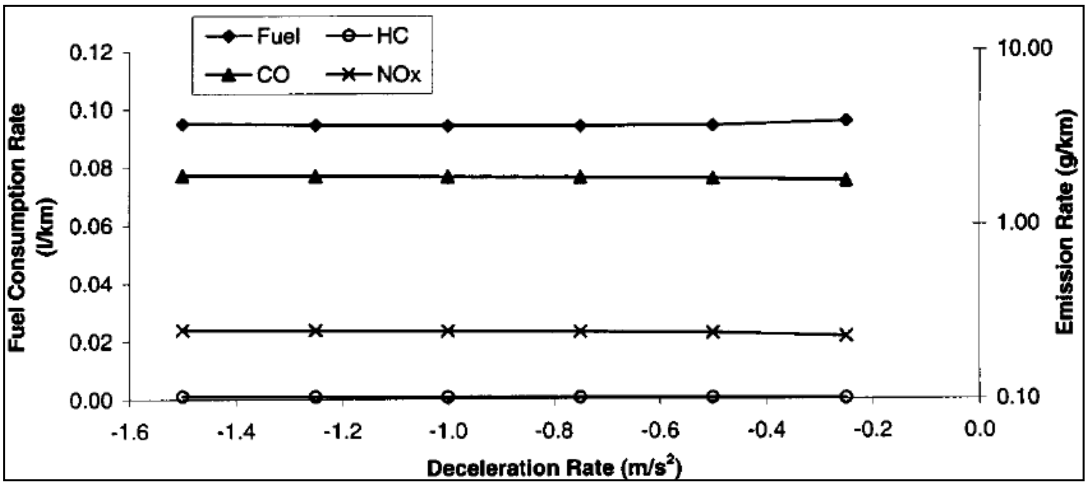


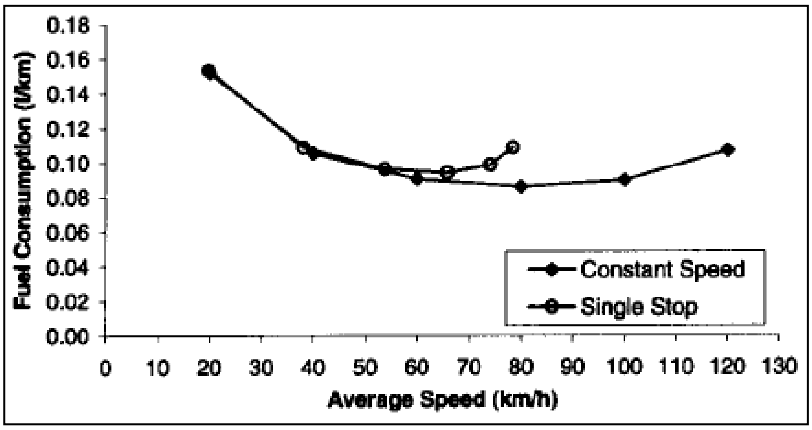
Figure 2-9: Variations in fuel consumption and emission rates as a function of deceleration level (Rakha and Ding 2003)



Stop and Braking

Drivers generally experience two types of driving at signalised intersections, namely interrupted driving and uninterrupted driving. In this study, interrupted driving is defined as driving that involves coming to a stop, idling and then accelerating at a signalised intersection. Increasing the number of interruptions and its subsequent accelerations aggravate CO_2 emissions (Chen and Yu 2007; Barth and Boriboonsomsin 2008). Delays and stops may constitute up to 25%-30% of the total CO_2 emissions (Midenet, Boillot et al. 2004) and busy city roads increased 20%-45% of the fuel consumption (De Vlieger, De Keukeleere et al. 2000). Delays and stops at signalised intersections are strongly and positively correlated with the increase in CO_2 emissions (Oda, Kuwahara et al. 2004; Chen and Yu 2007). However, Rakha and Ding, 2003 reported that when the average speed is below 50kph, introducing a stop to the 4.5km long trip (with an acceleration that is 20% of the maximum feasible acceleration) has insignificant impact on the fuel consumption (Figure 2-10).

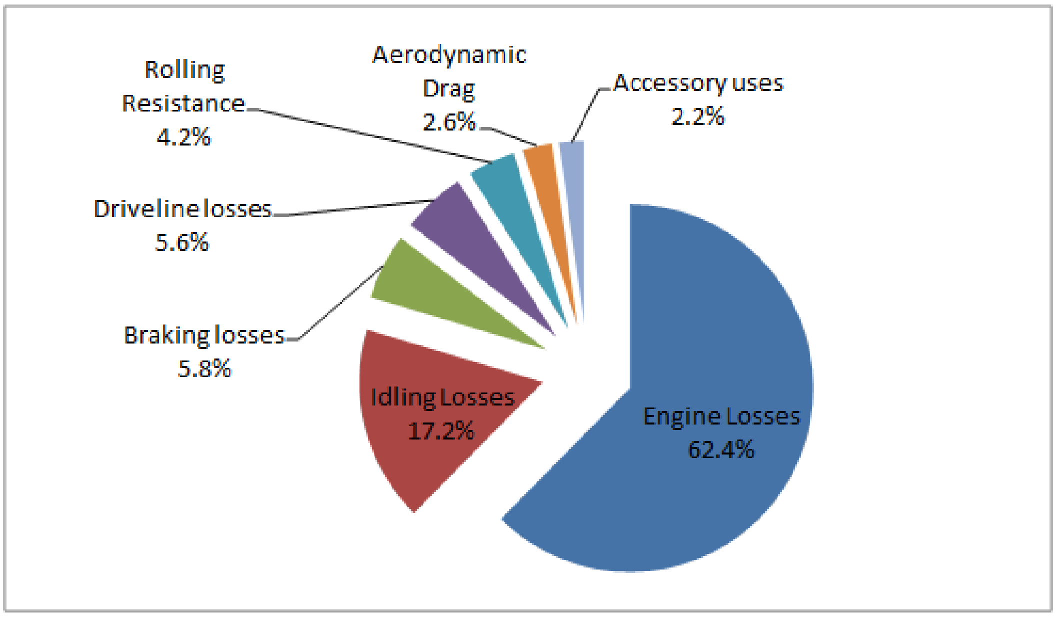
Figure 2-10: Impact of single vehicle stop on fuel consumption (Rakha and Ding 2003)



For the ICE vehicle, braking contributes 5.8% loss of the total energy per unit of fuel (Figure 2-11). The same amount of energy is required to regain a vehicle's inertia and to recover its speed. Therefore, better anticipation to maintain a constant speed and avoid braking is recommended in some of the eco-driving guidelines to reduce fuel consumption and carbon emissions[7].

[7] http://goinggreenfriendly.com/eco-driving/
http://paulhalton-som.com/site/eco-driving/
http://www.guardian.co.uk/money/2011/mar/22/driving-tips-save-money-pumps

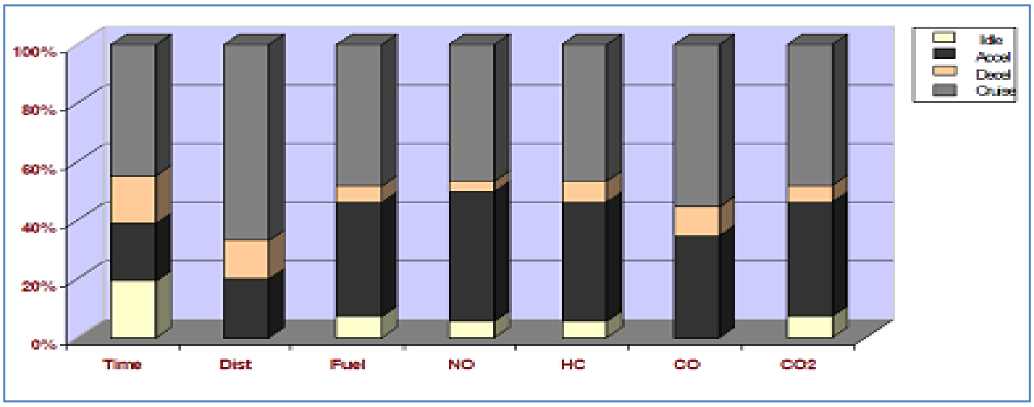
Figure 2-11: Energy uses and losses in a vehicle (U.S. DoE and U.S. EPA 2011)



MODE OF DRIVING

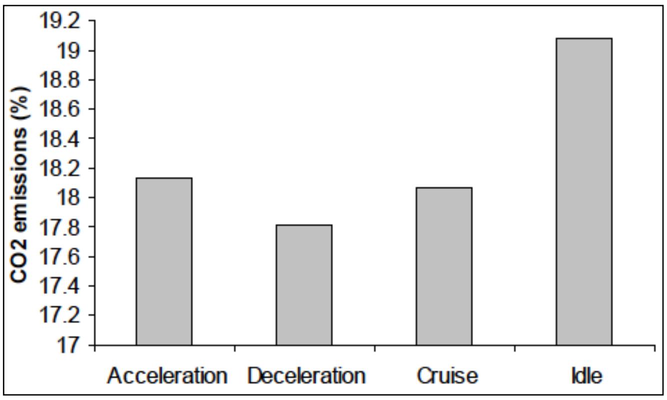
Under interrupted driving, passing the intersection involves three driving modes, namely deceleration, idle, acceleration. The amount of carbon emission depends on the duration/distance spent on the particular mode. The idling duration depends on traffic control, while duration/distance of travel under other driving modes mostly affected by the driver decision. According to Frey et al., 2000, of all driving modes, acceleration produced 40% of the total CO_2 emissions although the distance travelled was only 20% of the entire trip (Figure 2-12). This was based on 60 one-way runs conducted on Miami Boulevard, with one-way length of 5 miles consisted of 15 signalised intersections. Therefore, an increase in CO_2 emissions at signalised intersections is mainly caused by the acceleration mode, not idling or deceleration mode (Frey, Rouphail et al. 2000; Chen and Yu 2007).

Figure 2-12: Distribution of travel time, distance, fuel use and emissions by driving mode (Frey, Rouphail et al. 2000)



Besides the acceleration mode, idling could also be the highest CO_2 emitter of a trip (Figure 2-13), since the amount of CO_2 emissions produced during idling is greatly subjected to the idling duration. For signalised intersections, the acceleration mode, however, produced higher CO_2 than deceleration and cruise modes (Figure 2-13).

Figure 2-13: CO_2 emissions by driving modes on an urban route consists of signalised urban streets, avenue and local road (Noland, Ochieng et al. 2004)



Idling

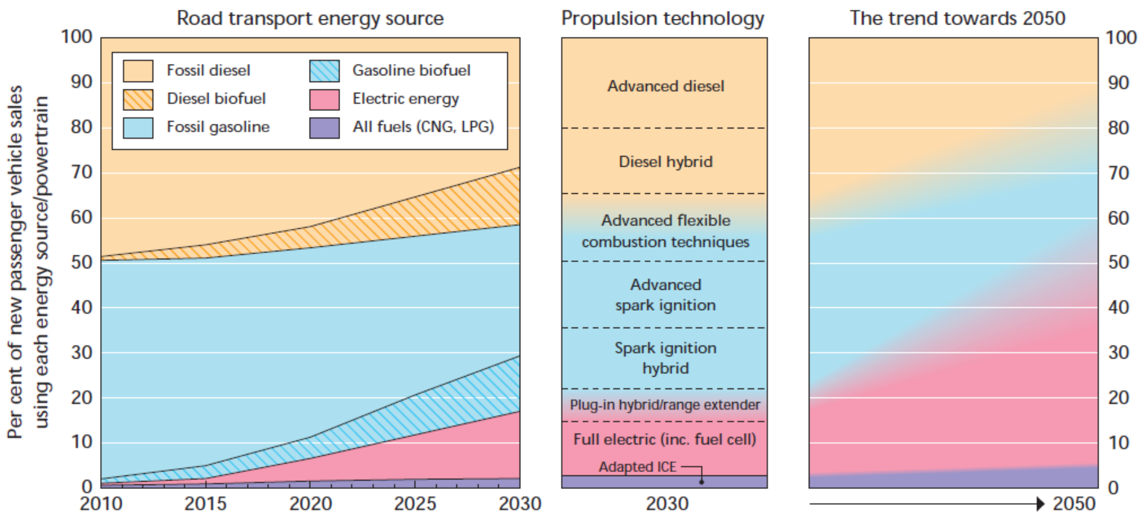
Under normal circumstances, the conventional internal combustion engine (ICE) will continue to burn fuel and emit carbon when the vehicle is idle. Idling generally consumes 17.2% of the energy in urban driving (Figure 2-11). The Florida Section of American Society of Mechanical Engineers (ASME) found that idling for six seconds used as much fuel as restarting the engine, while U.S. EPA recommends less than 30 seconds idling to avoid significant waste of energy. However, Liang et al., 2011, suggested that the amount of fuel used to restart the engine after the idle-stop is equivalent to 0.7 seconds of idling (Liang, Grama et al. 2011). Therefore, carbon savings from not burning fuel during idling is substantial for trips made on signalised urban roads.

Fuel consumption and carbon emissions due to idling can be prevented by 1) adopting the idle-stop/stop-start system (Motoda and Taniguchi 2003; Liang, Grama et al. 2011) and 2) anticipating traffic (Reichart, Friedmann et al. 1998; Duivenvoorden 2007). The idle-stop system turns off the engine when a vehicle is not in motion, whether stopping at intersections, unloading at parking or idling at roadsides. The idle-stop system could reduce CO_2 emissions up to 20% and increase fuel efficiency by 15% (Robert Bosch GmbH 2010; Liang, Grama et al. 2011). Turning off the engine manually could also save fuel up to 14% on urban roads that have many intersections (Motoda and Taniguchi 2003). Although an idle-stop system is a basic feature for all hybrid electric vehicles and battery electric vehicles, it can also be built into ICE vehicles.

2.3.2 Vehicle Attributes

The engine of a vehicle has an effect on carbon emissions. The engine defines the source of power for a vehicle, which varies from fossil diesel, diesel biofuel, fossil gasoline, gasoline biofuel, electric energy and other fuels (e.g., compressed natural gas, liquefied petroleum gas). The use of fossil fuels is expected to decline gradually, replaced by the growth in electric energy consumption (Figure 2-14). There will be a more significant shift of propulsion technology by year 2050 (Figure 2-14).

Figure 2-14: The evolution of passenger road transport energy source and propulsion technology, towards 2050 (European Road Transport Research Advisory Council 2010)



In terms of fuel economy, fuel cell electric vehicles (FCEVs) powered by hydrogen have the highest fuel efficiency, followed by hybrid electric vehicles (HEVs) and internal combustion vehicles (ICVs) (Figure 2-15). Fuel economy of the fuel-cell electric vehicles on hydrogen fuel is 2.4 times better than petrol/ethanol internal combustion vehicles (Figure 2-15).

Figure 2-15: Relative fuel economies compared to gasoline ICVs (Sandy Thomas 2009)

Vehicle	Fuel	GREET	NRC	GM/ANL	MIT	Average
SI ICV	Gasoline	1.00	1.00	1.00	1.00	1.00
SI ICV	Ethanol	1.00		1.00		1.00
SI ICV	Hydrogen	1.20		1.20		1.20
CICI ICV	Diesel	1.20		1.21	1.16	1.19
SI IC HEV	Gasoline	1.48	1.45	1.24	1.79	1.49
SI IC HEV	Ethanol	1.48		1.24	*est.* 1.79[a]	1.51
SI IC HEV	Hydrogen	1.60		1.48	*est.* 1.94[a]	1.67
CIDI IC HEV	Diesel	1.60		1.45	*est.* 1.94[a]	1.66
FCEV	Hydrogen	2.30	2.40	2.63	2.27	2.40

SI = spark ignition; ICV = internal combustion vehicle; CIDI = compression ignition direct injection; HEV = hybrid electric vehicle; FCEV = fuel cell electric vehicles.

a MIT numbers estimated by extrapolating MIT HEV data to keep relative averages realistic.

In terms of Well-To-Wheel (WTW) CO_2 emissions, conventional ICE vehicles produce a total of 145-215 g/km CO_2 emissions (Figure 2-16). The total WTW CO_2 emissions reduces as the proportion of electrification increases, especially with the increase in the use of renewable energy from solar and wind (Figure 2-16). The lowest WTW CO_2 emission that can be achieved is 8 g/km, by electric vehicles that are powered by 50% solar energy and 50% wind energy.

Figure 2-16: Comparison of WTW CO_2 emissions for conventional ICVs and EVs in relation to the electricity mix (Meyer 2010)

CO_2 in g / km / NEDC WTW for the Vehicle and LCA for the E-Energy source			
	Well to Tank (Batteries)	Tank (Batteries) to Wheels	Total CO_2 emissions
Conventional ICE Car	25-35	120-180	145-215 *
Electric Vehicle 27% Nuclear, 20% Renewable, 53% Fossils (EU-27 mix 2010)	85-105	0	85-105
Electric Vehicle 11% Nuclear, 20% Renewable, 69% fossils (Italian mix 2010)	120-140	0	120-140
Electric Vehicle 75% Nuclear, 20% Renewable, 5% Fossils (French mix 2010)	20-25	0	20-25
Electric Vehicle 30% Photo Voltaic on board, 60% other Renewables, 10% fossils	18-22	0	18-22
Electric Vehicle 50% Photo Voltaic, 50% Wind (Carbon free communities)	8 5 km per kWh and 40 g / kWh	0	8

2.3.3 Summary

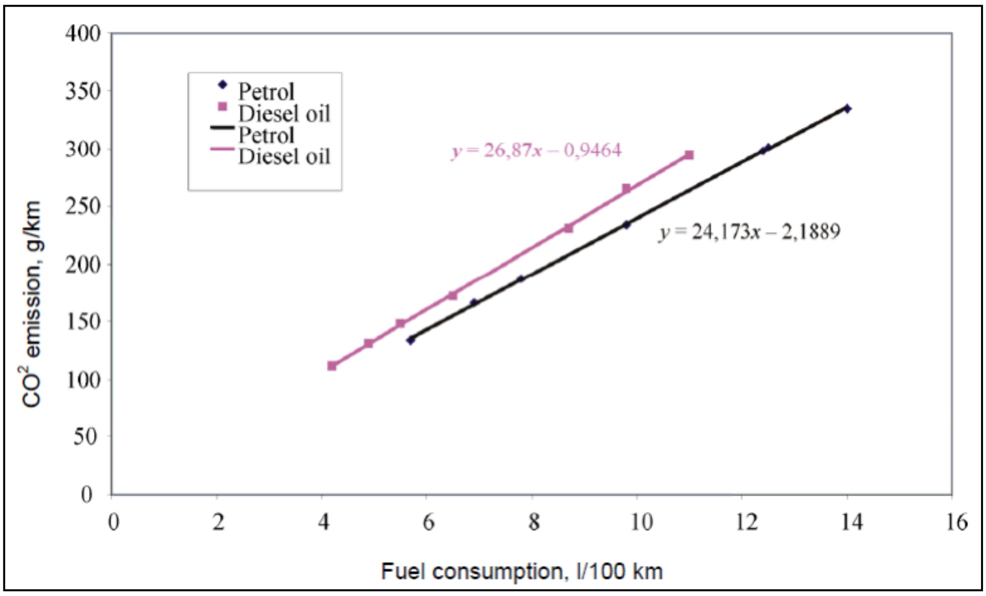
Carbon variations at signalised intersections are greater than on other road segments. Therefore, applying the carbon reduction strategy, such as changing driving behaviour, will be more significant at signalised intersections. Carbon emissions are affected by various variables/factors, such as vehicle attributes and vehicle operating conditions. Each of these variables has different impacts on carbon emissions on the roads, but very little research has been done to investigate their effects on carbon emissions at signalised intersections. For instance, the optimum speed range for freeways/links was found to lie between average speed of 72kph and 80kph. These tests were conducted on standard driving cycles that mainly consisted of link segments and did not involve extreme acceleration events. However, this optimum speed range would not be applicable to signalised intersections where average speed is much lower than 72kph. It is particularly important to identify the factors/variables governing carbon emissions at signalised intersections, which could be quite different from other road types.

Even though driving behaviour has a significant effect on carbon emissions, no relationship between carbon emissions and driving behaviour has been established for signalised intersections. Besides driving behaviour, differences in carbon emissions may depend on the type of road, traffic condition and vehicle attributes. Therefore, it is important to eliminate these variations before making a comparison between the driving behaviours.

2.4 Fuel Consumption vs. Carbon Emissions

Conceptually, CO_2 emissions are directly proportional to fuel consumption under stoichiometric combustion. This excludes the enrichment and lean events that could lead to fluctuation in CO_2 emissions (Cappiello, Chabini et al. 2002; Frey, Unal et al. 2003; Barth and Boriboonsomsin 2008). The stoichiometric combustion is an ideal combustion process where fuel is completely burned to produce CO_2, H_2O and SO_2. The Intergovernmental Panel on Climate Change (IPCC) established a guideline to calculate carbon emissions assuming the amount of CO_2 emissions is proportional to the quantity of carbon in fuel. Considering the ratio of the molecular weight of CO_2 to the molecular weight of carbon as 44/12, a gallon of fuel produces 8.8 kg of CO_2. This guideline has been widely adopted by the transport industry in which a linear relationship between CO_2 emissions and fuel consumption is used (Figure 2-17). In the absence of CO_2 emission data/results in Chapter 5, assumption was made that CO_2 emission rates are proportional to the fuel consumption. Therefore, all observations/findings about fuel consumption have the same effect on the CO_2 emissions.

Figure 2-17: Correlation between CO_2 emissions and fuel consumption of cars (Mickunaitis, Pikunas et al. 2007)



2.5 Conclusion

Previous studies on driving behaviour have been limited to tests that used standard driving cycles, which are rarely distinctive in terms of acceleration. These studies were conducted on a large spatial scale, over long standard driving cycles. Variations in speed and acceleration at signalised intersections, which provide the main contribution to high localised emissions, have often been overlooked. This study is aimed at investigating the high carbon emission events at signalised intersections. It intends to provide a microscopic analysis of the behavioural factors and correlate driving behaviour with carbon emissions.

Tests using a chassis dynamometer or simulator had been more commonly adopted in the past compared with field tests using an instrumented vehicle. This is mostly due to constraints in costs and resources. However, a chassis dynamometer or computer simulator is incapable of reproducing real-world driving. Therefore, an instrumented vehicle would a better tool to provide more realistic data to study the real world driving behaviour. In addition, high frequency data (10Hz) provided by the instrumented vehicle would be an advantage in capturing small changes in driving behaviour.

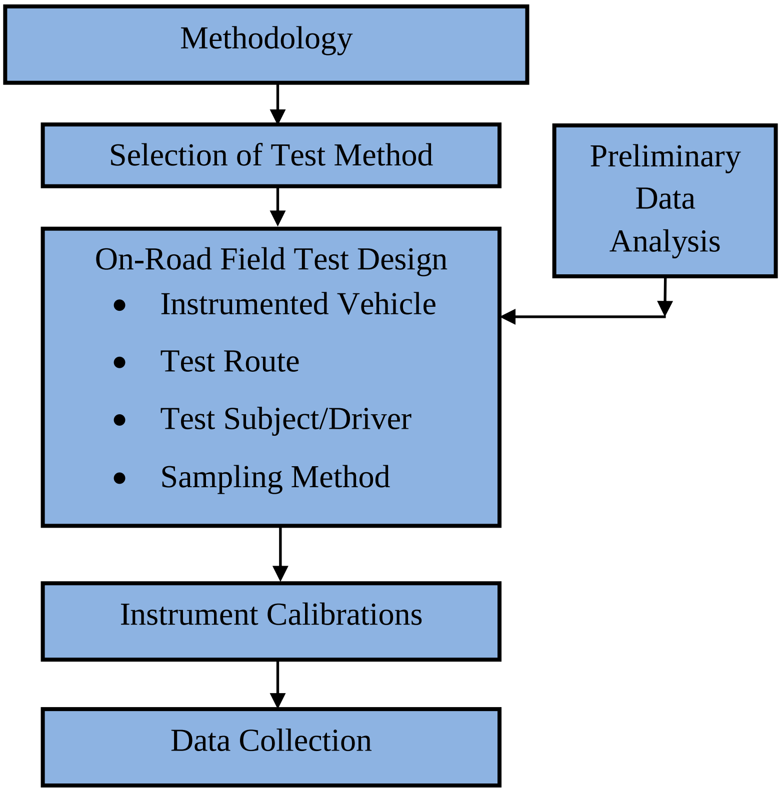
Ultimately, this study is expected to identify driving behaviour that produces high/low carbon emissions and to propose strategies that help to lower carbon emissions at signalised intersections.

Chapter 3 Methodology

3.1 Introduction

The design and planning of the main field test method are explained in this chapter (Figure 3-1). The chapter is divided into the following sections. Section 3.2: A review on available methods for measuring driving parameters. The reviewed methods include the chassis dynamometer, computer simulation and instrumented vehicle. Section 3.3: Information about the instrumented vehicle, on-board systems and instrument calibrations. Section 3.4: Details of the test route and considerations made during the selection of the route. Section 3.5: An explanation of the recruitment process for volunteer drivers, and some statistics about the driver sample. Section 3.6: Design of the sampling method in order to collect natural driving behaviour. Section 3.7: Characteristics of the parameters used in this study.

Figure 3-1: Methodology



3.2 Selection of Test Method

Methods used to collect driving data can be divided into three types, i.e., chassis dynamometer tests, roadside tests and on-road tests.

Chassis dynamometer tests are based on a system made of the chassis dynamometer, emissions analyser and computer. The computer controls speed of the test vehicle based on standard driving cycles, in which replicates driving on roads. The chassis dynamometer then simulates vehicle emissions based on the standard driving cycles, e.g., the U.S. Federal Test Procedure cycle (FTP), New European Driving Cycle (NEDC), etc.. Chassis dynamometer tests are simple to perform. However, the result could be unrealistic for the study of carbon emissions at signalised intersections if a standard driving cycle is used, as the standard driving cycles often omit extreme driving conditions and, therefore, do not represent the actual operational environment.

Roadside tests include video recording and/or remote sensing. Video recording has an advantage in obtaining large vehicle fleet data in terms of vehicle speed and headway. Data collection is relatively simple and direct. Good quality data could be achieved by placing cameras at the location that are not obstructed by any object during the data recording period. However, this method has a major data inconsistency issue. This is because the data, i.e., vehicle speed and headway is interpreted from video images. The data accuracy is, therefore, affected by the parallax, frame size and resolution of the video images. Additional data such as emissions, can be measured with the use of remote sensing. However, this method could not provide engine operating parameters such as engine speed, fuel consumption, gear changing, etc.

On-road tests using an instrumented vehicle equipped with a Portable Emission Measurement System (PEMS) is a reliable and accurate method of measuring tailpipe emissions (Rubino, Bonnel et al. 2009; Farzaneh, Schneider et al. 2010). This test has gradually become a preferred method since the reductions in the cost, size and weight of the instruments. The biggest advantage of this method is its ability to measure instantaneous engine and vehicle operating data in real-world driving, and synchronise the data with on-board instruments (refer Section 4.2 Data Synchronisation), e.g., OBS, VBOX-III, Dashdyno and GPS systems for additional parameters. Details of these on-board systems are given in the next section.

3.3 Instrumented Vehicle

The instrumented vehicle used in this study was assembled by the Transportation Research Group of the University of Southampton. Commissioned in 2006, this vehicle is a Fiat-Stilo 2.4 litre petrol engine, 2004 model with 5-speed semi-automatic gearbox (Table 3-1, Appendix B: Technical Details of the Instrumented

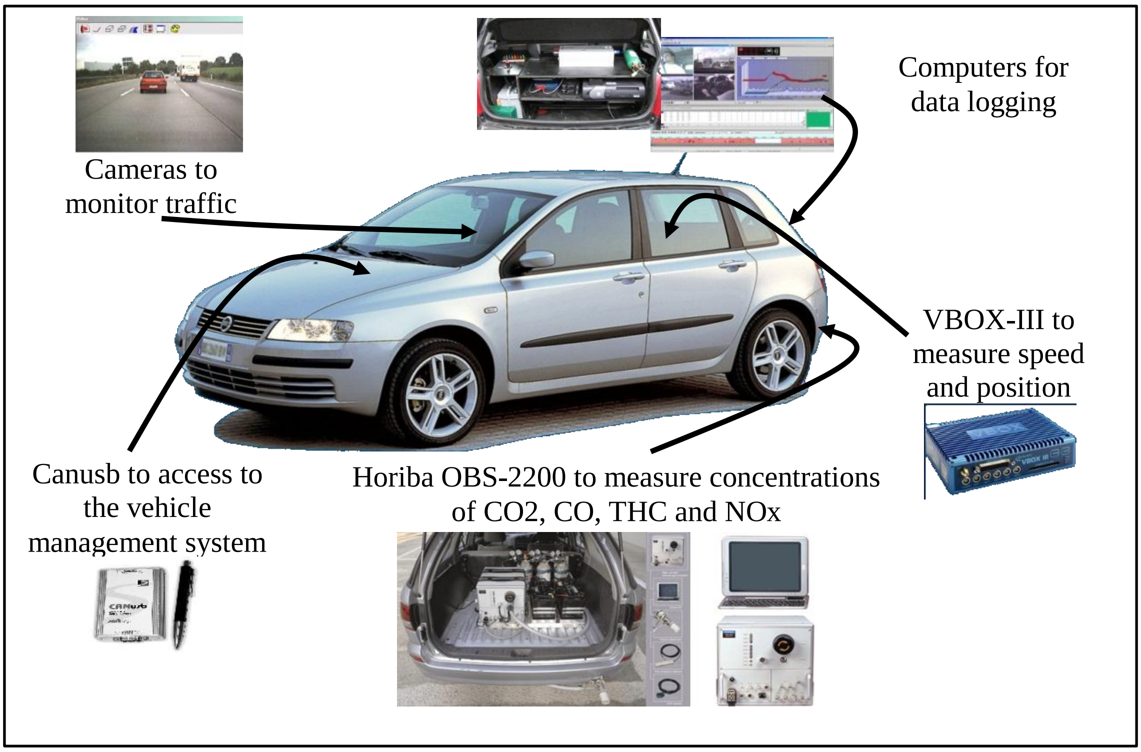
Vehicle). This vehicle is equipped with a number of on-board systems (Figure 3-2). However, only four systems were used in this study:

- On-board Emission Measurement System (OBS-2200)
- VBOX-III
- Canusb (connected to Canbus)
- Video cameras

Table 3-1: Characteristics of the instrumented vehicle

Model:	Prestigio Selespeed
Capacity:	2446cc
Max power:	170 bhp (125 kW-EEC) @ 6000 rpm
Peak torque:	221 Nm-EEC (22.5 kgm) / 163 lb ft @ 3500 rpm
Top speed:	136 mph
Fuel consumption:	1999/100 EC Directive: UK mpg (l/100 km) • urban 20.8 (13.6) • extra-urban 37.2 (7.6) • combined 28.8 (9.8)
CO_2 emissions:	233 (g/km)
Engine:	In-line 5-cylinder, 2446cc, 20v

Figure 3-2: Systems used in the instrumented vehicle



3.3.1 OBS

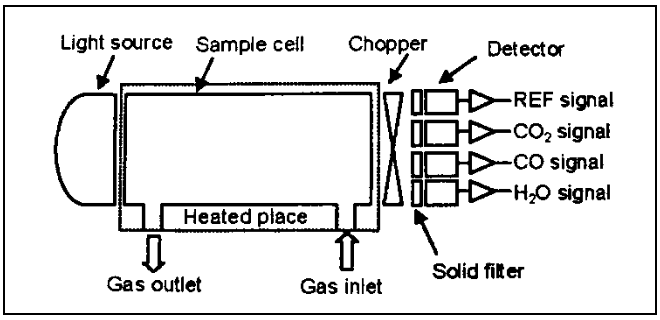
The on-board emission measurement system (OBS), also known as the Portable Emission Measurement System, provides real-time measurements of vehicle emissions. The system, Horiba model OBS-2200 (refer Appendix C: Specifications for OBS-

2200), consists of 1) a vibration-proof gas analyser for measurements of exhaust flow and emissions, 2) a tailpipe attachment bringing exhaust emissions to the gas analyser 3) a laptop for system control and data logging, 4) accessory tools include of a GPS receiver, and sensors for ambient temperature and humidity measurements and 5) two 12-volt deep-cycle gel batteries. The batteries were used to prevent an increase in engine load due to the use of power from the vehicle which would have affected fuel consumption and carbon emissions.

The OBS provides 1) concentration of gases, 2) exhaust's flow, temperature and pressure, and 3) ambient temperature, pressure and humidity as the output. Fuel consumption and emission rates (g/s) of CO, CO2, THC and NOx are calculated based on these measurements. The gas analyser of OBS provides CO_2 measurements at an accuracy of 0.03% of the full-range (0-20%) measurement (Horiba Instruments LTD 2009). In this study, all data was logged at 10Hz frequency, except for the GPS coordinate and speed that were logged at 1Hz frequency. The exhaust's flow, temperature and pressure are measured by the Pitot tube, which is attached to the exhaust pipe. With the full-scale flowrate of 10 m^3/min, the Pitot tube has an accuracy of ±1.5% of full-scale or ±2.5% of readings, whichever is the greatest (Horiba Instruments LTD 2009).

CO_2 emissions are measured by a heated-type non-dispersive infrared analyser (NDIR) developed based on the characteristic of the gases (CO, CO_2, NO, SO_2 and CH_4) that absorb infrared light. Concentration of the carbon dioxide (CO_2) is measured by running the gas through a heated sample cell at 60^{o}C. Infrared light sent from one end of the cell is then measured by the detector at the other end, where the concentration of gas is derived from the intensity of light detected (Figure 3-3).

Figure 3-3: Configuration of the heated NDIR analyser (Horiba Instruments LTD 2005)



3.3.2 VBOX-III

The VBOX-III system can provide non-contact measurements of the speed, distance, heading and position with dGPS. The differential Global Positioning System (dGPS) is an enhancement of the conventional GPS using a network of ground-based stations as an additional reference, in addition to satellite systems. The VBOX-III system can log data at frequencies between 100Hz and 1Hz at 12.5ms latency. However, parameters in this study were logged at 10Hz frequency to allow synchronisation with data from other sources. The speed measurement has an accuracy and resolution up to 0.1kph, while the distance measurement has an accuracy of 0.05%, which is less than 50cm per kilometre. With dGPS, the positioning has an accuracy and resolution up to 1.8 m and 1 cm, respectively.

3.3.3 CANBUS

The CANBUS is a multiplex wiring system used to connect intelligent devices, e.g., Electronic Control Units (ECU's) on vehicles. It is one of the five protocols used in the OBD-II's vehicle diagnostic standard, which is used for self-diagnosis and reporting on the condition of sub-systems in a vehicle. The information provided includes the engine torque, engine speed, throttle pedal and gas pedal positions, fuel consumption, brake pedal status, vehicle speed, etc.

3.3.4 Video System

The video system is a set of video cameras installed in the instrumented vehicle, which includes a front-facing camera to monitor the road environment and traffic ahead, a rear-facing camera to display the rear view and a middle camera positioned over the left shoulder of the driver to monitor the gear changing manoeuvre and body movement of the driver. The video images were used to determine the position of the vehicle in a queue and movements of lead vehicles. The images were also used for the validation of the braking status.

3.3.5 Extra Loads from Instrument Weight and Air Conditioning

The instruments weighed 115kg and consisted of three 12-volt-deep-cycle gel batteries[8] (57kg), one OBS main unit (29kg), one laptop (3kg), one flat screen monitor (3kg), one connection hub (3kg) and one CPU (20kg). In addition, air conditioning was required to maintain a suitable temperature range for the instruments. Higher fuel consumption and carbon emissions are expected because of the extra load. However, the load will not be the major concern in the investigation of CO_2 variations in this study. This is because the total load was maintained at a constant level. Therefore, relative differences in CO_2 emissions and their relationships with emission variables will be the same for each driver assessed.

3.3.6 Calibration of OBS

The OBS required calibrations on either periodical (zero/span) or one-time basis to ensure data accuracy. The gas analyser was calibrated prior to each test run. The calibration process consisted of zero and span calibrations. The zero calibration was performed using non-reactive gases, i.e., hydrogen and helium, to reset the gas analyser to initial values. The span calibration was performed using gases with predefined concentrations, i.e., propane, carbon monoxide, carbon dioxide, nitric oxide and nitrogen, to adjust the measurement to the correct value.

Other than the zero and span calibrations, another concern about the PEMS measurement was whether emissions measured at the tailpipe matched the actual emissions. This is because concentrations of CO_2 measured at the tailpipe might be delayed and diluted (Figure 3-4). Therefore, emission rates obtained from tailpipe measurements without corrections might lead to inaccuracy (Rhys-Tyler and Bell 2010). Emissions could be delayed by the response time and travel time. The response time is the time taken by the analyser to determine the gas concentration. OBS has a set of compensation time values to correct measurements of different gases to the actual

[8] 120 Ah, 12v, 410 mm × 176mm × 227mm, 19kg each.

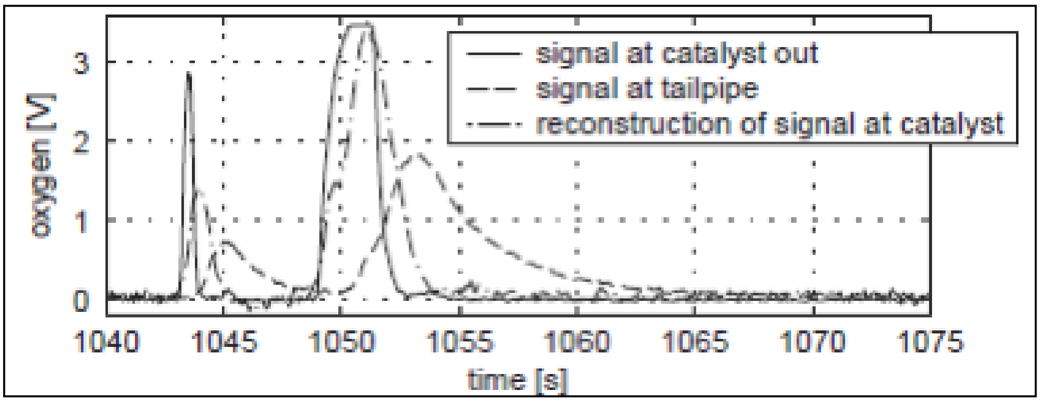
time the gases arrived at the gas analyser (Horiba Instruments LTD 2005). On the other hand, the travel time is the time elapsed when the gases flow from the engine/catalyst to the gas analyser. Travel time changes due to changes in exhaust flow are therefore difficult to calibrate. High exhaust flow induces a short delay time but low exhaust flow, especially one at or near idle, produces a long delay time (Weilenmann, Soltic et al. 2003).

Several methods had been proposed to reconstruct the actual emission output to be consistent with the vehicle operation condition. This included the equation inversion approach based on mathematical functions (Weilenmann, Soltic et al. 2003; Le Anh, Hausberger et al. 2006) and the static temporal realignment approach (Arregle, Bermúdez et al. 2006).

Le Anh's approach, validated by ARTEMIS[9], reconstructed the oxygen signal at the catalyst exit based on the analyser measurement at the tailpipe (Le Anh, Hausberger et al. 2006). Weilenmann's approach considered the dynamic flow of exhaust emissions, where the actual emission peak was reconstructed from a flattened emission signal at the analyser (Weilenmann, Soltic et al. 2003). The inversion of the exhaust system dynamics was found to be able to reconstruct the signal close to the measured signal at the catalyst (Figure 3-4). However, the inversion method has a limitation where the model parameterisation derived from a specific vehicle type may not be applicable to the other vehicle types.

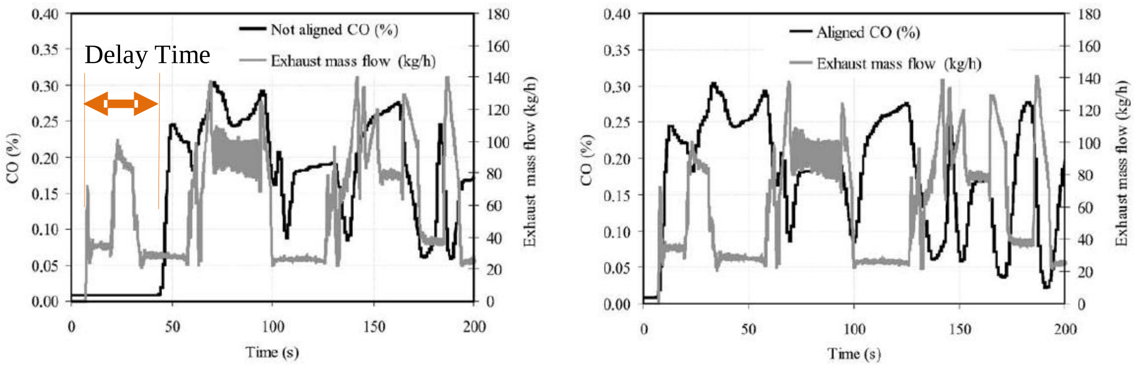
[9] Assessment and Reliability of transport Emission Models and Inventory Systems, a project by PHEM, is an instantaneous emission model based on engine emission maps created and applied at TU-Graz.

Figure 3-4: Reconstructed O_2 signal at catalyst, and signals measured at tailpipe and catalyst (Weilenmann, Soltic et al. 2003)



The static temporal realignment method shifts the measurements backward for a constant duration across the entire data series. This constant duration could be obtained based on the difference in time 1) between the engine gas flow and exhaust gas flow (Arregle, Bermúdez et al. 2006) or 2) between the surges of power (Messer, Clark et al. 1995). An example of static temporal alignment of CO emissions with the exhaust flow is illustrated Figure 3-5. Uniform shifting of delay time is most suitable for uniform exhaust flow or engine speed. Any variations in the exhaust flow might lead to different delay times and cause an error in the adjusted data (Arregle, Bermúdez et al. 2006). Overall, these methods had their reliability and feasibility problems because they are mostly designed for particular vehicle types and test conditions only.

Figure 3-5: Static temporal alignment (Arregle, Bermúdez et al. 2006)



In this study, CO_2 emissions measured by the OBS were compared with data from another source to determine if there is any delay in transport time. The second source of instantaneous CO_2 data was derived from fuel consumption logged by the CANBUS. Since CO_2 emissions derived from CANBUS correspond to the CO_2 output from the engine. The CANBUS data therefore does not suffer the delay problem and provide a suitable comparison with CO_2 emission record obtained from the OBS. Figure

3-6 illustrates a typical section of CO_2 plots for OBS and CANBUS data at signalised intersection. No significant delay in instantaneous CO_2 can be observed for the total of 551 runs. Delays were observed in a small number of runs. However, these delays were rather random and small (less than 2 seconds) (Figure 3-7). The scatterplot of instantaneous CO_2 emissions for OBS data and CANBUS data was nearly symmetrical between axis-x and axis-y (Figure 3-8), indicating that data from two sources were almost equal. The delay in CO_2 data was not calibrated/adjusted in this study. This is because of four reasons. Firstly, it is difficult to make the adjustment considering the delay was random. Secondly, the delay was not large (between 1-2 seconds). Thirdly, applying a simple static temporal realignment method might have induced error to parts of the data that did not suffer delay. This possibility is supported by the fact that the delay were found to be random across data. Finally, the inversion approach was rather complicated and highly subjected to the vehicle characteristic and test condition. Consequently, the original CO_2 data without additional adjustments was used in this study.

Instantaneous CO_2 emissions measured from the OBS were found to be smaller than those derived from the CANBUS, except during the idling mode. This might be due to flattening of the CO_2 emission signal, or the use of Horiba equation (Equation 5-1). Horiba's equation was found to be very similar to EPA's equation (U.S. Environmental Protection Agency 2005) in predicting CO_2 output for average trip condition. Therefore, both equations may not predict CO_2 emissions at special locations such as signalised intersections accurately.

Figure 3-6: Instantaneous CO_2 emissions from OBS and CANBUS (Run:1-1-5)

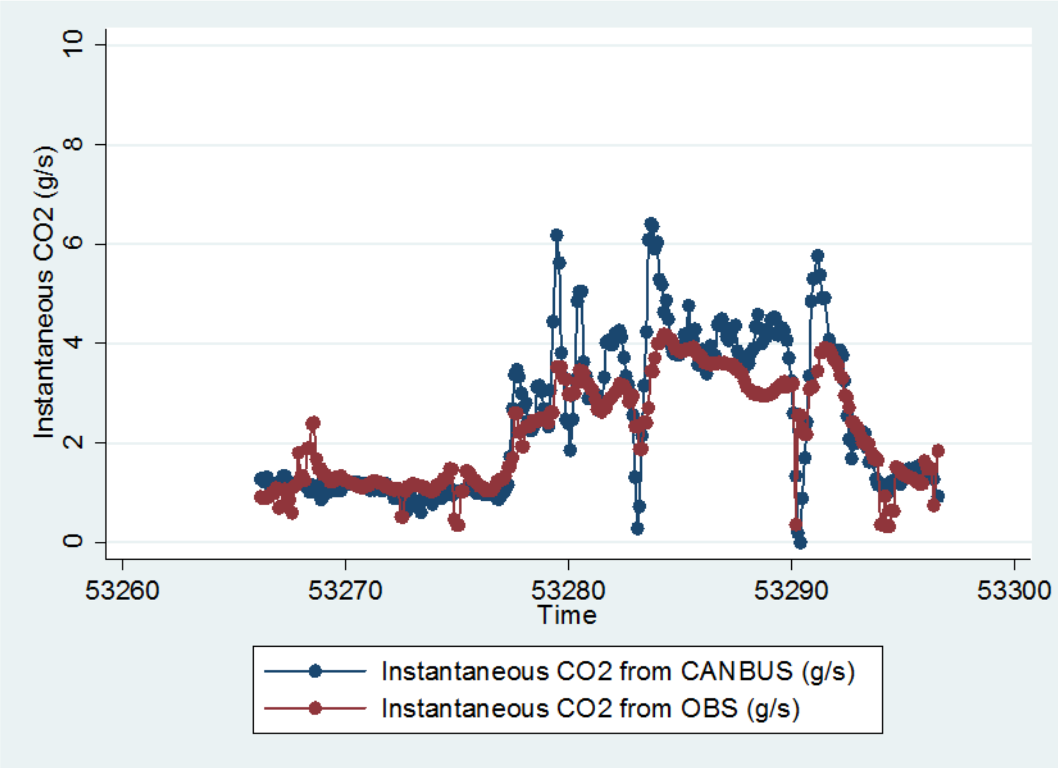


Figure 3-7: Instantaneous CO_2 emissions from OBS and CANBUS (Run:2-2-5)

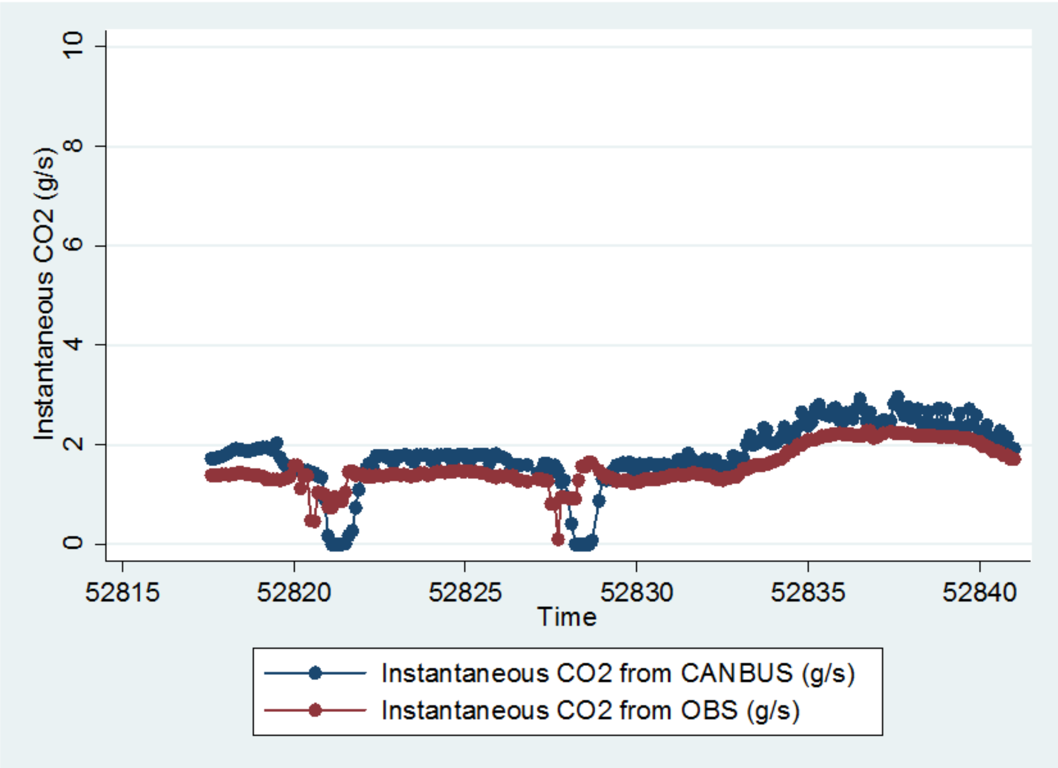
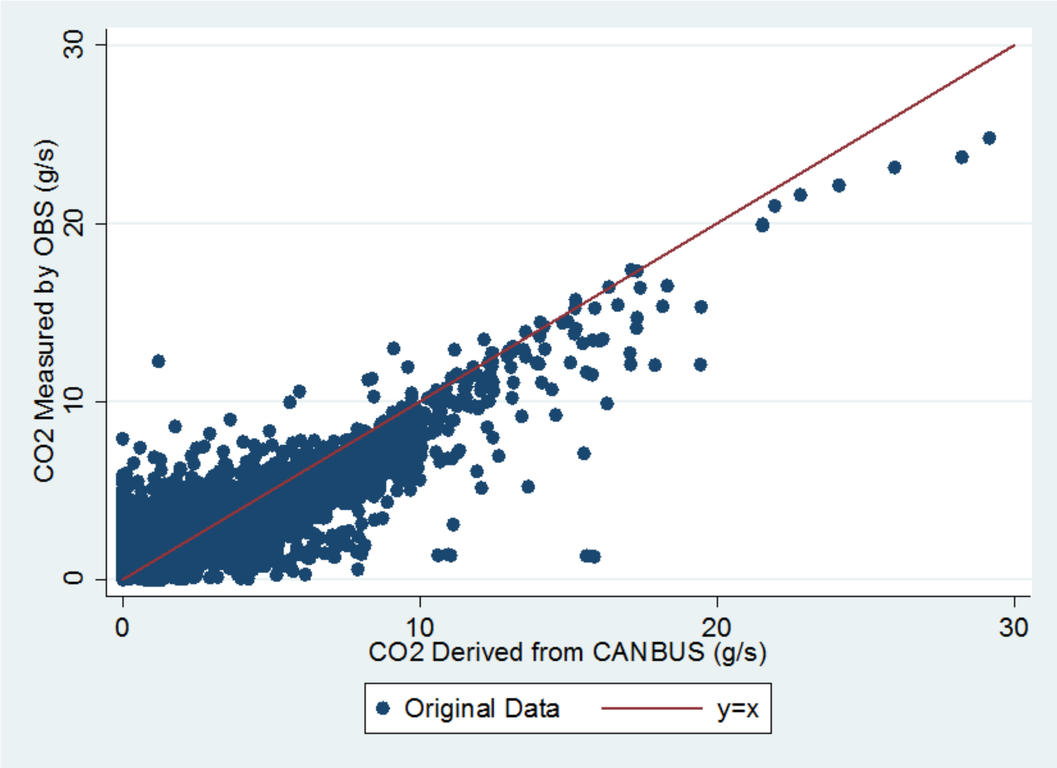


Figure 3-8: Instantaneous CO_2 from OBS vs. CANBUS



3.4 Test Route

The test route was designed based findings from preliminary analysis in Chapter 5. A number of considerations were made. Firstly, the route should be conveniently travelled from the research laboratory, which allowed instruments to be recharged and warmed-up between test runs. Secondly, the route should be at an appropriate length that allows repetition of test runs over the same signalised intersection. This allowed comparisons made on the same intersection to reduce the effects of intersection geometry variation. Thirdly, the route should have a sufficient number of signalised intersections. Lastly, the route should ideally be free from roadside parking/obstructions. This is because the vehicle manoeuvre could be severely affected by roadside obstructions. A test route was selected after taking into account all the criteria discussed above (Figure 3-9).

Four intersections were selected out of thirteen signalised intersections along the test route, and numbered as 5, 9, 10 and 11. Characteristics and layouts of the intersections are presented in Table 3-2. These intersections were selected based on the consideration of intersection boundaries, where the intersection was required to be at least 300m distance from the adjacent intersections. Refer Section 5.5 Intersection Boundary for the discussion on the intersection boundary.

The field tests were designed to be conducted during weekdays, over three weeks, using a fully warmed-up instrumented vehicle. This reduced the effect of a cold start and the effects due to variations in the road, traffic and environment. Therefore, the measured variations in CO_2 emissions would be mostly induced by the difference in driving behaviour.

Figure 3-9: Designated route for main field tests plotted on Google Map

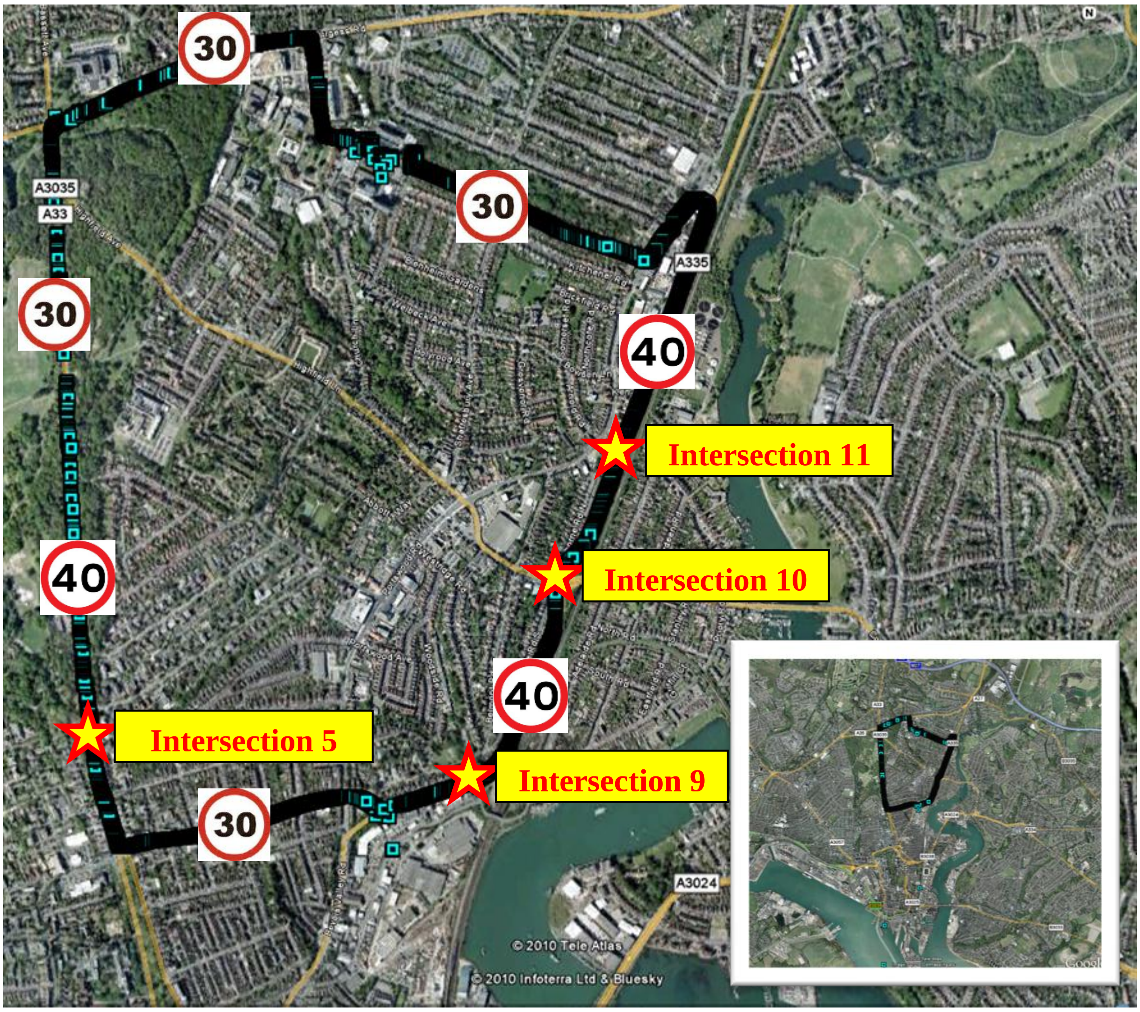
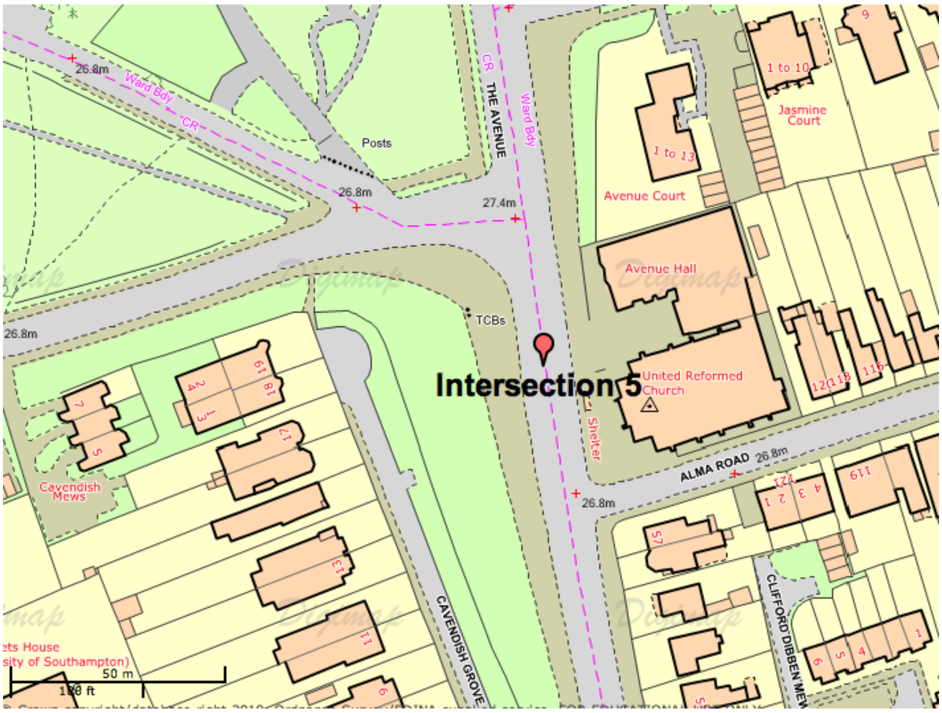
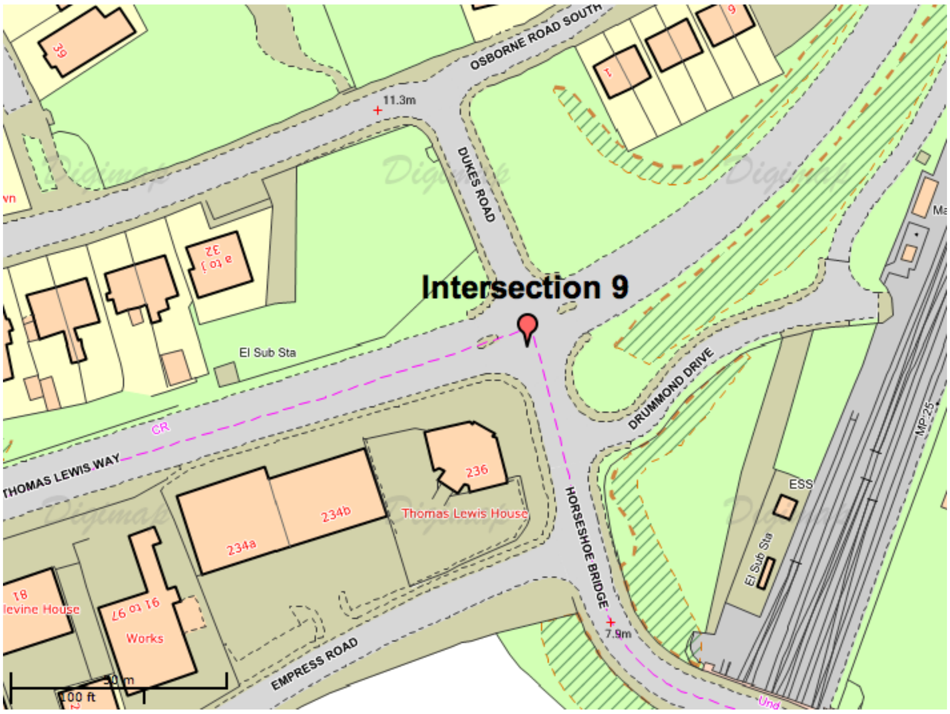
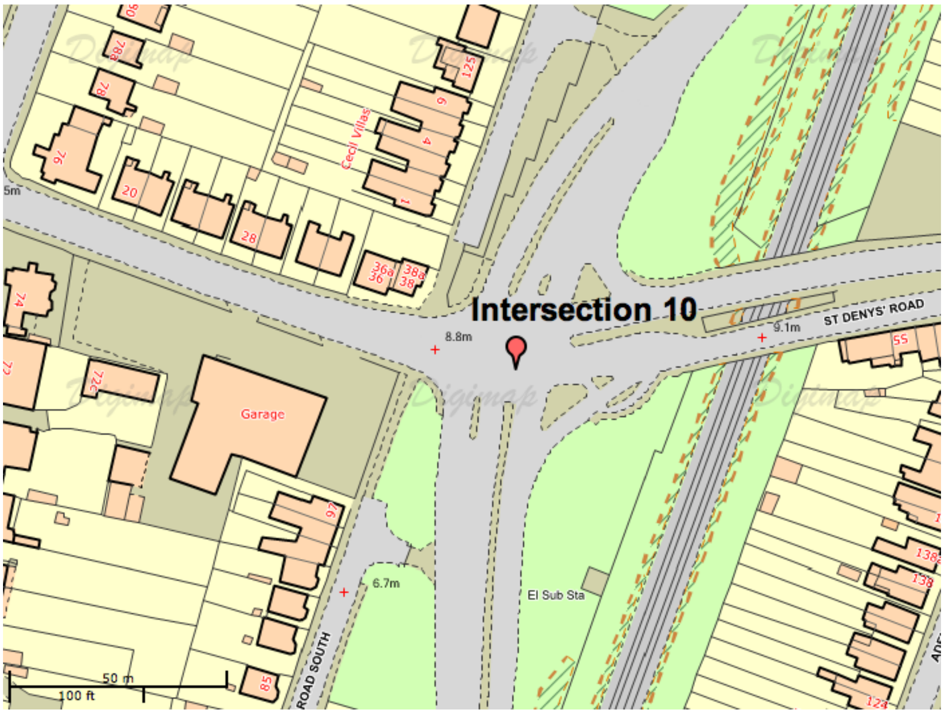
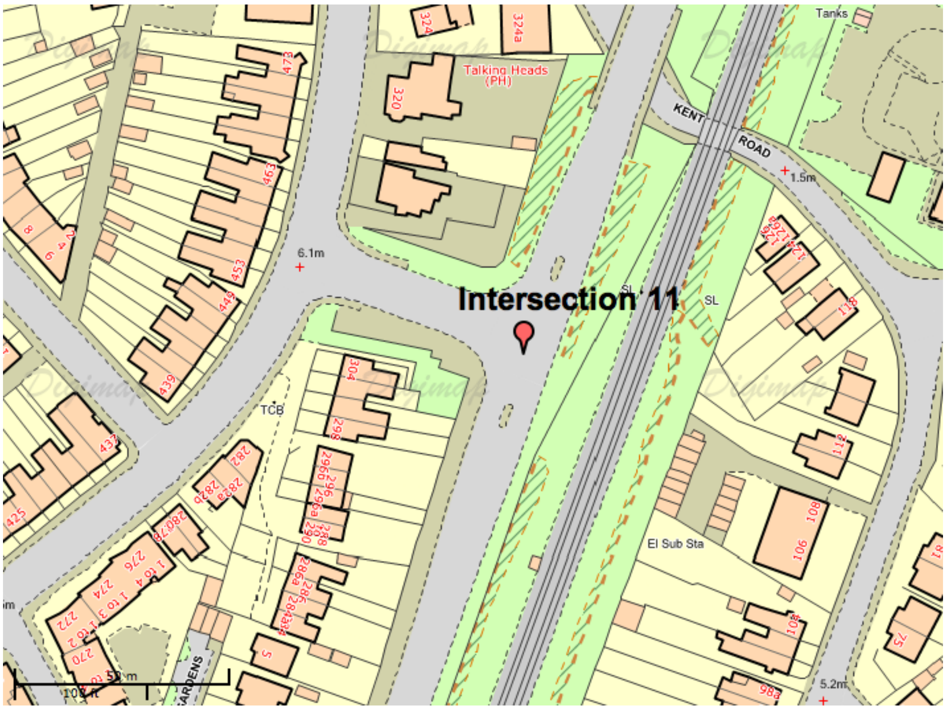


Table 3-2: Characteristics of the intersections

Intersection No.	Intersection Details
5	Pelican Crossing (The Avenue) Speed Limit: 30mph/48kph 
9	4-leg Intersection (Lodge Rd/Portswood Rd) Speed Limit: 40mph/64kph 

<table>
<tr><th>Intersection No.</th><th>Intersection Details</th></tr>
<tr><td>10</td><td>4-leg Intersection (Thomas Lewis Way/St Denys Rd)
Speed Limit: 40mph/64kph

</td></tr>
<tr><td>11</td><td>3-leg Intersection (Thomas Lewis Way/Mayfield Rd)
Speed Limit: 40mph/64kph

</td></tr>
</table>

3.5 Test Subject/Driver

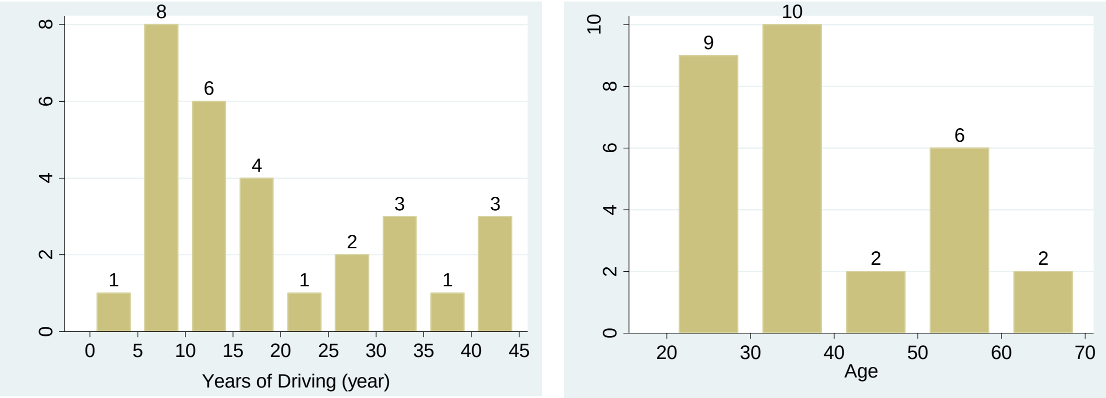
The preliminary analysis showed that there are significant differences between aggressive and economical driving and their fuel consumptions. However, this result may not be conclusive because data was collected from two drivers only for the instructed driving styles. Therefore, 32 volunteer drivers were recruited to provide a more comprehensive real world driving behaviour with their natural driving. Drivers were reminded to drive as naturally as they could and efforts were made to create a familiar driving environment for the drivers, which included the uses of music/radio, air-conditioning and a pre-test drive.

The volunteered drivers were recruited using various methods, i.e., the leaflet advertisement, poster advertisement, online advertisement, word of mouth advertisement and email circulation. Respondents to the advertisement were given a set of questionnaires (refer Appendix D: Questionnaire) prior to the selection process. The respondents were questioned about their driving experience, and asked to subjectively classify their driving behaviour, i.e., economical, normal or aggressive. The questionnaire could not be used to define the type of driving behaviour of a driver because it is difficult to categorise one's driving behaviour based on a few questions. However, the questionnaire allowed a rough classification of the drivers into three driving behaviour groups, i.e., aggressive, normal and economical. This is important as the total number of drivers to be recruited was limited to 32 only. Therefore, the rough classification helped to ensure there were representatives from each group.

Out of 120 respondents, an equal number of volunteers was randomly selected from each category. The selected test subjects were provided with an information sheet about the test and a consent form (refer Appendix E: Information Sheet & Consent Form). The volunteers were requested to drive in their normal way. Each driver completed at least four to five laps so that comparison on different driving behaviours within the driver could be made.

Thirty-two drivers were recruited for main field tests. However, data from three drivers was excluded due to malfunctioning equipment. The remaining twenty-nine drivers consisted of twelve females and seventeen males. The average age was 38.7 with the youngest 26 years old and the oldest 62 years old. Average driving experience was 18.4 years with a minimum experience of four years and a maximum experience of 44 years (Figure 3-10). This sample of drivers with different driving experiences, ages and genders have been recruited in an effort to embrace the diversity in driver population.

Figure 3-10: Distribution of driving experience and age of drivers



3.6 Sampling Method

Two types of driving, i.e., instructed driving and natural driving were considered when choosing the most appropriate sampling method to measure the variation in driving behaviour. Differences between the two methods depend on whether or not driving instructions are given and the sample size. Each method has its own merits and drawbacks.

The instructed driving method required a very small number of drivers, often less than five drivers, to produce sufficient data. On the other hand, the natural driving method demands a larger number of drivers but has an advantage of capturing more natural driving behaviour. However, there is a risk of getting an uneven sample size for different driving behaviour groups. For instance, majority of the data could be normal driving behaviour (the dominant type), with little data for aggressive or economical driving. Considering the importance of investigating natural driving, the natural driving method was chosen for this study.

Stratified sampling was adopted in order to overcome the uneven sample size problem discussed earlier. This stratified sampling method organised the drivers into three strata based on driving behaviour, i.e., aggressive, normal and economical. An equal number of drivers was randomly selected from each group. This stratified sampling method minimised the variability within a stratum, and maximised the variability between the strata (Albright, Winston et al. 2008). Therefore, all driving behaviour within a stratum would be strongly correlated in terms of CO_2 emissions.

3.7 Primary Variable/Data

All variables used in this study were obtained from the instrumented vehicle. The characteristics, usage and accuracy of the parameters/variables are discussed in this section, and validations of the variables are presented in Chapter 4.

3.7.1 Instantaneous CO_2 Emissions

CO_2 emissions are the most essential parameters for this study. This parameter was investigated in terms of instantaneous and cumulative values. Instantaneous CO_2 emissions were obtained from the OBS at 10Hz and 1Hz frequencies. 10Hz data was used for most of the analyses, while 1Hz data was sometimes used in the hypothesis analysis. Cumulative CO_2 emissions were the aggregated CO_2 emissions based on the driving mode, intersection, etc.

Accuracy of the CO_2 analyser was within 2.5% of the full scale at the measurement range of 0-20% (Horiba Instruments LTD 2005). The actual accuracy tested for the OBS analyser used in this study was 0.03% of the full scale (Horiba Instruments LTD 2009). The only external factors affecting accuracy came from fluctuations in temperature and pressure. However, the influence of these factors was only ±1% and ±2% of the reading on the span calibration. Therefore, the effect was considered relatively insignificant to the CO_2 measurement accuracy (Horiba Instruments LTD 2005) and ignored in the subsequent analysis.

3.7.2 Speed and Acceleration

Speed is one of the important emission variables. The speed parameter can be analysed in terms of the instantaneous speed and average speed. Two on-board systems provided high quality speed data in this study, i.e., CANBUS and VBOX-III. In this study, main speed data came from the CANBUS, with an accuracy of ±0.0625kph. VBOX-III with a resolution of 0.018kph was used for validation of the speed obtained from the CANBUS. All speed data was measured at 10Hz frequency.

Similarly, acceleration is also an important emission variable, and has often been used in defining driving aggressiveness. The acceleration was derived from instantaneous speed. Different intensity of acceleration could result in diverse driving behaviours. The acceleration variable could also be combined with speed to predict the CO_2 output of driving.

3.7.3 Distance

The distance parameter was used to normalize carbon emission rates to a standard unit (e.g., grams per meter) for the comparison of different driving behaviours. This parameter was also used to outline the spatial boundaries of the signalised intersections. The distance measured by VBOX-III has a resolution of 1cm and accuracy up to 0.05%. The VBOX-III distance was validated with the distance derived from the CANBUS speed (refer Chapter 4).

Distance parameters were used in terms of the distance-from-intersection and the cumulative distance. The distance-from-intersection is a relative distance of the instrumented vehicle from the centre of an intersection. A positive value indicates a distance towards downstream, and conversely, a negative value indicates a distance towards upstream. Distance-from-intersection could be plotted against speed to observe the difference in driving behaviour. The cumulative distance is the aggregated distance of driving based on the driving mode, intersection, etc., which was used for the normalisation of cumulative CO_2 emissions.

3.7.4 Instantaneous Fuel Consumption

The fuel consumption parameter is a substitute for CO_2 emissions in the absence of emission data, and a supplement for the validation of emission data considering there is a strong correlation between these two variables. Fuel consumption measurements were obtained from two instruments, i.e., CANBUS and OBS. Instantaneous fuel consumption logged from the CANBUS has an accuracy of ±2.5% at 10Hz frequency. CANBUS measured fuel consumption based on fuel injection rates, while OBS derived fuel consumption from exhaust emissions and flowrates. Fuel consumption logged from the OBS was calculated using the following equations. A fuel density of 735g/l was assumed when converting fuel from volume (in litres) to mass (in grams) (Sparks, Smith et al. 2010).

$$FC(t) = \frac{C_{CHC} \times HC_m(t) + \frac{M_C}{M_{CO}} \times CO_m(t) + \frac{M_C}{M_{CO2}} \times CO2_m(t)}{C_B}$$

Equation 3-1

$$C_B = \frac{M_C}{\alpha \times M_H + \beta \times M_O + M_C}$$

Equation 3-2

$$C_{CHC} = \frac{M_C}{\alpha_{EX} \times M_H + M_C}$$

Equation 3-3

- *FC(t)* is the fuel consumption ratio in time, *t* (g/s).
- C_B is the carbon balance in fuel.
- C_{CHC} is the average carbon mass balance of *HC* in the exhaust gas.
- *HCm(t)* is the *HC* real time mass emissions in time, *t* (g/s).
- $CO_m(t)$ is the *CO* real time mass emissions in time *t* (g/s).
- $CO2_m(t)$ is the CO_2 real time mass emissions in time *t* (g/s).
- *Mc* is the carbon atomic mass (12.011g).
- *Mco* is the carbon monoxide molecular mass (28.01g).
- Mco_2 is the carbon dioxide molecular mass (44.01g).
- *MH* is the hydrogen atomic mass (1.008g).
- *Mo* is the oxygen atomic mass (15.999g).
- α is the *H/C* atomicity ratio in the fuel (1.85 for gasoline).
- β is the *O/C* atomicity ratio in the fuel (0.0).
- α_{EX} is the average *H/C* atomicity ratio of *HC* in the exhaust gas (1.85 for gasoline).

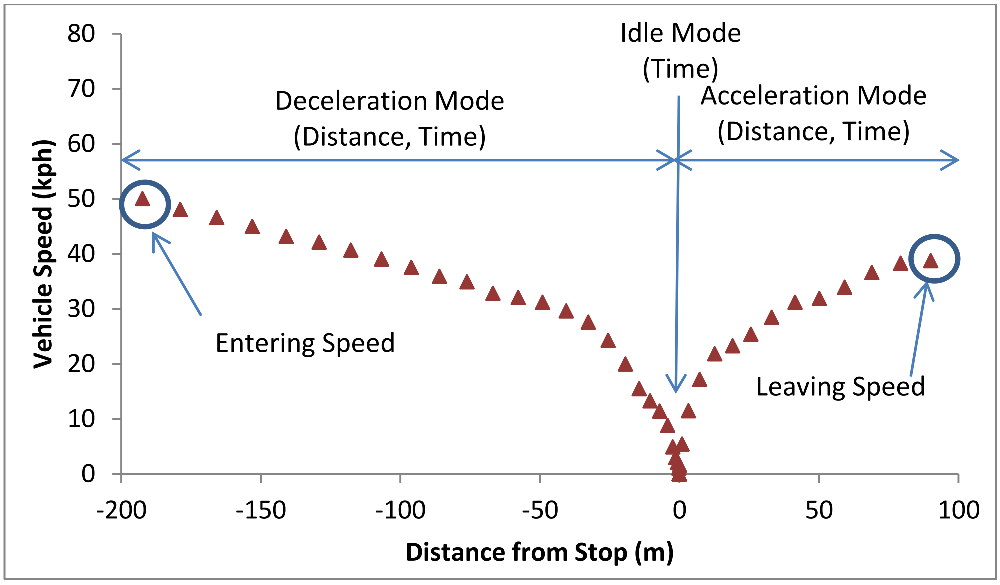
3.7.5 Vehicle Trajectory

The vehicle trajectory recorded from the VBOX-III was logged in the format of GPS coordinates, i.e., the latitude and longitude, at 10Hz frequency. The accuracy of GPS data was ensured by securing at least four satellite signals during test runs. The secondary GPS dataset of 1Hz frequency was obtained from the OBS to validate the values logged by VBOX-III. GPS coordinates were used to extract data for the designated study area by knowing the location of the instrumented vehicle.

3.8 Secondary Variable/Data

Primary data collected from the field tests was comprehensive for various analyses in later chapters. However, the primary data was divided/labelled based on the driving mode and condition for different analyses. New variables such as deceleration distance/time, acceleration distance/time, leaving speed, entering speed, etc., were introduced (Figure 3-11).

Figure 3-11: New variables



Secondary data generated based on primary data is equally important for the study. The secondary data is usually in the form of cumulative (i.e., CO_2 and duration) and average values generated from 10Hz data. These secondary variables were explained in Table 3-3.

Table 3-3: Definitions of the variables

Variable	Definition
Cumulative CO_2 Emissions	Total amount of CO_2 emissions (at 10Hz) for a driving through a signalised intersection (300m).
Average Speed	Average of instantaneous speed (at 10Hz) for a driving through a signalised intersection (300m).
Non-optimum-speed Duration	Total amount of time when speed is outside the optimum speed range (60-80kph), for a driving through a signalised intersection (300m).
Average Acceleration	Average of instantaneous acceleration (at 10Hz) for a driving through a signalised intersection (300m).
Positive Acceleration Duration	Total amount of time when the acceleration exceeds $0.0m/s^2$, for a driving through a signalised intersection (300m).
Negative Acceleration Duration	Total amount of time when the acceleration is below $0.0m/s^2$, for a driving through a signalised intersection (300m).
High Acceleration Duration	Total amount of time when the acceleration exceeds $1.5m/s^2$, for a driving through a signalised intersection (300m).
Braking Duration	Total amount of braking time for a driving through a signalised intersection (300m).
Idling Duration	Total idling time for a driving through a signalised intersection (300m).
Low Gear Duration	Total amount of time when the gear engaged is between gear one and gear three, for a driving through a signalised intersection (300m).

3.9 Data Frequency

Conceptually, 10Hz emission data could map emissions with the engine state better than 1Hz data. This is because some "emission peaks" last less than 1 second, and therefore, might be missed in the 1Hz emission data (Ajtay, Weilenmann et al. 2005). However, 10Hz data tends to exhibit more noise than 1Hz data, which might require smoothing to eliminate the outliers. Without the proper smoothing, the quality of 10Hz data might be worse than 1Hz data. In this study, 10Hz data was used for the microscopic analysis of carbon emissions resulting from driving behaviour, and 1Hz data was used for the hypothesis analysis. However, none of the 10Hz data collected in this study showed a significant level of noise, except for the acceleration parameter derived from speed. Therefore, smoothing was applied to the 10Hz acceleration data to reduce the level of noise (refer Section 4.5 Smoothing Acceleration Data).

3.10 Methodology for Statistical Analysis

Statistical analyses used in this study were the hypothesis testing and cluster analysis. The former investigated variations in CO_2 emission between different driving behaviour. The latter was used to categorise driving behaviour based on the corresponding CO_2 output. Procedures for hypothesis testing and cluster analysis were presented in Figure 3-12 and Figure 3-13.

Figure 3-12: Hypothesis testing steps

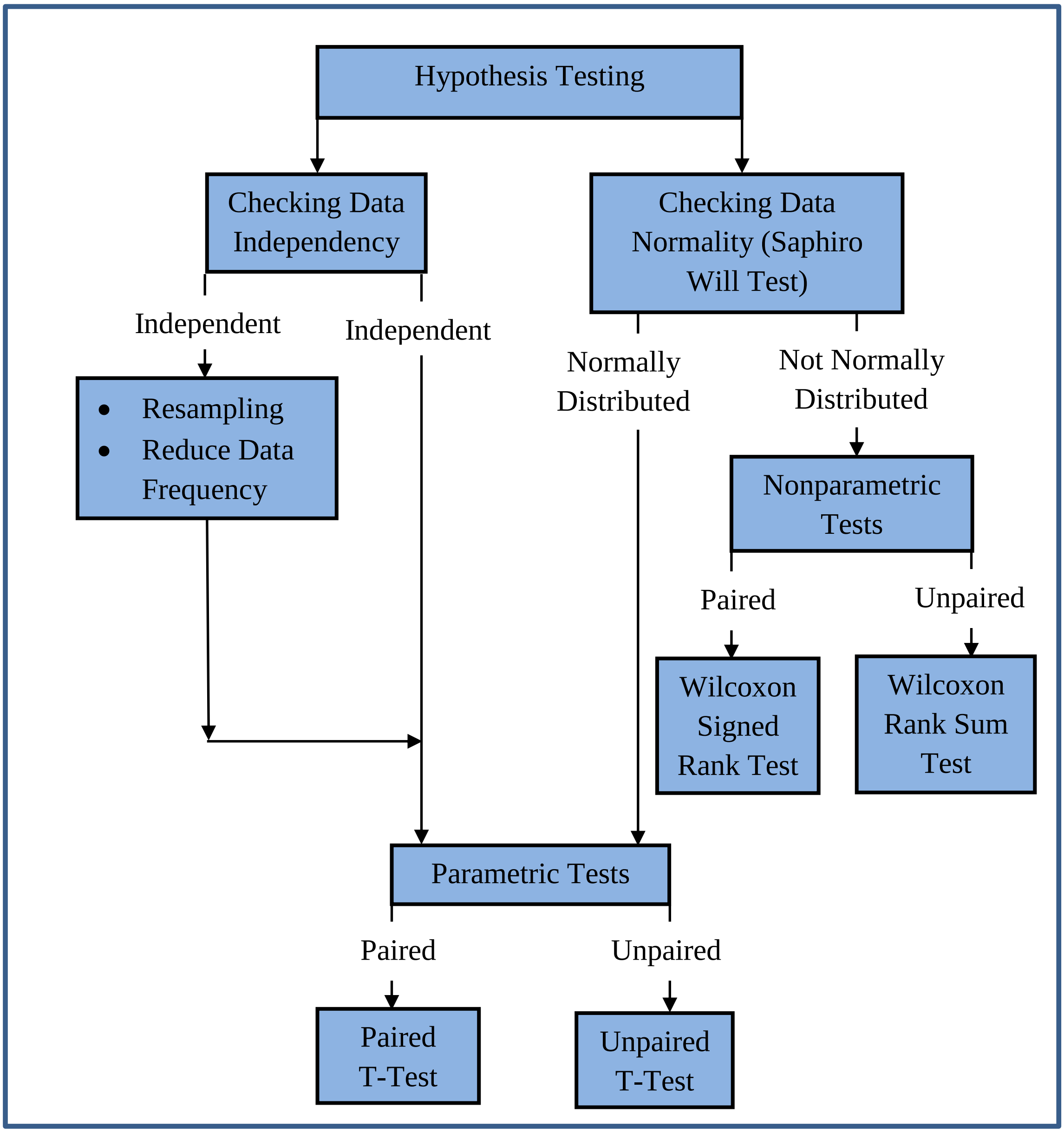
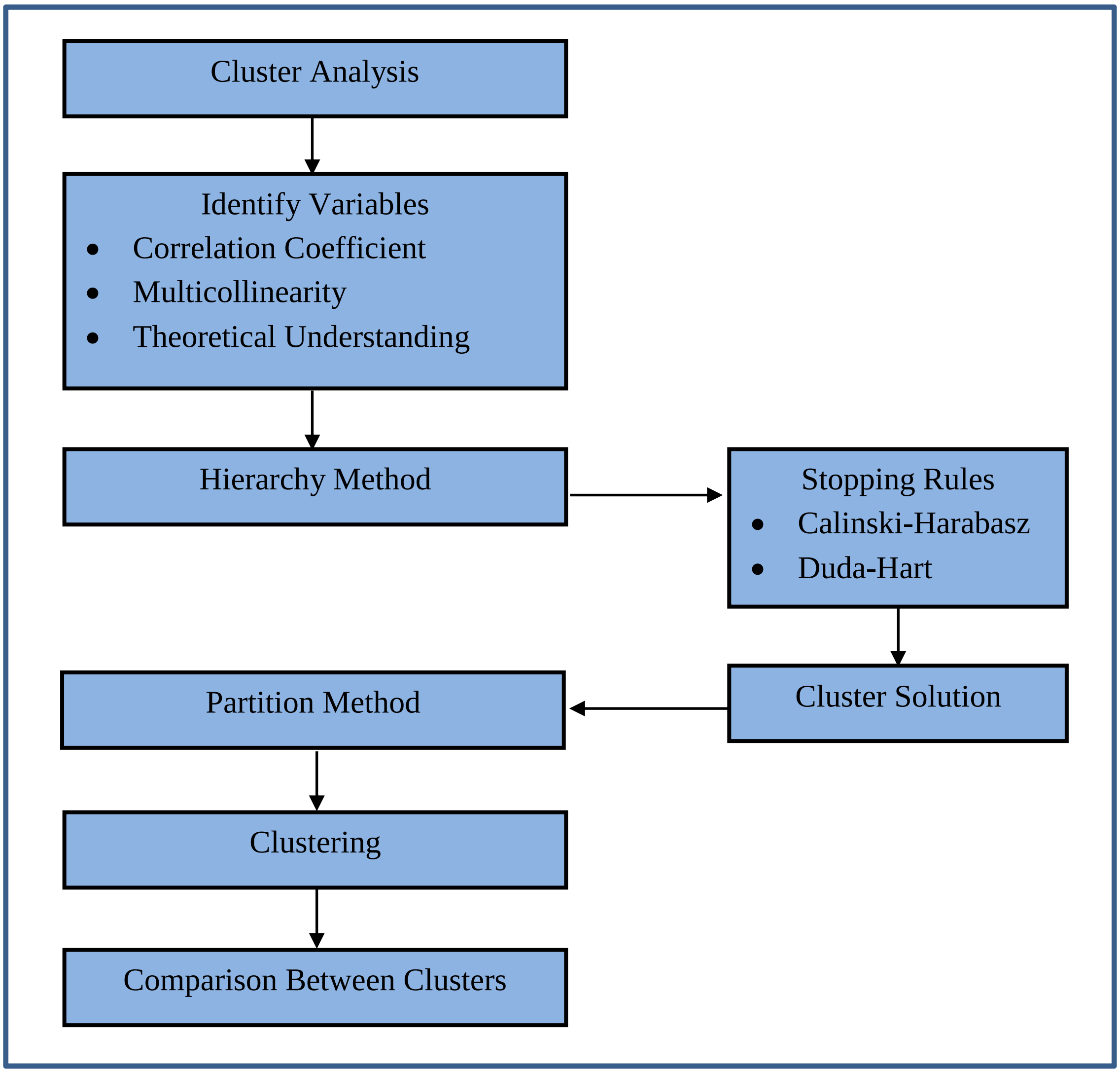


Figure 3-13**: Cluster analysis steps**



Chapter 4 Data Preparation

4.1 Introduction

A systematic data processing method could reduce significantly the analysis time, and prevent errors. Therefore, massive dataset collected from on-road tests was processed before the main analysis. Steps involved in the data processing were presented in following sections. Section 5.2: Synchronisation of data from different sources. Section 5.3: Validation of the parameters collected from the instrumented vehicle. Section 5.4: Extraction and labelling of data to the designated study area according to the predefined intersection boundaries. Section 5.5: Resampling of data from different sources to the standard timestamp and frequency. Section 5.6: The sensitivity analysis on the data frequency to determine the most appropriate frequency for the main analysis. Section 5.7: Smoothing of instantaneous acceleration to remove outliers. Section 5.8: Meeting assumptions of the hypothesis test.

4.2 Data Synchronisation

Data was collected from a number of instruments at different frequencies and clocks. Therefore, the synchronisation is important to allow these data to be combined, so that the measured driving behaviour can be accurately matched with the emissions and vehicle operation conditions. This was achieved in two stages, i.e., the clock synchronisation and frequency synchronisation.

Every instrument has its own computer clock. The difference in clock time between the instruments could be several seconds. Without clock synchronisation, events logged from different instruments would not match each other. A synchronisation software was therefore used to synchronise the computer clocks of each instrument. The software, NTP FastTrack, was developed by facelab® based on Network Time Protocol (Seeing Machines 2007).

The frequency synchronisation can be achieved by resampling data of different frequencies to 10Hz with a standard timestamp. This was achieved by using a resampling program written in Matlab (refer Appendix F: Data Resampling Program Code). The resampling program interpolated the values between two points linearly at a constant interval of 0.1 s across the entire dataset (Figure 4-1).

As the result of the interpolation, the gear-engaged status and brake-pedal status were converted into decimal values. The variables were then rounded to the nearest integer to correct the values.

Figure 4-1: Resampling (Left) Before, (Right) After

Time_CANBUS	Event_No	Gear_Engaged	Speed_CANBUS
52800.24	2	3	37.8125
52800.34	2	3	37.8125
52800.44	2	3	37.875
52800.55	2	3	37.875
52800.63	2	3	37.6875
52800.73	2	3	37.6875
52800.82	2	3	37.375
52800.92	2	3	37.25
52801.04	2	3	37.3125

Original Data

Timestamp (s)	Event_No	Gear_Engaged	Speed_CANBUS
52800.3	2	3	37.8125
52800.4	2	3	37.85
52800.5	2	3	37.875
52800.6	2	3	37.757813
52800.7	2	3	37.6875
52800.8	2	3	37.444444
52800.9	2	3	37.275
52801	2	3	37.291667
52801.1	2	3	37.151786

Standard Timestamp at 10Hz

4.3 Data Validation

The main parameters, such as CO_2 emissions, fuel consumption, vehicle speed, distance, brake pedal status, GPS coordinates, etc., were collected from the CANBUS, VBOX-III and OBS. Validations of these parameters is important to ensure the reliability of the data and results. These parameters were validated by comparing the data obtained from different instruments using hypothesis tests and visual check of emission plots. Non-parametric hypothesis tests were performed to comply with the assumptions (refer Section 4.6 Meeting Assumptions of Hypothesis Test).

4.3.1 Carbon Emissions

In order to validate the instantaneous CO_2 emissions measured from the OBS, a comparison can be undertaken by using CO_2 values derived from fuel consumption (reported by the CANBUS). Fuel consumption data can be used to approximate the equivalent CO_2 value using the following equation (Horiba Instruments LTD 2005).

$$IC = IF * \frac{Mco_2}{\alpha M_H + Mc} * Cco_2 = 3.14\, IF$$

Equation 4-1

- IC is the instantaneous CO_2 emissions (g/s)
- IF is the instantaneous fuel consumption (g/s)
- M_{CO2} is the carbon dioxide molecular mass (44.01 g)
- α is the H/C atomicity ratio in the fuel (1.85 for petrol, 1.9 for diesel)
- M_H is the hydrogen atomic mass (1.008 g)

- M_C is the carbon atomic mass (12.011 g)
- C_{CO2} is the ratio of CO_2 per total emissions (0.99).

The U.S. Environmental Protection Agency, 2005, also suggested a similar fuel consumption model. It was based on assumptions that 1) 99% of the carbon in fuel is oxidised to CO_2, 2) one gallon of petrol consists of 2421g of carbon (C), 3) the ratio of the CO_2 molecular weight to Carbon is 44/12 (U.S. Environmental Protection Agency 2005). Therefore, for petrol density of 735 grams/litre, one gram of petrol produces 3.16 grams of CO_2.

CO_2 values logged from the OBS and CO_2 values derived from the CANBUS (using Equation 4-1) were plotted against time (Figure 4-2 shows a typical plot for one of the driving test). The curves representing instantaneous CO_2 emissions from two different sources were found to be quite similar (Figure 4-3).

However, hypothesis tests are required in order to find out whether or not data from two sources are the same. Two types of hypothesis tests can be used, namely parametric and non-parametric tests. The former required the data to meet the normality and independent assumptions. The latter are applied to data that does not meet these assumptions. Shapiro-Wilk test for normality check was performed and histogram was plotted for CO_2 data obtained from the OBS and CANBUS. The Shapiro-Wilk test showed a probability of 0.0000, indicating that the data was not normally distributed (Figure 4-4). Histograms for both data also showed non-Gaussian distributions (Figure 4-5). T-Test is not valid for testing hypothesis of these data. Therefore, the non-parametric hypothesis test (Wilcoxon Signed-Rank test) was performed.

Results of Wilcoxon Signed Rank test showed that the distribution of CO_2 emissions measured from the OBS was significantly different from that of CANBUS. However, this does not mean that CO_2 measured from the OBS is not accurate, but indicated that CO_2 emissions predicted from fuel consumption (e.g. using US EPA or Horiba's equations) cannot accurately reflect the changes in CO_2 emissions at intersections. Nonetheless, a pairwise correlation coefficient of 0.9159 for two data sources indicated that changes in CO_2 recorded by the OBS were accurately reflected by that of CANBUS. Besides, the mean CO_2 emission for OBS measurements was only 1.6% different from the CANBUS, with standard deviations ranging between 1.8 and 2.2 (Table 4-1). This indicates that in overall, CO_2 measurements obtained from the OBS were not greatly different from the measurements of CANBUS.

In summary, CO_2 data could not be validated using data derived from fuel consumption, because the existing CO_2 model prediction based on fuel consumption is for average trips, which is not suitable for signalised intersections that experienced more extreme vehicle operating conditions. However, the average CO_2 emissions obtained from the OBS were not greatly different from those obtained from the CANBUS (Figure 4-2, Table 4-1).

Figure 4-2: A typical plot of instantaneous CO_2 emissions for OBS and CANBUS

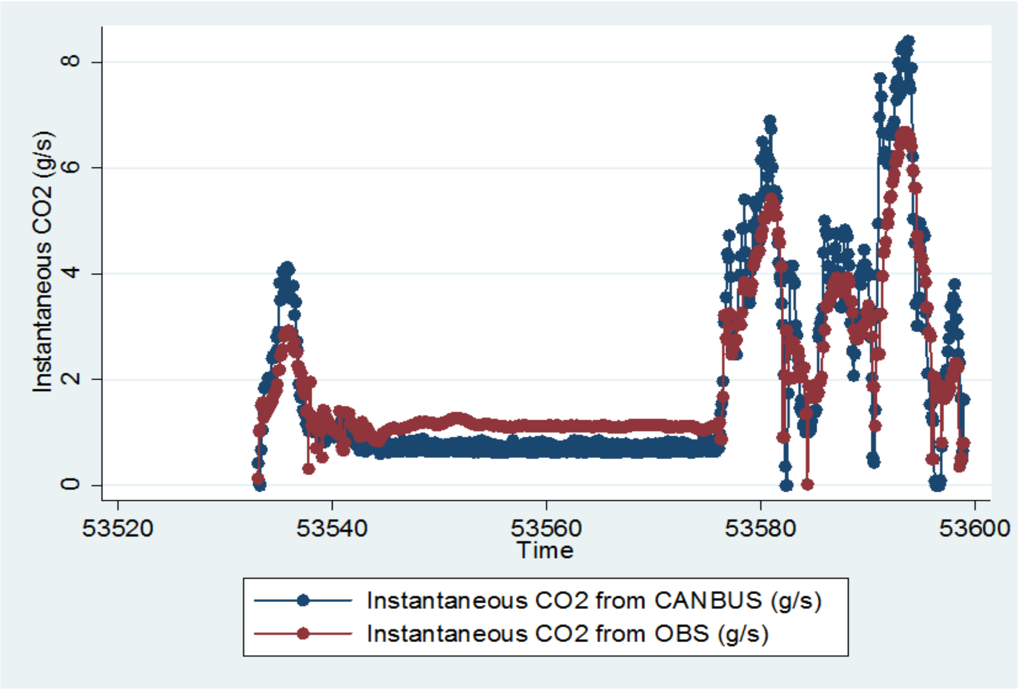


Figure 4-3: CO_2 emissions plots for OBS vs. CANBUS

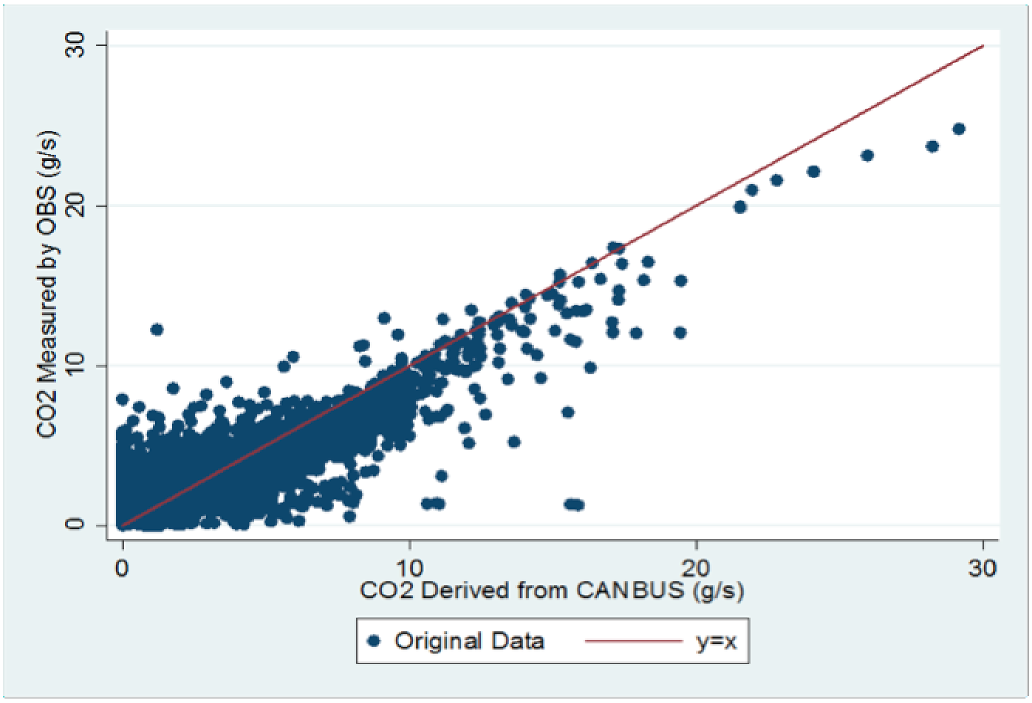


Figure 4-4: Shapiro-Wilk Test

```
. swilk co2_obs

                   Shapiro-Wilk W test for normal data

    Variable |        Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
     co2_obs |     200742    0.86013    6742.579    24.894    0.00000

. swilk co2_canbus

                   Shapiro-Wilk W test for normal data

    Variable |        Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
  co2_canbus |     200747    0.84613    7417.692    25.163    0.00000
```

Figure 4-5: Histograms: (Left) CO_2 logged by OBS (Right) CO_2 derived from CANBUS

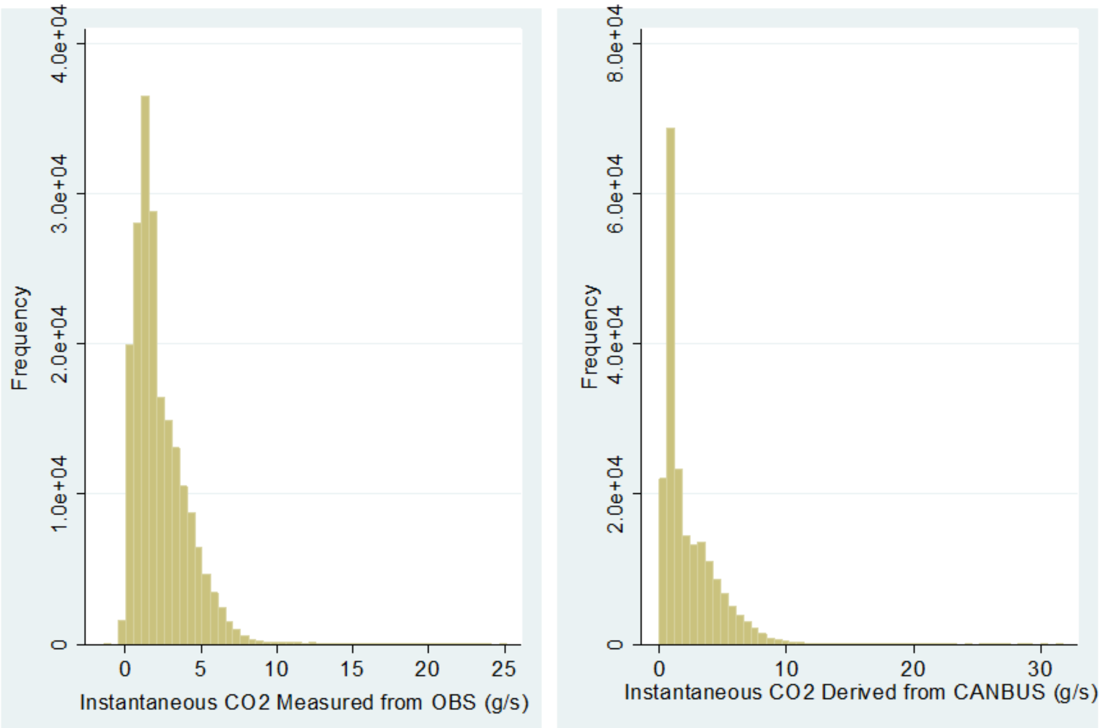


Table 4-1: Statistics for CO_2 data obtained from OBS and CANBUS

	co2_OBS (A)	co2_CANBUS (B)	Difference (%) (|A-B|)/B
Mean	2.353	2.315	1.6
Standard Deviation	1.820	2.210	17.6
Inter Quartile Range	2.159	2.525	14.5
95th Percentile	5.729	6.615	13.4

4.3.2 Distance

VBOX-III measures the distance based on GPS coordinates. This distance was validated with the distance derived from the instantaneous vehicle speed reported by the CANBUS. The distance values were found to match well between the two sources, except at certain locations where satellite signals were poor (Figure 4-6). However, the affected segments have no impact on the analysis because the lost data was relatively small and the segments were outside the intersection boundaries. A normality test indicated that the data was not normally distributed (Table 4-3). Therefore, Wilcoxon Signed Rank test was required for testing the hypothesis. The distance data obtained from two sources, VBOX and CANBUS was found to be significantly different at 95% confidence level (Table 4-2). However, this might because the result of the large differences between these two sources during the loss of the satellite signal. Since the data shows great resemblance between the two sources, except during the loss of the satellite signal (Figure 4-6), speed data obtained from the field test was considered accurate.

Figure 4-6: A section of instantaneous distance plot for VBOX-III and CANBUS

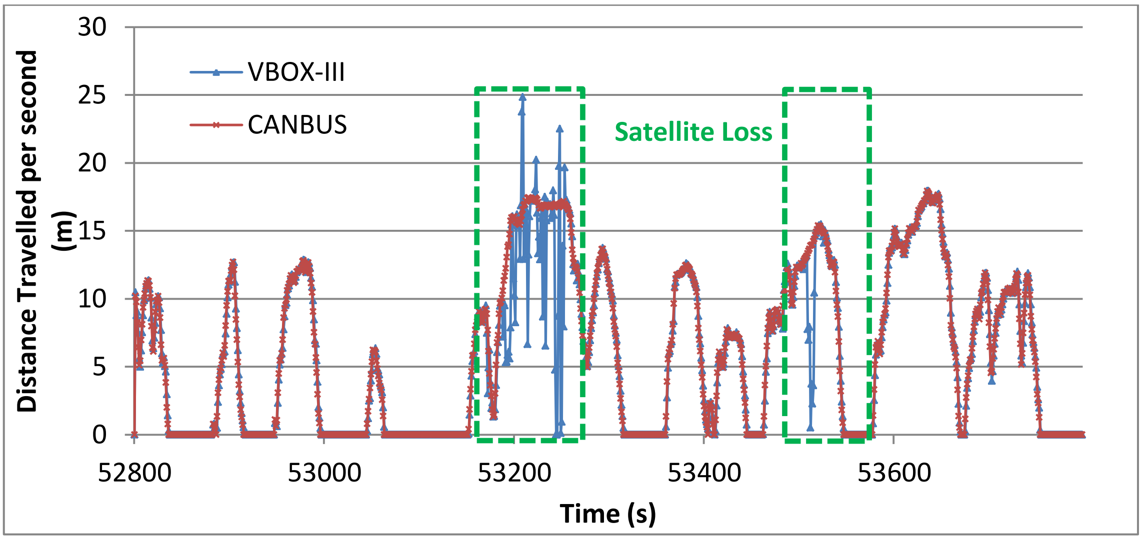


Table 4-2: Wilcoxon Signed Rank Test on distance data

Wilcoxon signed-rank test

sign	obs	sum ranks	expected
positive	1695	4895765.5	4388175
negative	1260	3880584.5	4388175
zero	1492	1113778	1113778
all	4447	9890128	9890128

unadjusted variance 7.331e+09
adjustment for ties -7.625
adjustment for zeros -2.771e+08

adjusted variance 7.054e+09

Ho: distance_vbox = distance_canbus
z = 6.044
Prob > |z| = 0.0000

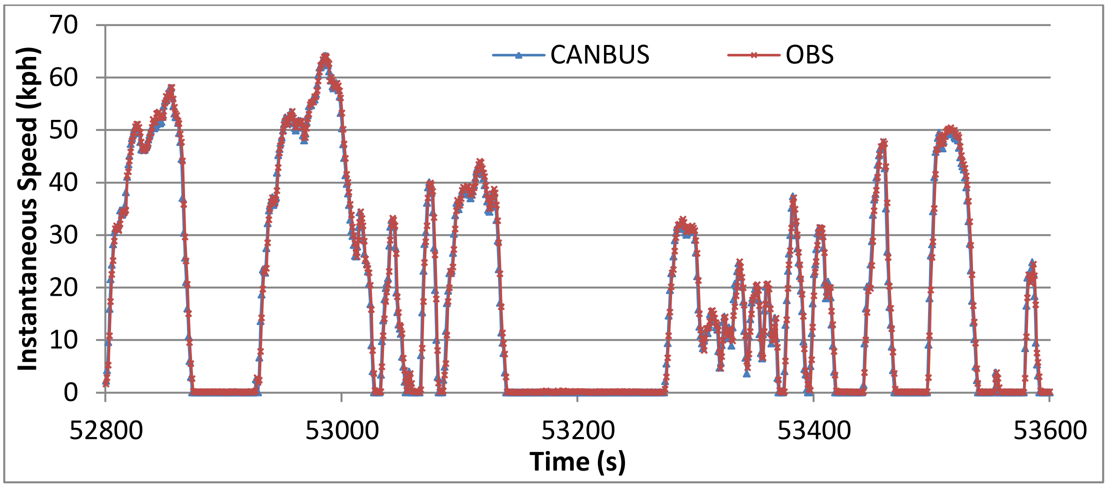
Table 4-3: Normality test on distance data

Shapiro-Wilk W test for normal data					
Variable	Obs	W	V	z	Prob>z
distance_v~x	4447	0.95897	100.128	12.042	0.00000
distance_c~s	4447	0.96528	84.733	11.606	0.00000

4.3.3 Vehicle Speed

Vehicle speed (1Hz) obtained from the CANBUS was used as the main dataset, which was validated with speed logged by the OBS. A good match was found between the two datasets (Figure 4-7).

Figure 4-7: A section of instantaneous speed plot for CANBUS and OBS



4.3.4 Brake Pedal Status

A test was established to validate the brake pedal status with the video image in the laboratory. Firstly, the clock of video cameras was synchronised with the clock of the CANBUS. Then, a video camera was positioned at the bottom of the dashboard, which is adjacent to the brake and gas pedals. During the validation process, the brake pedal was pressed and released at different times.

Brake pedal status was logged as either 0 or 1, where 0 is when the brake pedal is not applied and, 1 represents the brake pedal is applied. Brake pedal status logged from the CANBUS was found matching with the actual pedal movement in the video image. For example, the brake pedal was applied, and the brake pedal status (Brake_Pedal_Sts) was recorded as 1 at 16:02:02:89 hour (Figure 4-8). The brake pedal status was recorded as 0 when the brake pedal was released at 16:02:08:22 hour (Figure 4-9).

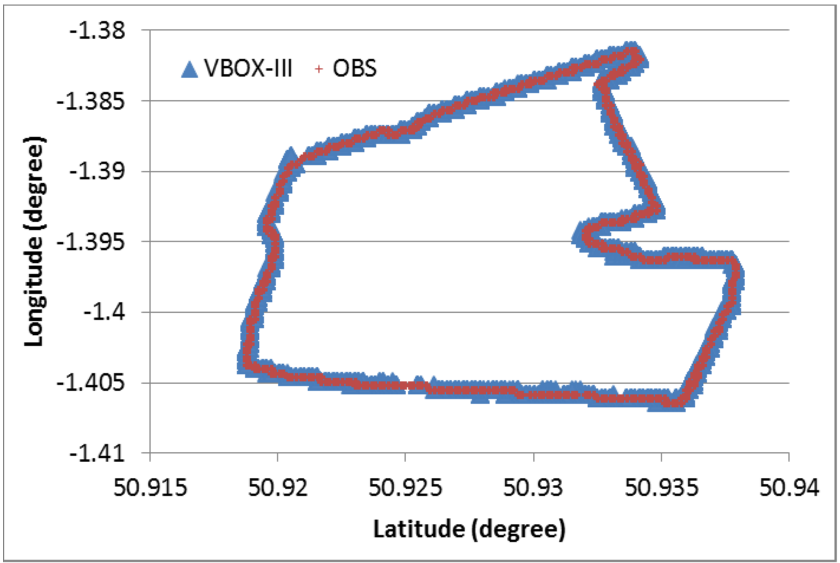
Figure 4-8: Brake pedal status and corresponding video image when brake was applied

Figure 4-9: Brake pedal status and corresponding video image when brake was released

4.3.5 GPS Coordinates

In preliminary data, VBOX-III lost the satellite signals when there was a roadside obstruction or in poor weather conditions. In a typical test run, 57 out of 9401 GPS coordinates and speed data were lost. However, the remaining GPS coordinates were found to be identical to GPS coordinates obtained from the OBS (Figure 4-10), and the GPS data of the OBS was used in the main analysis.

Figure 4-10: Plots of GPS coordinates at 10Hz



4.4 Data Extraction and Labelling

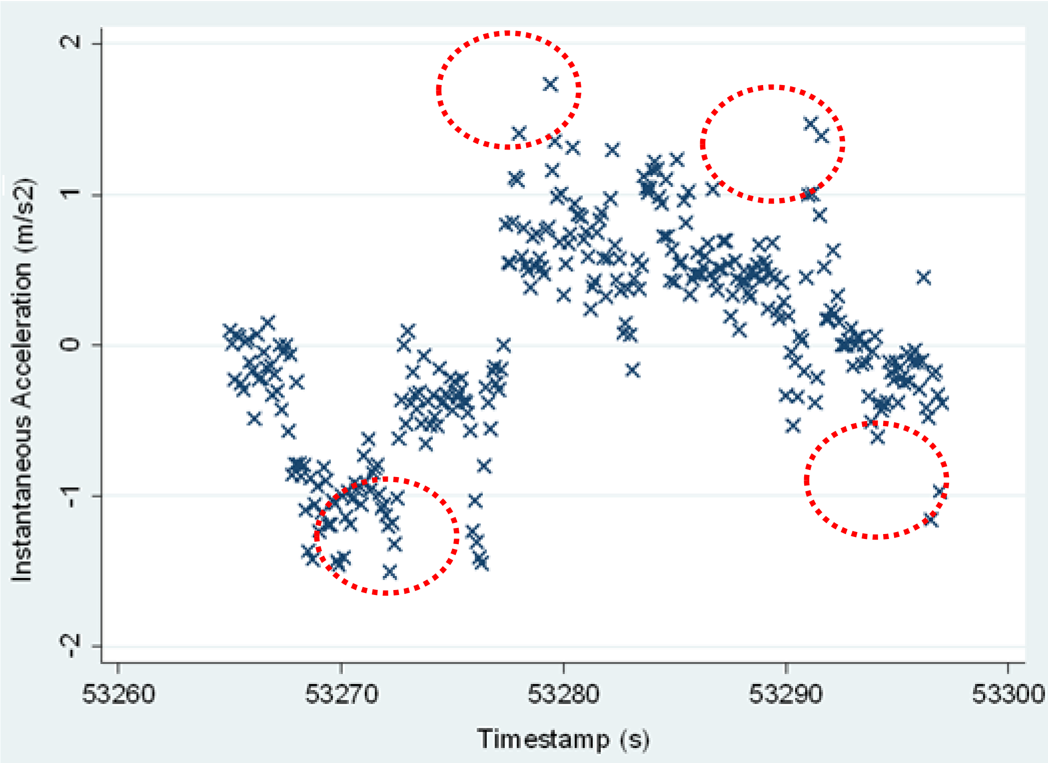
Data extraction was used to extricate data for intersection region only. This is useful in focusing on the driving behaviour at signalised intersections. In addition, it reduced computing time and complexity of the analysis. This step was performed after the data was synchronised in terms of clock time and data frequency.

All data within 200m distance upstream and 100m distance downstream of the signalised intersections was extracted based on the intersection boundaries defined earlier. Data for every 0.1 seconds interval was then labelled according to the driver identity, intersection number, lap number and driving mode (deceleration, acceleration, idle and cruise).

4.5 Smoothing Acceleration Data

Acceleration data used in this study was time series data derived from speed. Time series data has an inherent flaw of random noise at high frequency. The acceleration data was found to show some levels of noise at 10Hz frequency (Figure 4-11). Lowering the data frequency might reduce the noise. However, considering the emission peak could be shorter than 1s, data at 0.1s interval (10Hz) can better capture the extreme emission event. An appropriate method of reducing random noise is through smoothing, where applying an appropriate smoothing could remove noise and reveal the underlying trend of the data (StatSoft Inc. 2011).

Figure 4-11: Instantaneous acceleration at 10Hz frequency

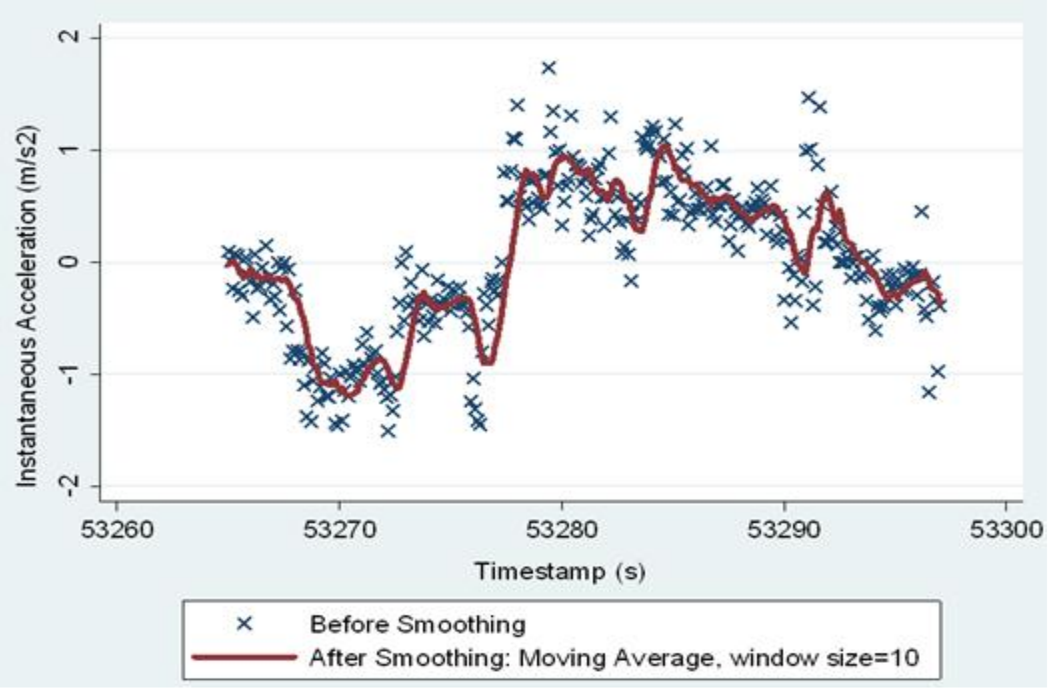


Time series data in transportation could be smoothed by two methods, i.e., Moving Average and Exponentially Weighted Average (Washington, Karlaftis et al. 2003).

Moving Average Method

According to Statsoft Inc., 2010, the Moving Average method uses a linear phase filter to calculate the local mean for one-period-ahead prediction, *y(t)*, where *y(t)* is equal to the simple average of the last *k* observations centred at the period *t-(k+1)/2*. The moving average method is simple to use. However, all the estimated local means have a uniform time lag of *(k+1)/2* periods. The extent of smoothing and lag is lesser if the *k* value is smaller and vice versa. Often, the best fit of data could be obtained by adjusting the *k* value through a visual check of the original data and one-period-ahead prediction (StatSoft Inc. 2011). Applying the Moving Average method to acceleration data in this study using a smoothing window size, *k* equal to 10, the smoothed acceleration data was found to be notably lagged (Figure 4-12).

Figure 4-12: Initial acceleration and smoothed acceleration using moving average method (k = 10)



Exponentially Weighted Moving Average Method

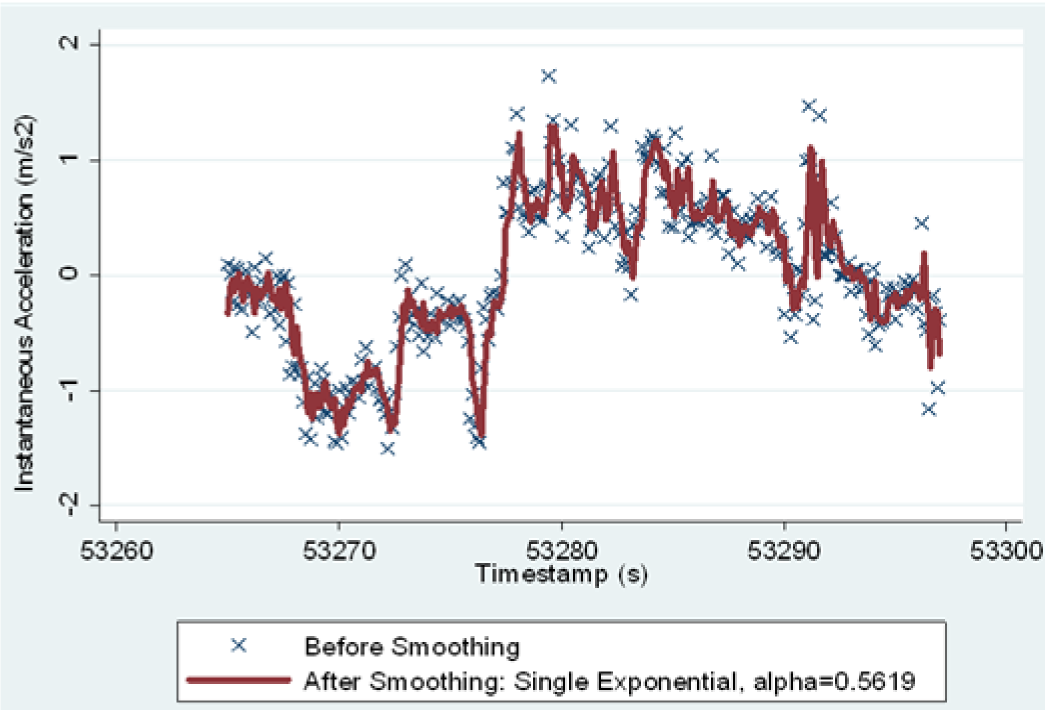
The Exponentially Weighted Moving Average method is modified from the Simple Moving Average Method. Different filters could be used for this method based on the trend of data. The filters can be categorized into single exponential, linear exponential and quadratic exponential types. In general, these filters apply an algorithm that assigned more weight to the recent data point, and progressively reduced the weight of the past data point. The algorithm is typically suitable for modelling traffic conditions near congestion since such data tends to display extreme peaks, unstable behaviour and rapid fluctuations (Washington, Karlaftis et al. 2003), which is similar to the condition at signalised intersections. Therefore, its ability to respond quickly, and smaller influence on the current value (from preceding values) make this exponential smoothing method a useful traffic engineering forecasting tool (Williams B.M., Durvasula P.K. et al. 1998).

According to Statsoft Inc., 2010, the prediction using the Exponentially Weighted Moving Average method is based on an interpolation between previously predicted values and the current observation, where the smoothing constant, α, controls the closeness of the interpolated value to the most recent observation. The degree of the exponent dictates the number and type of smoothed series used in the prediction. The forecasting is based on an extrapolation of trends, either linear or quadratic, between centres of the smoothed series. Single exponential used only one smoothed series, whereas linear and quadratic exponentials extrapolate through two smoothed series based on linear and quadratic curves, respectively. The single exponential approach works well if the data contains no trend or cyclic pattern, and the most-recent values are more significant than past values. Linear exponential is most appropriate for data with a trend but without a cyclic pattern, while quadratic exponential deals with data containing both trend and cyclic patterns (StatSoft Inc. 2011).

No specific trend or cyclic pattern was found in the acceleration dataset in this study, and the most recent value was more significant in the one-period-ahead prediction compared with the past values. Therefore, the single exponential method was used for the smoothing. Sum-of-Squared-Error (SSE) and Mean-Squared-Error (MSE), the most commonly used lack-of-fit indicators in statistical fitting procedures (StatSoft Inc. 2011), were used as the index of fitness in this method. A smoothing constant of 0.5619 was then applied to the acceleration dataset based on the minimum SSE value.

According to Statsoft Inc., 2010, a visual check can be a powerful method of determining whether the smoothing model fits the data (StatSoft Inc. 2011). A visual check on the observed data vs. smoothed data plot showed that the use of optimal smoothing reduced some noise but still maintained a reasonable acceleration profile (Figure 4-13).

Figure 4-13: Initial acceleration and smoothed acceleration using optimal smoothing constant of 0.5619 based on least SSE



4.6 Meeting Assumptions of Hypothesis Test

The hypothesis test, e.g., paired and unpaired T-Test or Z-Test can be used to compare the difference between study cases. T-Test commonly used for a sample size equals or smaller than 30, while Z-Test is applied to the sample size bigger than 30. Z-Test requires the sample to meet the normality assumption, while T-Test is less robust than Z-Test that the assumption of normality is not critical, especially when the sample size is larger than 30 (Hamilton 2009). This is because for a sample size larger than 30, the central limit theorem can be applied, which assumed the mean of a sufficiently large number of independent random variables, each with finite mean and variance, will be approximately normally distributed. In this study, T-Tests were used for sample sizes larger than 30 and normally distributed. Besides the assumption of normal distribution, T-Test also required the data to be independent. When T-Test was used, two adjustments were made on the instantaneous data (10Hz) to help to meet the assumption. Firstly, data would be extracted at 1Hz frequency to reduce the dependence on the adjacent points, thereby, creating a new independent dataset. Alternatively, a sample with a minimum size larger than 30 would be randomly extracted from the initial dataset to create an independent sample. With these adjustments, the assumptions of T-Test would be met, and the analysis result would be reliable.

The data is considered to be independent if the occurrence of one event has no effect on the other event in the same sample. However, this assumption of independence for T-Test has often been neglected in many transportation studies. Many analyses of the instantaneous traffic data are often time-based and usually strongly correlated to the data in the previous/next time-step. Applying a T-Test on time series data may therefore violate the assumption and lead to inaccurate results.

If the data is not normally distributed or if the sample size is too small, the use of T-Test would not be valid. Non-parametric tests, i.e., Paired Wilcoxon Signed-rank test, Wilcoxon Rank Sum test and Kruskal Wallis Rank test were used to test the hypothesis for such situations.

Chapter 5 Preliminary Analysis

5.1 Introduction

Data collected from preliminary field tests using a highly instrumented vehicle (IV) is examined in this chapter. The field tests used two male drivers driving the TRG instrumented vehicle along the designed route (Figure 5-1). Each driver was instructed to perform one aggressive and one economical driving test to develop an understanding of the fuel consumption (refer GLOSSARY section for the definitions of aggressive driving and economical driving used in this study). This preliminary data was part of the field test collected during previous research project of TRG.

This preliminary analysis is divided into the following sections to achieve different purposes. Section 4.2: To provide details of the field tests, i.e., the test route and source of data. Section 4.3: To understand parameters obtained from the instrumented vehicle and to identify additional parameters required for the main analysis later. Section 4.4: To validate the parameters to ensure data is reliable and accurate. Section 4.5: To define the intersection boundary. Section 4.6: To investigate the possibility of changing driving behaviour and the impact of different driving behaviours on fuel consumption. Section 4.7: To identify the driving mode that produces the highest CO_2 emissions. Section 4.8: To investigate the effects of interruption, acceleration and speed on fuel consumption, and to establish fuel consumption equations based on acceleration and speed variables. Section 4.9: Conclusions.

5.2 Test Route

The field tests were conducted on a designated route (Figure 5-1) using the TRG instrumented vehicle. The test runs were named 1E, 1A, 2E and 2A, in which 1 and 2 represent the driver identities, and E and A represent their driving styles, i.e., economical and aggressive driving, respectively. Economical driving in this chapter is referring to defensive/normal driving rather than the formally known eco-driving. This is because these drivers were not trained for eco-driving prior to their driving task. Instead, they were given instructions listed below to perform the desired driving styles. Clearly, such tests are artificial as, although there is evidence of within driver variations in normal driving, the individual driver's interpretation of economical and aggressive driving will be subjective individually. However, this preliminary study was intended to appreciate the scale of differences which may occur and help formulate the later surveys.

Economical driving:

- Use moderate acceleration and braking during driving.
- Obey the speed limit at all times.
- Overtake as you feel appropriate on dual carriageway sections.
- Coasting/sitting on the clutch is not allowed.

Aggressive driving:

- Use hard acceleration and heavy braking during driving
- When behind a vehicle keep pace with the vehicle at a distance at which you feel safe.
- Attempt to reach the speed at which you would normally travel along that road as quickly as possible.
- Overtake as you feel appropriate on dual carriageway sections.
- Coasting/sitting on the clutch is not allowed.

The 36km long test route consisted of 37 signalised intersections and Pelican crossings (Figure 5-1). This comprehensive field data allows investigation of driving behaviour and fuel consumption within and between drivers at the trip and intersection levels. Driving data for entire test route was used for the analysis at the trip level. At the intersection level, field data consisted of deceleration, idle, and acceleration modes was extracted from the intersections. Attributes of the intersections and driving are summarised in Table 5-1.

Table 5-1: Characteristics of intersections and test runs

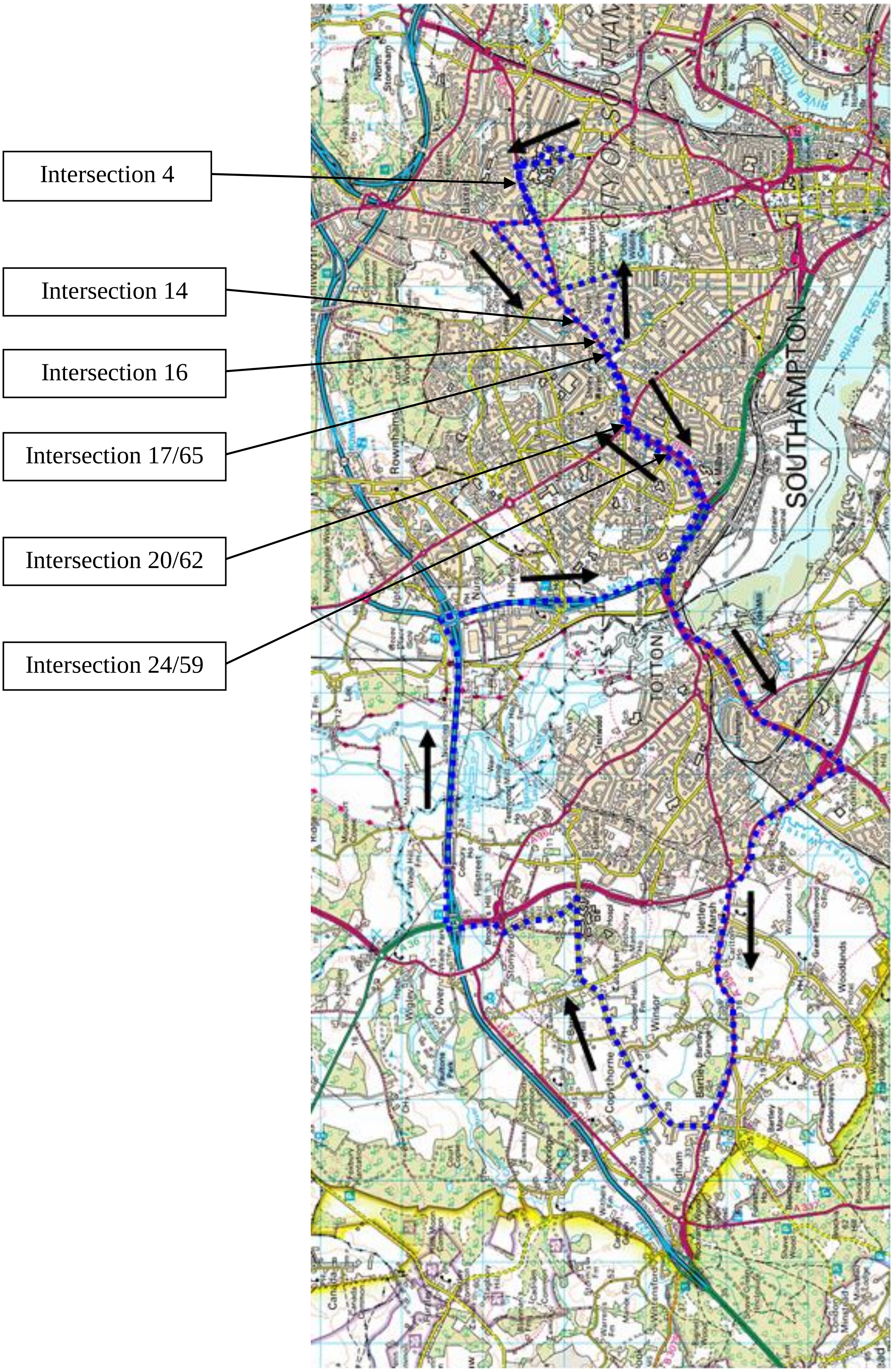
Intersection No.	Intersection Details	Speed Limit (kph)	Driver 1		Driver 2	
			1E	1A	2E	2A
4	3-leg Intersection (Burgess/Glen Eyre)	48	**T**	**T**		
14	3-leg Intersection (A35/Bladon)	48	**T**			
16	3-leg Intersection (A35/Dale)	48				
17	4-leg Intersection (A35/St James)	48	**T**			
20	4-leg Intersection (A35/A3057)	48				**NF**
24	4-leg Intersection (Tebourba/Oakley)	80	**NF**	**NF**		
59	4-leg Intersection (Tebourba/Oakley)	80	**T**			
62	4-leg Intersection (A35/A3057)	48	**T**	**T**		
65	4-leg Intersection (A35/St James)	48	**NF**	**T**		

Note: Shading indicates the test vehicle stopped at the intersection.
Note: **NF** indicates non-following case.
Note: **T** indicates the test vehicle start tailing only at the intersection.

The route used in these preliminary field tests encompasses signalised urban streets and rural roads, in which rural roads provide very little signalised intersection data. In order to obtain sufficient field data for intersections, selection of the test route for the main field tests in the later stage had considered the followings:

- The route should include signalised intersections and avoid rural roads without signalised intersections.
- The length of the route should be reasonably short to allow the repetition of driving within the allocated time.
- The route should be near the TRG's laboratory for the convenience of battery charging and equipment calibration.

Figure 5-1: Designated route of preliminary tests plotted on Digimap



5.3 Data and Variables

The instrumented vehicle provides data from a number of sources/instruments, i.e., CANBUS, Dashdyno SPD^{TM}, XBOX-III and OBS.

- CANBUS: A multiplex wiring system used to connect intelligent devices, such as Electronic Control Units (ECU's), on a vehicle to provide information about the state of a vehicle, for example, about engine torque, engine speed, throttle and gas pedal positions, fuel consumption, brake pedal status, vehicle speed. CANBUS is one of the five protocols used in the OBD-II vehicle diagnostics standard, which can be connected to an external computer. In this study, speed measured by Datron was also embedded into CANBUS's database. Datron is a non-contact optical sensor manufactured by Correvit® for a slip-free measurement of vehicle speed and distance (refer Appendix G: Specifications for Datron).
- Dashdyno SPD^{TM}: An in-vehicle mounted device manufactured by Auterra that features dynamometer, acceleration tests and fuel economy measurements (refer Appendix H: Specifications for Dashdyno SPDTM).
- VBOX-III: An on-board unit that measures vehicle velocity and GPS coordinates in terms of the altitude, latitude and longitude (refer Appendix I: Specifications for VBOX-III).
- OBS: An on-board emission system that is known as Portable Emissions Measurement System (PEMS). This system measures emissions, temperature and pressure in the exhaust pipe, ambient temperature and humidity, GPS locations and atmospheric pressure. The emission rate and fuel consumption are calculated based on concentrations of emission gases. The exhaust flow rate is also provided. The model used in this study is OBS-2000 manufactured by Horiba®. OBS data was not available in the preliminary field tests.

Variables obtained from preliminary tests consisted of instantaneous data logged at 10Hz frequencies. For some of the analyses, 1Hz data was drawn from 10Hz data by taking 1 out of 10 data at every second time interval for all analyses in this chapter. The Moving average method had not been used to produce the 1Hz data. Therefore, the 1Hz dataset can be considered to be independent.

Variables measured by the instrumented vehicle include the vehicle speed, vehicle trajectory, fuel consumption and travelled distance. Exhaust emissions were not available in preliminary data because the On-board Emission Measurement System (OBS) was not installed during the preliminary field tests. Despite the lack of CO_2 emission data, preliminary data provided a good understanding on the available parameters and helped in identifying potential issues related to the nature of the experiment. CO_2 emission data can be derived from the fuel consumption data using the equations in Section: 2.4 Fuel Consumption vs. Carbon Emissions and Section: 4.3.1 Carbon Emissions. However, these equations are valid if the assumption that CO_2 emissions are proportional to fuel consumption is true. Therefore, in this chapter fuel consumption was investigated instead of CO_2 to provide insight on impacts of driving behaviour while maintaining the accuracy of the findings.

5.4 Validation of Variables

Essential variables such as speed and distance were validated using data obtained from different sources. The validation of data from different sources ensures the accuracy and reliability of the data. In this section, scattergrams and linear regressions were employed to compare the data. These selected methods were able to provide the relationship between two data sources graphically and produce the mathematical relationship as well as correlations between the data. Validations for other variables are given in Section 4.3 Data Validation.

5.4.1 Distance

Distances travelled by the instrumented vehicle were measured by two instruments, the VBOX-III and Dashdyno SPD™. Data from these two sources was compared using the continuous variable and single value variable, i.e., the instantaneous distance and total travel distance. A comparison of the total travel distances between VBOX-III and Dashdyno SPD™ showed no significant differences. The maximum difference found was only 2% (Table 5-2). For instantaneous distance data, a linear trend/line was found from the plot between two sources of data, i.e., distance measured by Dashdyno vs. distance measured by VBOX (Figure 5-2). A linear regression between these two data showed that the line crossed at the origin of the graph with a gradient of 1.0 (coef.=0.9989±0.0000, Table 5-3). This indicated that the distance measured by both instruments were almost identical. Therefore, the data was considered sufficiently accurate and reliable. In this study, the distance measured by VBOX-III was used in the analysis because it provided data frequencies up to 10Hz.

Table 5-2: Comparison between total distance measured by VBOX-III and Dashdyno SPD™

Test Run	Distance Measured by VBOX-III (km)	Distance Measured by Dashdyno SPD™ (km)	Difference (%)
1A	36.17	36.21	0
2E	36.20	36.05	0
2A	35.64	36.21	2

Figure 5-2: Instantaneous distance measured by Dashdyno and VBOX (1Hz)

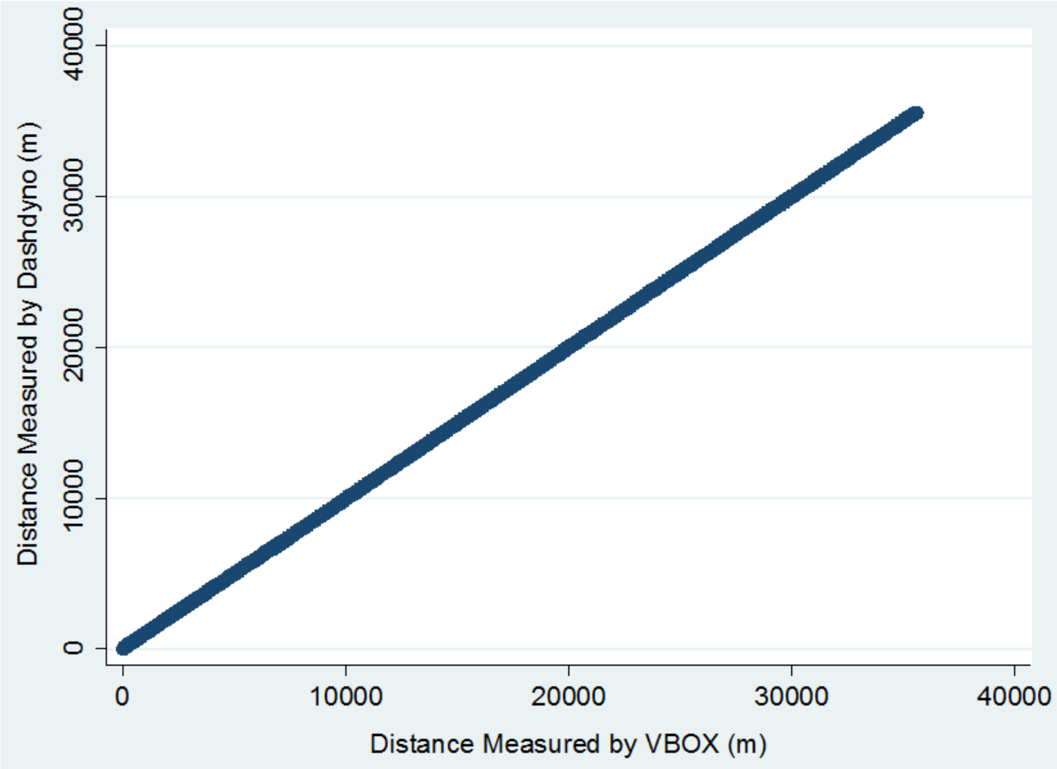


Table 5-3: Linear regression between distances measured by Dashdyno and VBOX

Source	SS	df	MS
Model	1.5377e+12	1	1.5377e+12
Residual	9816027.03	3648	2690.79688
Total	1.5377e+12	3649	421397241

Number of obs =	3649
F(1, 3648) =	.
Prob > F =	0.0000
R-squared =	1.0000
Adj R-squared =	1.0000
Root MSE =	51.873

DashdynoDi~e	Coef.	Std. Err.	t	P>|t|	Beta
vboxDistance	.9989496	.0000418	2.4e+04	0.000	.9993757

5.4.2 Vehicle Speed

A number of instruments provide speed data. Speed data used in this chapter was obtained from two sources smoothed VBOX-III and Datron data. The smoothing of VBOX-III data was performed using a Matlab program, based on the moving average smoothing algorithm (refer Appendix J: Speed Smoothing Program Code). Speed measured by Datron was plotted against speed measured by VBOX. The graph was found to be symmetric with respect to the origin (Figure 5.3), in which case the line crossed at the origin with a gradient of 1 (coef.=0.9833±0.0006, Table 5-4). This indicated that speed data measured by the Datron and VBOX were almost identical. Therefore, smoothed speed measured by VBOX was accurate and used for analyses in this chapter.

Figure 5-3: Instantaneous speed measured by Datron vs. VBOX

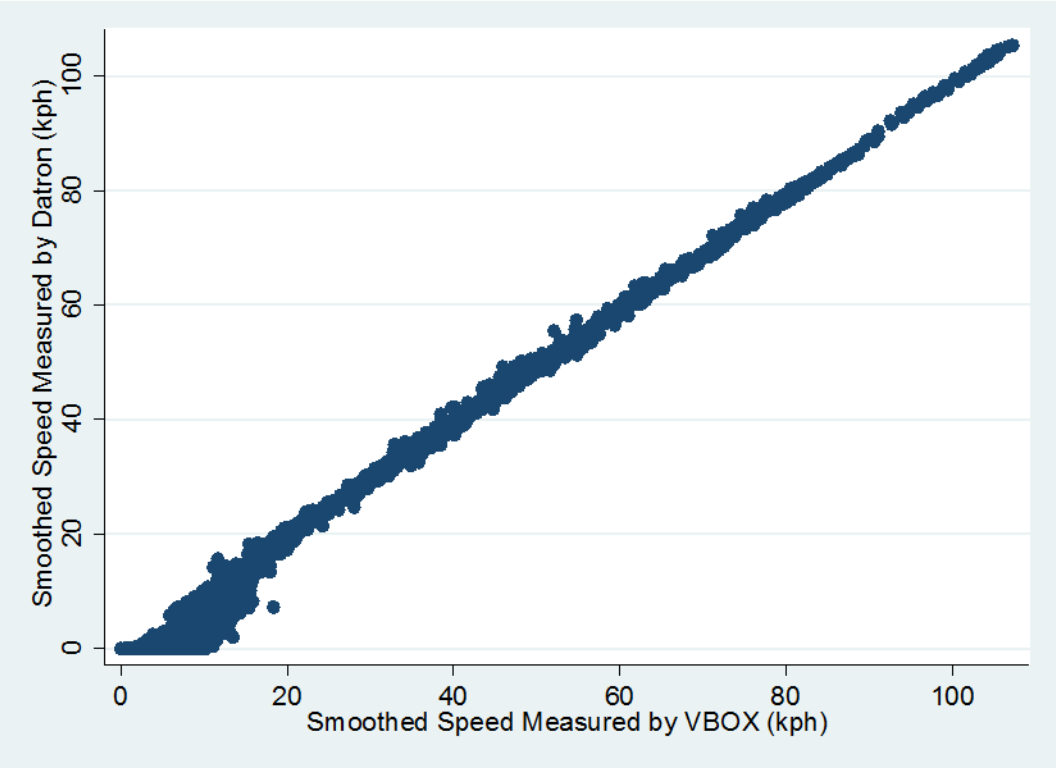


Table 5-4: Linear regression between Instantaneous Datron speed and VBOX-III speed

Source	SS	df	MS
Model	7162665.35	1	7162665.35
Residual	10765.0017	3646	2.95255122
Total	7173430.35	3647	1966.94005

Number of obs	=	3647
F(1, 3646)	=	.
Prob > F	=	0.0000
R-squared	=	0.9985
Adj R-squared	=	0.9985
Root MSE	=	1.7183

DatronSpeed	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
VboxSpeed	.9832549	.0006313	1557.54	0.000	.9820172	.9844926

5.5 Intersection Boundary

Intersection boundaries were established for this study to focus at signalised intersections. The boundaries were designed to cover the total travel distance of all driving modes, i.e., deceleration, idling and acceleration during interrupted driving. This boundary limit was also applied to driving under the cruise mode. This allowed comparisons between interrupted and uninterrupted driving based on the same driving distance. A deceleration distance covers the deceleration process to the point at which the vehicle stopped at the intersection, and an acceleration distance covers the acceleration process to the point positive acceleration ended (Figure 3-11). The deceleration and acceleration distances were found different from one driving to another. For instance, some drivers performed short deceleration distance with high negative acceleration while others performed long acceleration distance with low positive acceleration (Figure 5-6).

No general guideline is available for the selection of intersection boundaries. This study selected intersection boundaries that cover 200m before and 100m after the intersection based on a number of considerations (Figure 5-4). These boundaries were selected mainly because of the limitation of the site. Due to the need for recharging the instruments batteries, the test route has to be near the TRG laboratory which is located in the city of Southampton. However, the city of Southampton has a high density of traffic lights, and spacing between signalised intersections was considerably small, mostly around 300-400m. Although a larger section with farther boundaries could provide more coverage of all driving modes, the 300m long segment was selected after taking into consideration the limitations discussed earlier. Preliminary data showed that adequate deceleration and acceleration distances both are about 100m (Figure 5-5). Some typical speed profiles from the main test showed that the selected boundaries, a 200m distance before the intersection (which includes queuing distance) and 100m after the intersection sufficiently covered the deceleration and acceleration events at an intersection (Figure 5-6). Therefore, the selected boundaries should have very little effect on the analysis of driving behaviour at signalised intersections.

Figure 5-4: Boundaries for intersection

Figure 5-5: Speed profiles of preliminary tests

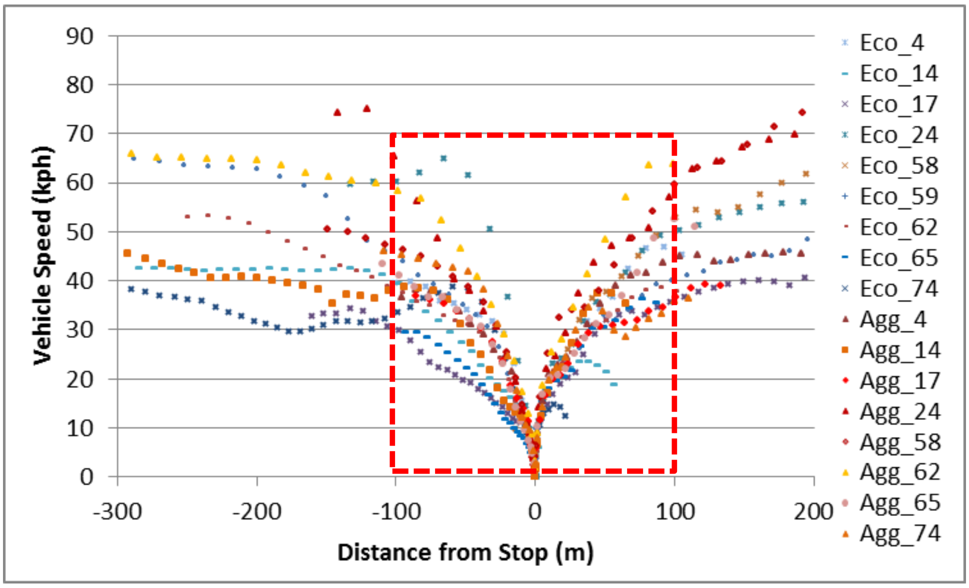
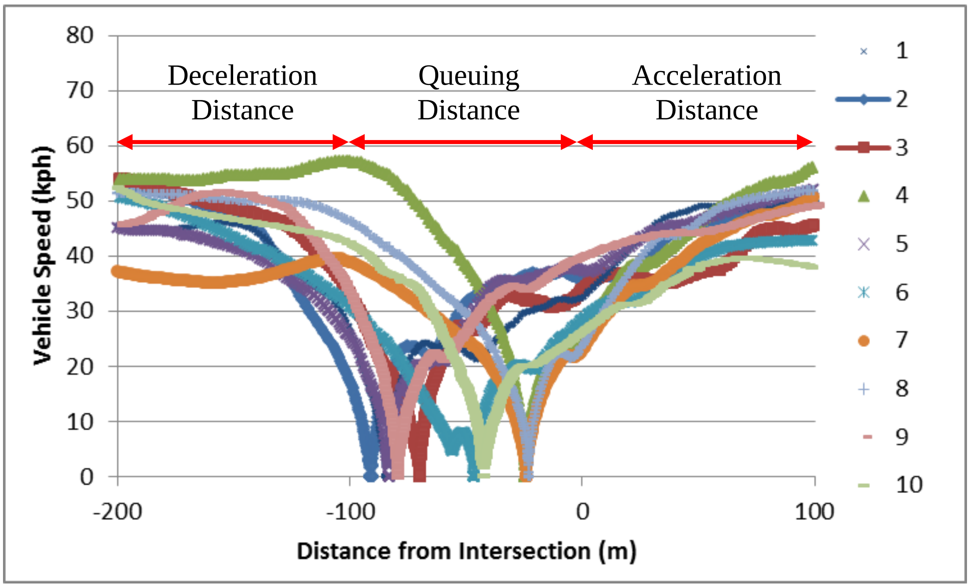


Figure 5-6: Speed profiles of the main field tests



5.6 Variation of Fuel Consumption Within and Between Drivers

Changing one's driving behaviour to reduce carbon emissions at signalised intersections could be very cost effective. In particular, it is important to determine the possibility of changing driving behaviour and, correspondingly, the amount of reductions in fuel consumption/carbon emissions. The former required testing of a hypothesis that there is a significant difference in driving behaviour between different driving styles. The latter involved investigating the impacts of changing driving behaviour on fuel consumption. Considering the linear relationship between fuel consumption and carbon emissions, any reduction in fuel consumption found in this section should imply an equivalent reduction in carbon emissions. Data from two intersections, i.e., Intersection 4 and Intersection 62, was used for the analysis in this section.

5.6.1 Difference in Driving Behaviour

Differences in driving behaviour were investigated by comparing speed profiles from different driving tests. Speed data was tested for normality using the Shapiro Wilk test, a probability value less than 0.05 indicated that none of the groups was normally distributed (Figure 5-7). Therefore, following analyses (comparisons between speed profiles) were conducted using the non-parametric hypothesis test, in which the Wilcoxon Rank Sum test was used.

Figure 5-7: Normality test for speed profiles of 1E, 1A, 2E and 2A

```
-> group = 1

                    Shapiro-Wilk W test for normal data

    Variable |    Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
   SpeedVbox |    645    0.94627     22.751     7.596    0.00000

-----------------------------------------------------------------------
-> group = 2

                    Shapiro-Wilk W test for normal data

    Variable |    Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
   SpeedVbox |    557    0.94213     21.457     7.406    0.00000

-----------------------------------------------------------------------
-> group = 3

                    Shapiro-Wilk W test for normal data

    Variable |    Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
   SpeedVbox |    245    0.91032     15.979     6.441    0.00000

-----------------------------------------------------------------------
-> group = 4

                    Shapiro-Wilk W test for normal data

    Variable |    Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
   SpeedVbox |    218    0.89745     16.493     6.477    0.00000
```

Note: Group 1 represents 1E, Group 2 represents 1A, Group 3 represents 2E and Group 4 represents 2A.

Within Driver

Speed profiles of economical driving and aggressive driving for the same driver were compared using the non-parametric Wilcoxon Rank Sum test. It was found that speed profiles of economical driving were significantly different from aggressive driving for both Driver 1 (Prob>|z|=0.0344, Table 5-5) and Driver 2 (Prob>|z|0.0331, Table 5-6).

Table 5-5: Wilcoxon Rank Sum test on instantaneous speed of 1E and 1A

```
Two-sample Wilcoxon rank-sum (Mann-Whitney) test

       group |      obs    rank sum    expected
-------------+---------------------------------
           1 |      422      154999      161415
           2 |      342      137231      130815
-------------+---------------------------------
    combined |      764      292230      292230

unadjusted variance  9200655.00
adjustment for ties        0.00
                     ----------
adjusted variance    9200655.00

Ho: SpeedV~x(group==1) = SpeedV~x(group==2)
             z =  -2.115
    Prob > |z| =   0.0344
```

Note: Group 1 represents 1E and Group 2 represents 1A. The idling mode was excluded in this analysis.

Table 5-6: Wilcoxon Rank Sum test on instantaneous speed of 2E and 2A

```
Two-sample Wilcoxon rank-sum (Mann-Whitney) test

        group |      obs    rank sum    expected
--------------+---------------------------------
            3 |      138       16291       17526
            4 |      115       15840       14605
--------------+---------------------------------
     combined |      253       32131       32131

unadjusted variance   335915.00
adjustment for ties        0.00
                     ----------
adjusted variance     335915.00

Ho: SpeedV~x(group==3) = SpeedV~x(group==4)
             z =  -2.131
    Prob > |z| =   0.0331
```

Note: Group 3 represents 2E and Group 4 represents 2A. The idling mode was excluded in this analysis.

Between Drivers: Economical vs. Economical & Aggressive vs. Aggressive

Speed profiles under the same driving behaviour between Driver 1 and Driver 2 were compared using the non-parametric Wilcoxon Rank Sum test. No significant differences were found for a) economical driving (Prob>|z|=0.2545, Table 5-7) and b) aggressive driving (Prob>|z|=0.9414, Table 5-8).

Table 5-7: Wilcoxon Rank Sum test on instantaneous speed of 1E and 2E

```
Two-sample Wilcoxon rank-sum (Mann-Whitney) test

        group |      obs    rank sum    expected
--------------+---------------------------------
            1 |      422      120251      118371
            3 |      138       36829       38709
--------------+---------------------------------
     combined |      560      157080      157080

unadjusted variance  2722533.00
adjustment for ties        0.00
                     ----------
adjusted variance    2722533.00

Ho: SpeedV~x(group==1) = SpeedV~x(group==3)
             z =   1.139
    Prob > |z| =   0.2545
```

Note: Group 1 represents 1E and Group 3 represents 2E. The idling mode was excluded in this analysis.

Table 5-8: Wilcoxon Rank Sum test on instantaneous speed of 1A and 2A

```
Two-sample Wilcoxon rank-sum (Mann-Whitney) test

        group |      obs    rank sum    expected
--------------+---------------------------------
            2 |      342       78228       78318
            4 |      115       26425       26335
--------------+---------------------------------
     combined |      457      104653      104653

unadjusted variance  1501095.00
adjustment for ties        0.00
                     ----------
adjusted variance    1501095.00

Ho: SpeedV~x(group==2) = SpeedV~x(group==4)
             z =  -0.073
    Prob > |z| =   0.9414
```

Note: Group 2 represents 1A and Group 4 represents 2A. The idling mode was excluded in this analysis.

Between Drivers: Aggressive vs. Economical

Aggressive driving was compared with economical driving between different drivers. Speed profiles of economical driving for Driver 1 were not found to be significantly different from aggressive driving of Driver 2 (Prob>|z|=0.1420, Table 5-9). This indicates that economic driving of Driver 1 was more similar to aggressive driving of Driver 2. On the other hand, the speed profile of aggressive driving for Driver 1 was significantly different from economical driving for Driver 2 (Prob>|z|=0.0108, Table 5-10). This result indicates that aggressive driving may significantly differ between different drivers since perception on driving aggressiveness for every individual driver could be different. Economical driving of an aggressive driver could be similar to aggressive driving of a normal driver.

Table 5-9: Wilcoxon Rank Sum test on instantaneous speed of 1E and 2A

```
Two-sample Wilcoxon rank-sum (Mann-Whitney) test

        group |      obs    rank sum    expected
--------------+---------------------------------
            1 |      422      111352      113518
            4 |      115       33101       30935
--------------+---------------------------------
     combined |      537      144453      144453

unadjusted variance  2175761.67
adjustment for ties        0.00
                     ----------
adjusted variance    2175761.67

Ho: SpeedV~x(group==1) = SpeedV~x(group==4)
             z =  -1.468
    Prob > |z| =   0.1420
```

Note: Group 1 represents 1E and Group 4 represents 2A. The idling mode was excluded in this analysis.

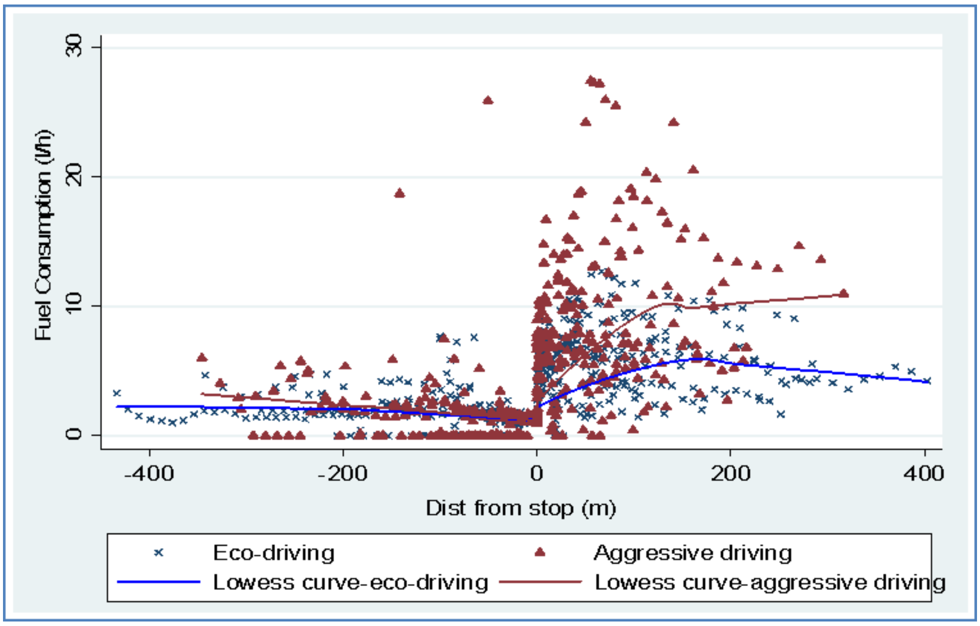
Table 5-10: Wilcoxon Rank Sum test on instantaneous speed of 1A and 2E

```
Two-sample Wilcoxon rank-sum (Mann-Whitney) test

       group |      obs    rank sum    expected
-------------+---------------------------------
           2 |      342       85755       82251
           3 |      138       29685       33189
-------------+---------------------------------
    combined |      480      115440      115440

unadjusted variance  1891773.00
adjustment for ties        0.00
                     ----------
adjusted variance    1891773.00

Ho: SpeedV~x(group==2) = SpeedV~x(group==3)
             z =   2.548
    Prob > |z| =   0.0108
```

Note: Group 2 represents 1A and Group 3 represents 2E. The idling mode was excluded in this analysis.

In general, aggressive driving consumed more fuel than economical driving, especially during acceleration. However, fuel consumption may not be very different between aggressive and economical driving during deceleration (Figure 5-8).

Figure 5-8: Instantaneous fuel consumption vs. distance-from-stop at all intersections



Summary

No significant difference was found within the same driving behaviour/style between the drivers. This indicates that the driving style was consistent despite different drivers. On the other hand, aggressive driving behaviour was significantly different from the economical driving behaviour, within and between drivers, except between driving 1E and 2A. Therefore, changing driving behaviour from an aggressive style to a more economical style is possible, and the IV approach used is likely to be able to quantify its benefit in a larger study.

5.6.2 Variation in Fuel Consumption

Variation in fuel consumption was investigated by comparing instantaneous fuel consumption (l/h) and fuel efficiency (mpg) of different driving behaviours. Instantaneous fuel consumption is the fuel consumption measured at 1Hz frequency while fuel efficiency is the amount of fuel consumed over a period of time. Normality of instantaneous fuel consumption data was tested for each driving tests using the histogram and Shapiro Wilk test. Both results showed that the data did not meet the normality distribution assumption. Therefore, Wilcoxon Rank Sum tests were performed to investigate if there is a significant difference in terms of fuel consumption between four driving tests.

Instantaneous Fuel Consumption

The Wilcoxon Rank Sum test shows that the fuel consumption profile (g/s) of economical driving 1E was significantly different from the aggressive driving 2A (Table 5-11).

Table 5-11: Wilcoxon Rank Sum test on fuel consumption for different driving behaviours

```
Two-sample Wilcoxon rank-sum (Mann-Whitney) test

 grp_agg_eco |      obs    rank sum    expected
-------------+---------------------------------
           1 |      422      110573      113518
           2 |      115       33880       30935
-------------+---------------------------------
    combined |      537      144453      144453

unadjusted variance  2175761.67
adjustment for ties    -1652.92
                     ----------
adjusted variance    2174108.74

Ho: fuel_c~p(grp_ag~o==1) = fuel_c~p(grp_ag~o==2)
             z =  -1.997
    Prob > |z| =   0.0458
```

Note: Group 1 represents 1E and Group 2 represents 2A. The idling mode was excluded in this analysis.

Fuel Efficiency at trip level

Economical driving had better fuel efficiency than aggressive driving (Table 5-12). The average fuel consumption of economical driving was 27% lower than aggressive driving (Table 5-13). This means that the choice of driving behaviour, either aggressive or economical, would affect the fuel economy/consumption of driving. However, differences in fuel efficiency/consumption between aggressive and economical driving varied from one driver to another. The differences could be due to the driver’s personality, their understanding of the driving instructions and their ability to perform the desired driving style. Therefore, instructing drivers to perform particular driving styles could potentially lead to unrealistic results.

Table 5-12: Fuel efficiency per trip for different driving

Driving	Travel Distance (metres, m)	Fuel Used (litres, l)	Kilometres Per Litre (km/l)	Miles Per Gallon (mpg)
1A	36170.5	4.09	25.0	20.8
2E	35643.8	3.75	26.9	22.4
2A	36199.3	4.28	23.9	19.9

Note 1: 1 km/l = 2.3521 mpg

Note 2: Fuel efficiency of the trip is not calculated for 1E because of missing data.

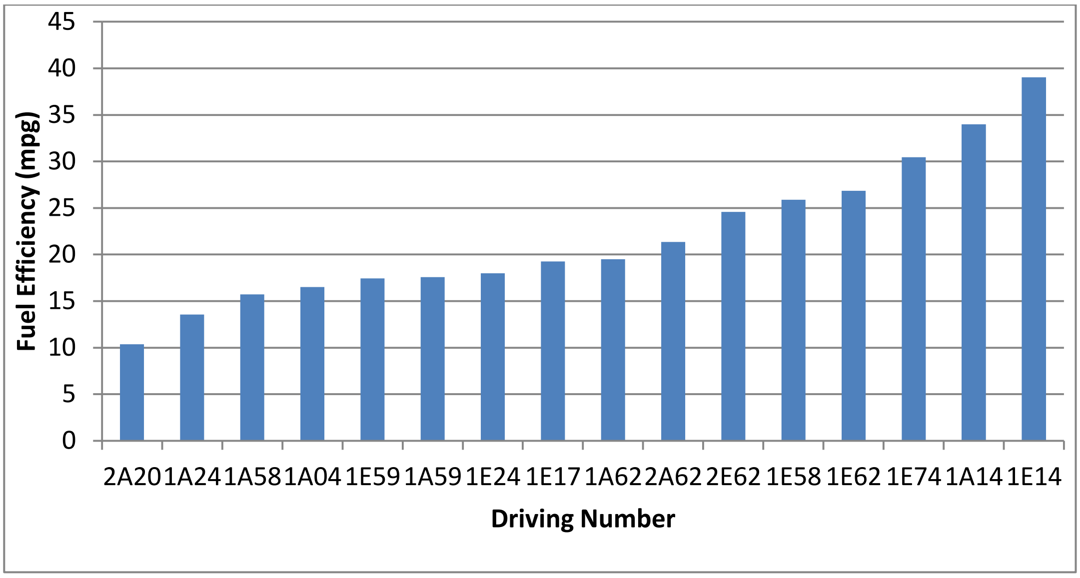
Table 5-13: Average fuel consumption for 1E, 2E, 1A and 2A at all intersections

Driving	Driver	Average Fuel Consumption (l/h)	Average Fuel Consumption With the Same Driving Behaviour (l/h)
Economical	1	2.56	2.500
	2	2.44	
Aggressive	1	3.31	3.425
	2	3.54	

Fuel efficiency at intersection level

Fuel efficiency was found to range between 9mpg and 39mpg for 300m of driving at the signalised intersections (Figure 5-9). The 30mpg difference in fuel efficiency might be caused by the variations in driver, travel distance and traffic control. Regardless of the causes of the difference, this indicates an opportunity to reduce fuel consumption/carbon emissions at intersections.

Figure 5-9: Fuel efficiency for each driving at signalised intersection



Note: The driving numbers represent: driver identity (1 or 2), aggressive/economical driving (E or A) and intersection numbers (04, 16, 17, 20, 24, 58, 59 or 65)

Summary

A substantial difference in fuel efficiency (30mpg) was found, which indicates a real opportunity to reduce fuel consumption at signalised intersections. This could be achieved by changing low fuel efficiency driving (Aggressive) to high fuel efficiency driving (Economical).

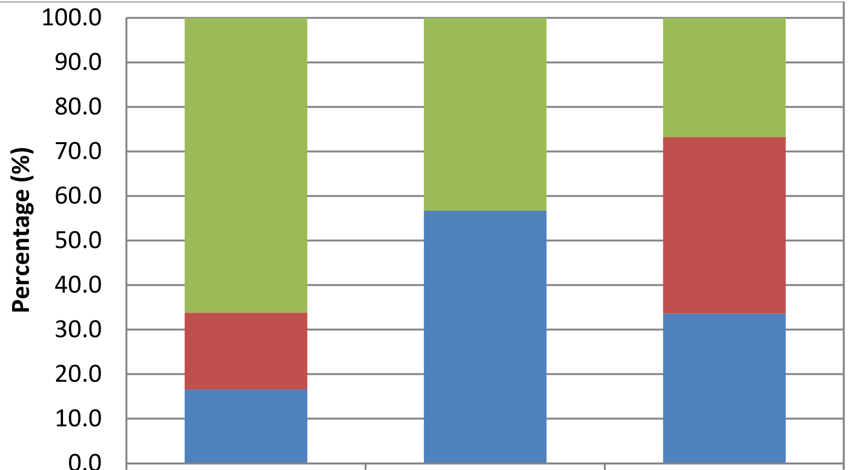
5.6.3 Summary

There was a significant difference between aggressive driving and economical driving. Fuel efficiency of economical driving was better than that of aggressive driving at both trip and intersection levels. This indicates a chance of saving fuel by changing aggressive driving to economical driving. The potential reduction in fuel consumption infers a similar opportunity for a carbon reduction through changing driving behaviour.

5.7 Proportion of Fuel Consumption by Driving Mode

Cumulative fuel consumption was different between the driving modes. Cumulative/total fuel consumption refers to the total fuel consumed under particular driving mode, e.g., acceleration, deceleration, idle, positive acceleration, negative acceleration, braking, etc. For average trips on a semi-urban artery, acceleration contributed 40% of the total CO_2 emissions, although the distance travelled during the acceleration period was only 20% of the entire trip (Frey, Rouphail et al. 2000). For intersection regions, this study found that the acceleration mode consumed an average of 66.2% of the total fuel and covered 43.3% of the distance (Figure 5-10). The average of total fuel consumption for acceleration mode was found to be 5 and 6 times higher than deceleration and idle modes, respectively (Table 5-14).

Figure 5-10: Percentage of total fuel consumption, travel distance and travel duration for each driving mode at intersections 4 and 62



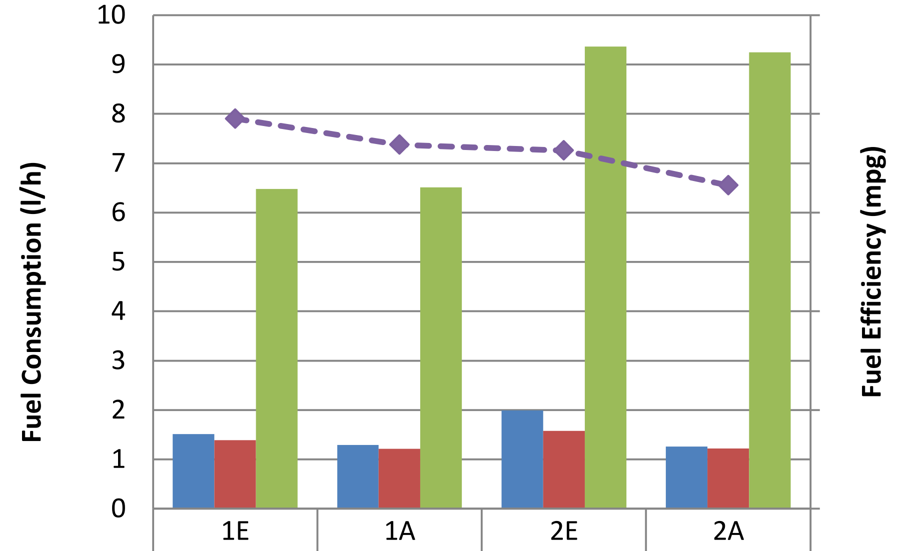
	Fuel Consumption	Distance	Duration
Acceleration	66.2	43.3	26.7
Idle	17.3	0.0	39.6
Deceleration	16.5	56.7	33.6

Table 5-14: Average fuel consumption for each driving mode at intersections 4 and 62

Driving Mode	Average Fuel Consumption (l/h)
Deceleration	1.53688
Idle	1.33169
Acceleration	7.97595

In terms of fuel efficiency, deceleration and idling modes were similar, with the acceleration mode being the worse (Figure 5-11). Fuel efficiency could be expressed as the total distance travelled per unit of fuel, in miles per gallon (mpg) or litres per 100km (l/100km). Fuel efficiency was found to be reduced by 1.4-1.7mpg over the intersection if driving were to change from economical to aggressive (Figure 5-11). Fuel efficiency decreased as fuel consumed during the acceleration mode increased and fuel spent during deceleration decreased. Defining aggressiveness by the fuel consumption (g/s) during acceleration, increasing level of aggressiveness was found to lower the fuel efficiency.

Figure 5-11: Fuel consumption (g/s) and fuel efficiency (mpg) for 1E, 1A, 2E and 2A at Intersections 4 and 62



	1E	1A	2E	2A
Deceleration (g/s)	1.5112	1.2944	1.9926	1.2575
Idle (g/s)	1.3900	1.2144	1.5786	1.2213
Acceleration (g/s)	6.4766	6.5112	9.3664	9.2482
Fuel Efficiency (mpg)	19.8	18.4	18.1	16.4

5.8 Variables Affecting Fuel Consumption

5.8.1 Stop/Interruption

In this section, two driving conditions are compared in order to investigate the effect of stop/interruption on fuel consumption, namely, interrupted driving and uninterrupted driving. Interrupted driving refers to driving where the instrumented vehicle encountered at least one stop at an intersection and uninterrupted driving represents driving where the instrumented vehicle passed the intersection without stopping.

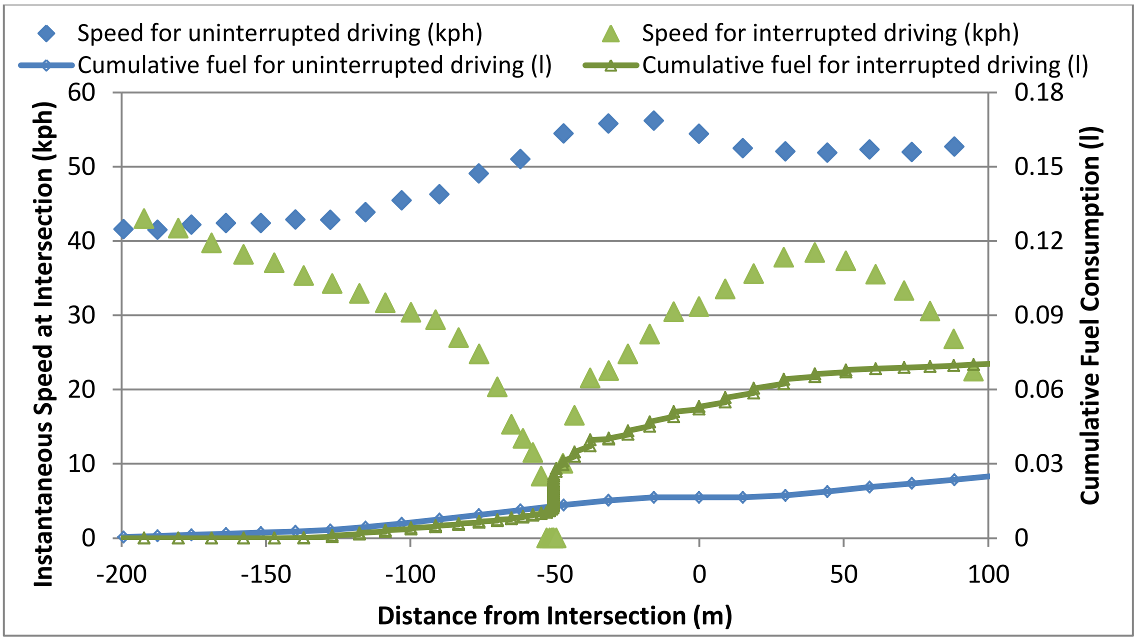
Fuel efficiencies between interrupted and uninterrupted driving at Intersection-62 were compared. The comparison was made on economical driving behaviour performed by single driver at the same signalised intersection. Fuel efficiency of the interrupted driving was about a third of the uninterrupted driving (Table 5-15). A large reduction in fuel efficiency due to interruption may not be conclusive based on this single case. However, the finding provided evidence that the interruption/stop reduces fuel efficiency.

Table 5-15: Fuel consumption, travel distance and fuel efficiency of 1E at Intersection 62

	Uninterrupted Driving	Interrupted Driving
Fuel Consumption (l/h)	0.025	0.070
Travel Distance (km)	0.303	0.305
Average Speed (kph)	48.6	16.9
Fuel Efficiency (km/l)	12	4
Fuel Efficiency (mpg)	34	12

Based on the same case study, cumulative fuel consumption was plotted for both interrupted and uninterrupted driving. Cumulative fuel consumption increased at a rather uniform rate during uninterrupted driving. However, cumulative fuel consumption of the interrupted driving increased drastically at the beginning of the acceleration event (Figure 5-12). This indicates that acceleration could be the main reason for the increase in fuel consumption during interrupted driving.

Figure 5-12: Cumulative fuel consumption and instantaneous speed vs. distance-from-intersection



5.8.2 Instantaneous Acceleration

Instantaneous acceleration data (1Hz) was plotted against instantaneous fuel consumption (1Hz) to investigate the relationship between these two parameters. This section explores the relationship by considering the effects of driving modes and speed. In this section, instantaneous acceleration was divided into three categories, i.e., negative acceleration, zero acceleration and positive acceleration. Negative acceleration is when the vehicle speed reduces over a period of time, zero acceleration is when the speed is constant and positive acceleration is when the speed increases over a period of time. Zero fuel consumption due to the changes of gears observed in data was not considered in this section's analysis. Few data points that were identified as noise were removed from the database when they were found to be out of range and affecting the overall result. A special care was exercised to ensure that the removed data corresponded to noise.

By Driving Mode

Acceleration was found to be the dominant mode in the region of high instantaneous fuel consumption (Figure 5-13). Increasing instantaneous acceleration was found to increase instantaneous fuel consumption. However, at higher acceleration, the increase in instantaneous fuel consumption was considerably varied between different cases. No equation with adequate strength could be established for fuel consumption and acceleration variables, where the coefficient of determination was found to be relatively poor. Fuel consumption was found to be insensitive to the change in acceleration during idling, while increases in acceleration during the acceleration mode had a larger impact on fuel consumption as compared with the deceleration mode. This finding was in a good agreement with other research findings, e.g., Chen and Yu, 2007 as well as Rakha and Ding, 2003 (Rakha and Ding 2003; Chen and Yu 2007). On the other hand, the result also showed that fuel consumption increased significantly when instantaneous acceleration increased beyond -1 m/s^2 (Figure 5-14).

Figure 5-13: Scatterplot of instantaneous fuel consumption vs. instantaneous acceleration

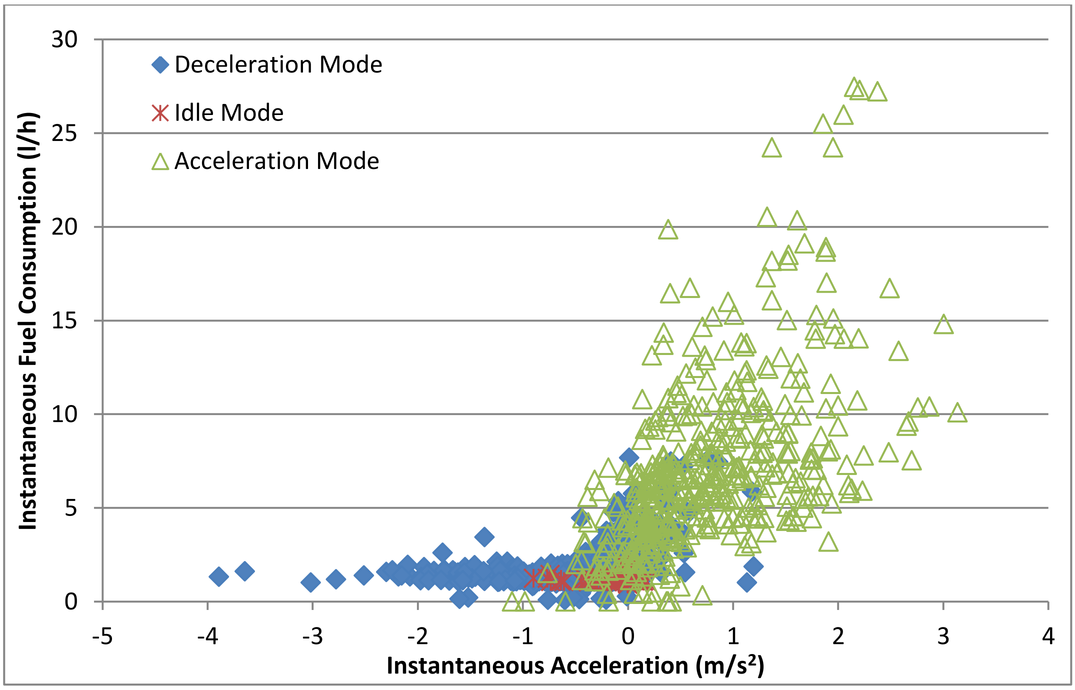
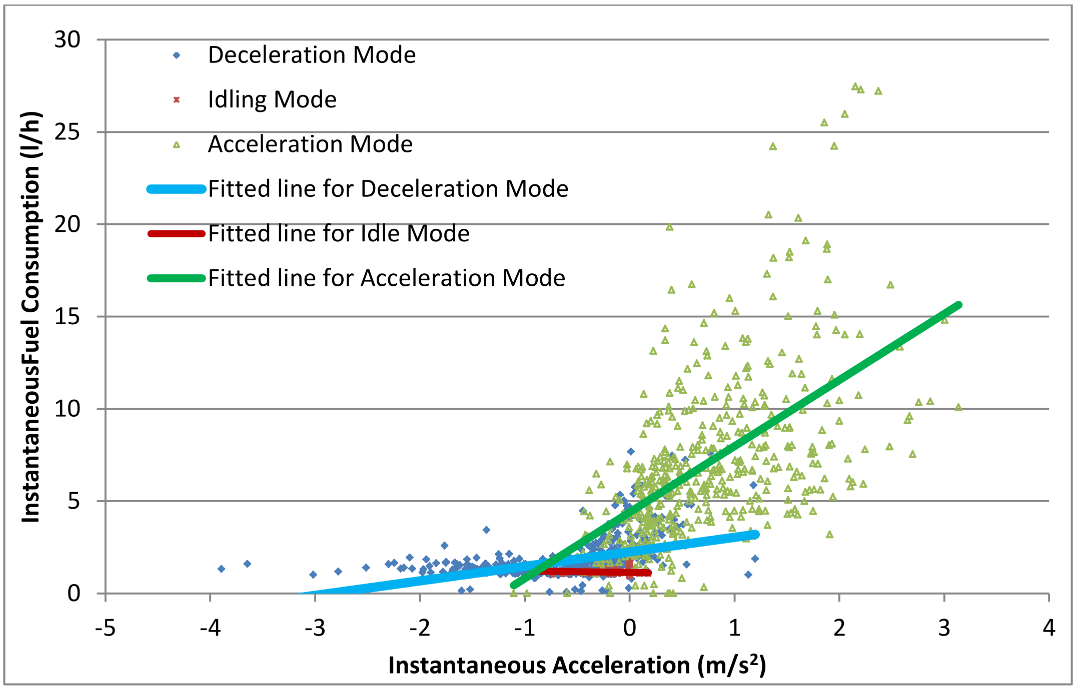


Figure 5-14: Fitted line for fuel consumption vs. acceleration plot for a) deceleration, b) idle and c) acceleration modes



By level of Instantaneous Speed

An increase in positive acceleration was found to be highly correlated with the increase in fuel consumption. Similar effects on fuel consumption were observed for negative acceleration between 0m/s^2 and -0.5m/s^2. However, fuel consumption was insensitive to negative acceleration below -0.6m/s^2 (Figure 5-15). On the other hand, increasing speed was found to intensify the impact of acceleration on fuel consumption (Figure 5-15). This may be due to the fact that higher speed is often a result of greater acceleration. Larger power is required to achieve the same amount of acceleration at high speed than at low speed. Specifically, the impact of acceleration and speed upon fuel consumption could be categorised into three zones. Cluster analyses using the Hierarchical method suggested a three-cluster solution (Table 5-16, refer Chapter 6 for detailed clustering methodology) where Cluster 1 covered the acceleration range below -0.6 m/s^2. Cluster 2 represented the acceleration range between -0.6 m/s^2 and 0.7 m/s^2. Cluster 3 covered the acceleration range beyond 0.7 m/s^2 (Figure 5-16, Table 5-17). Cluster 1 is a low-impact zone, where acceleration was negative. Changes in acceleration and/or speed had an insignificant effect on the fuel consumption. Cluster 2 is an intermediate-impact zone, where increases in fuel consumption were mainly due to changes in acceleration. Cluster 3 is a high-impact zone where both acceleration and speed had significant impacts on fuel consumption.

The overall instantaneous fuel consumption, F can be expressed as:

$$F = 1.8849e^{0.7688a}$$

Equation 5-1

Where F is the fuel consumption in litres per hour (l/h) and a is the acceleration in metres per squared second (m/s^2) (Figure 5-17).

Figure 5-15: Fuel consumption vs. acceleration plot for different ranges of speed at all intersections

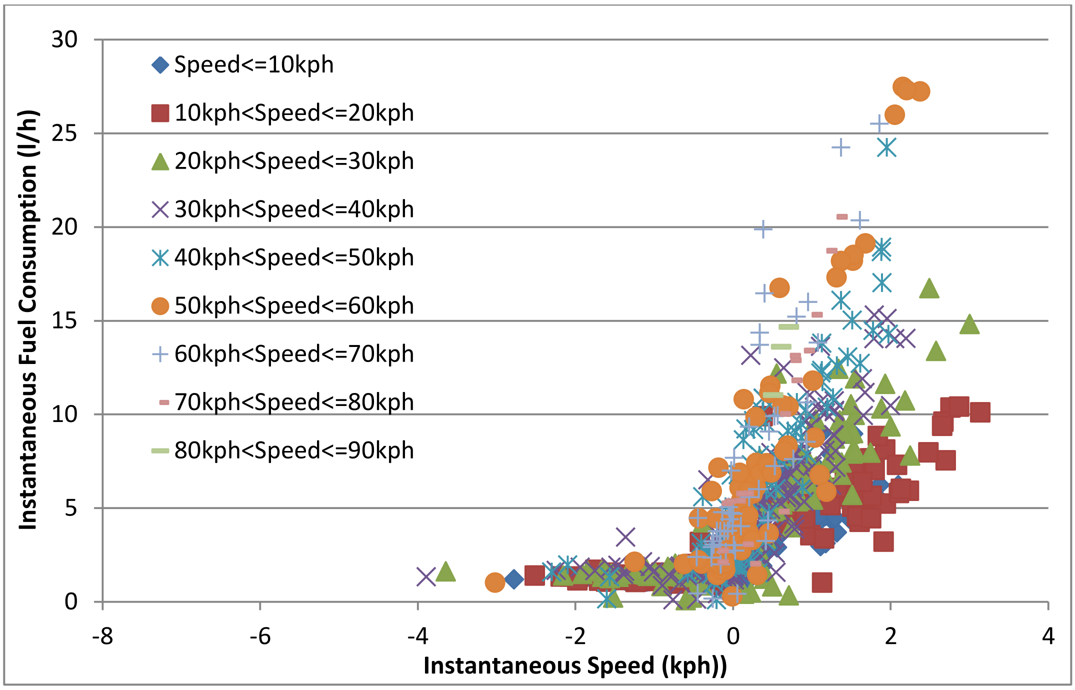


Table 5-16: Stopping rules for Hierarchical method cluster solution

Number of Cluster	Calinski-Harabasz Pseudo-F	Duda-Hart	
		Je(2)/Je(1)	Pseudo-T-Squared
1	NA	0.628	984.08
2	984.08	0.6638	751.09
3	1074.66	0.5738	130.7
4	789.96	0.4273	1933.01
5	1683.5	0.1148	38.56
6	1361.38	0.3191	360.61
7	1299.77	0.2362	1364.94

Figure 5-16: Impact zones

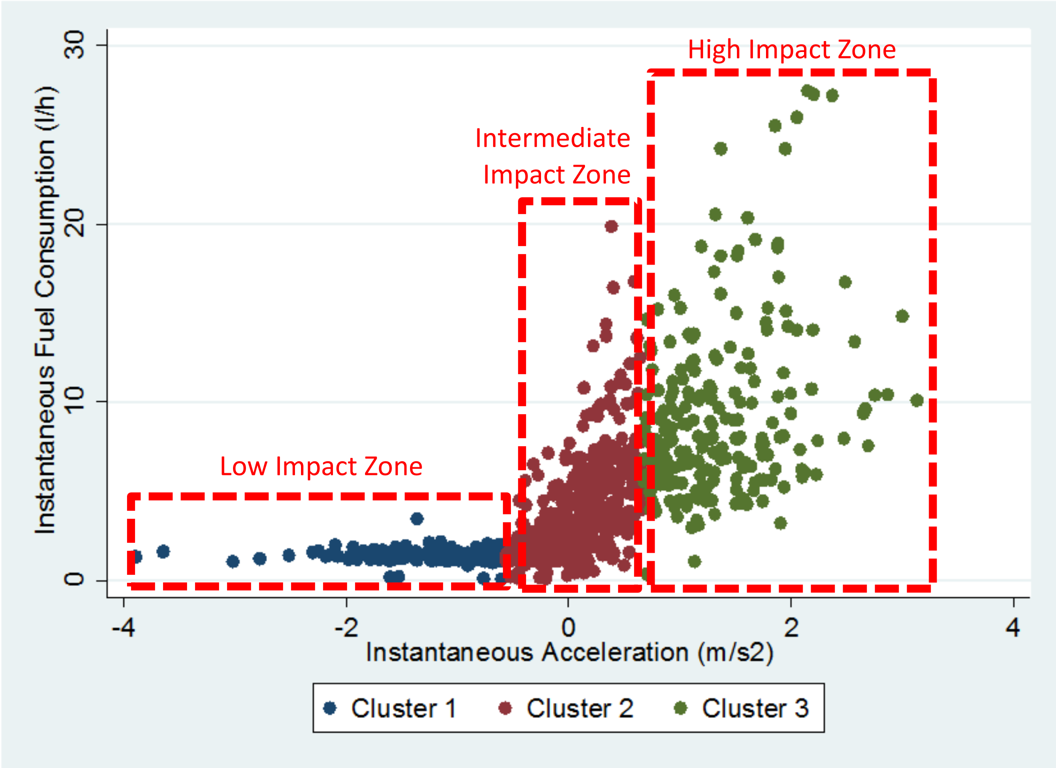
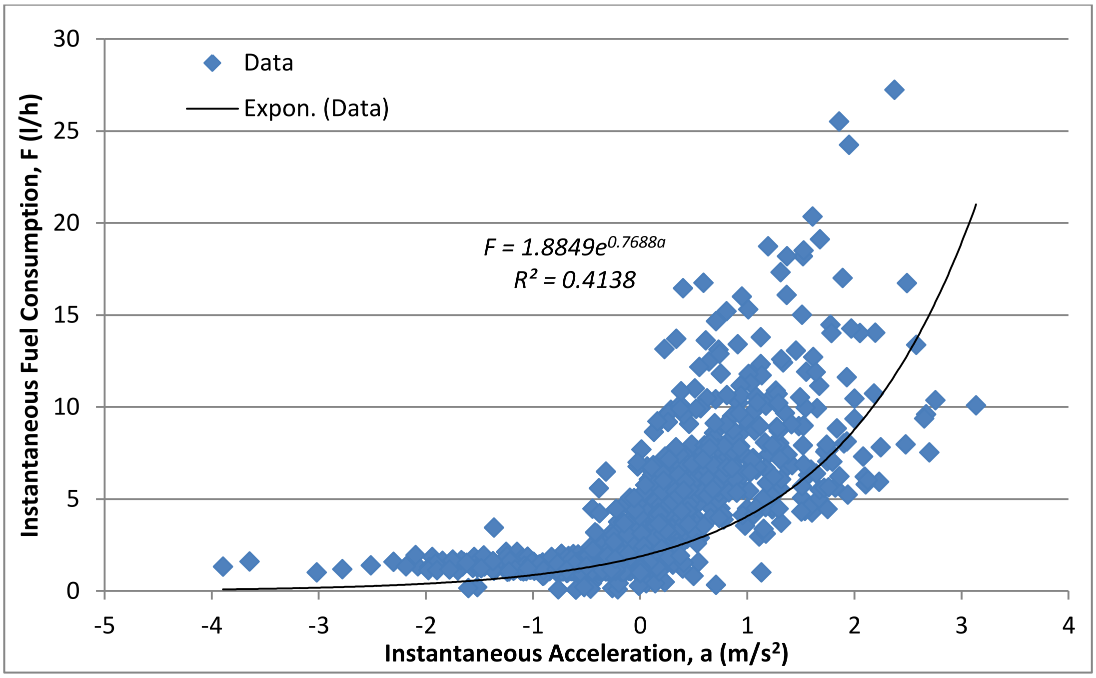


Table 5-17: Maximum and minimum acceleration values for each cluster

Cluster	Observation	Variable	Min	Max
1	242	Speed (kph)	0.0	69.9
		Fuel (l/h)	0.0	3.4
		Acceleration (m/s^2)	-3.9	-0.6
2	1197	Speed (kph)	0.0	85.1
		Fuel (l/h)	0.0	19.9
		Acceleration (m/s^2)	-0.6	0.7
3	224	Speed (kph)	2.5	81.1
		Fuel (l/h)	0.3	27.5
		Acceleration (m/s^2)	0.7	3.1

Figure 5-17: Function for fuel consumption based on instantaneous acceleration



5.8.3 Summary

Interruptions/stops decreased fuel efficiency at signalised intersections. Fuel consumption for interrupted driving was approximately three times higher than for uninterrupted driving, and this difference was likely to be due to the acceleration of the vehicle.

Fuel consumption was less sensitive to deceleration (negative acceleration), except for negative acceleration between -0.5 m/s^2 and 0 m/s^2. An increase in positive acceleration increased fuel consumption, and the impact of the acceleration on fuel consumption became greater at higher speed. The impacts of speed and acceleration on fuel consumption can be divided into three zones based on the acceleration level, i.e., low-impact, intermediate-impact and high-impact zones. Fuel consumption was found to increase significantly beyond 0.6 m/s^2.

5.9 Conclusions

Conclusions in this chapter are divided into two parts: the field test design and new findings.

5.9.1 Field Test Design

Based on the analysis performed on preliminary data, following design aspects were considered important and incorporated into the methodology design for the main field tests. This could enhance the accuracy and reliability of the data by minimising potential errors due to the nature of the experiment.

- The test route should consist of a sufficient number of signalised intersections. It should allow driving to be repeated on the same route for every driver. It should also be located within a reasonable distance from TRG's laboratory for battery recharging purposes.
- The instrumented vehicle provided a good database for this study. Instantaneous data recorded at 10Hz frequency, i.e., the vehicle speed, vehicle location, fuel consumption and travel distance was useful in the study of the difference in driving behaviour and its impact on fuel consumption. However, an additional on-board emission measurement system is required to provide instantaneous CO_2 emission data for the main analysis.
- The validation showed that data provided by the instrumented vehicle, i.e., vehicle speed, distance and GPS coordinate was correct and reliable.
- Intersection boundaries with300m long distance are recommended for the study of driving behaviour at signalised intersections. This is because interrupted driving in this study mostly happened within the suggested 300m distance at intersections. Most importantly, signalised intersections in this study have small spacing between the intersections, which is approximately 300m apart.

5.9.2 New Findings

Although the preliminary analysis consisted of data of two drivers and two types of driving behaviour, the findings in this chapter still provide insights about real world driving and its impact on fuel consumption. Findings from the analysis of driving behaviour and fuel consumption are summarised as below. :

- There is a significant difference between economical and aggressive driving, in terms of instantaneous speed and instantaneous fuel consumption. Fuel efficiency of an urban trip using economical driving is better than that of aggressive driving. This indicates the possibility of changing driving behaviour to reduce carbon emissions.
- For interrupted driving over 300m signalised intersections, the acceleration mode has the highest fuel consumption (an average of 66%). Average fuel consumption of the acceleration mode was significantly higher than the deceleration/idle modes. On the other hand, economical driving was found to

reduce average fuel consumption by 27% at intersections, compared with aggressive driving.

- An interruption in driving increases fuel consumption and reduces fuel efficiency essentially during acceleration. In average, fuel consumption of an interrupted driving is three times of an uninterrupted driving over a 300m long signalised intersection.
- The impacts of speed and acceleration levels on fuel consumption can be divided into three zones, i.e., low-impact, intermediate-impact and high-impact zones. Fuel consumption is insensitive to the changes in speed and/or acceleration levels in low-impact zones. The acceleration level has a stronger impact on fuel consumption than the speed level in the intermediate-impact zone. Both acceleration and speed levels have significant impacts on fuel consumption in the high-impact zone.
- During the acceleration mode, instantaneous fuel consumption increases correspondingly to the increase in acceleration. This increment in fuel consumption could be further intensified by the increase in the speed level.

Chapter 6 Cluster Analysis

6.1 Introduction

Results from the preliminary analysis showed that a driver could drive differently, e.g., aggressive vs. economical, if they wished. However, in the main field tests, drivers had driven in a way more closely representing their natural driving. In order to investigate the driving behaviour that leads to high or low emissions, cluster analyses were used to find out whether there is any significant difference in driving behaviour and carbon emissions. The cluster analysis also helped to identify variables that are essential for defining low carbon and high carbon driving behaviour.

The cluster analysis in this section categorised driving behaviour based on a number of emission variables. Data used in the cluster analysis consisted of 551 driving profiles generated by 29 drivers at 4 intersections.

This chapter is divided into the following sections. Section 6.2: A review on the cluster analysis methods to determine the best method for clustering driving behaviour. Section 6.3: A review on the cluster analysis algorithms of the Hierarchical method to select an algorithm that is most suitable for the data in this study. Section 6.4: A selection process to choose the variables that are significant for the cluster analysis. This includes investigation of correlation and multicollinearity of the variables to ensure that clusters created based on driving behaviour are different in carbon emissions. Section 6.5: An initial cluster analysis for an overview of driving behaviour. Section 6.6: A further cluster analysis based on the initial cluster analysis, which created clusters of driving behaviour that are truly different in terms of carbon emissions, for both interrupted and uninterrupted driving.

Definitions of the variables used in this chapter and Chapter 7 are given in Table 6-1.

Table 6-1: Definitions of the variables

Variable	Definition
Cumulative CO_2 Emissions	Total amount of CO_2 emissions (at 10Hz) for a driving through a signalised intersection (300m).
Average Speed	Average of instantaneous speed (at 10Hz) for a driving through a signalised intersection (300m).
Non-optimum-speed Duration	Total amount of time when speed is outside the optimum speed range (60-80kph), for a driving through a signalised intersection (300m).
Average Acceleration	Average of instantaneous acceleration (at 10Hz) for a driving through a signalised intersection (300m).
Positive Acceleration Duration	Total amount of time when the acceleration exceeds $0.0m/s^2$, for a driving through a signalised intersection (300m).
Negative Acceleration Duration	Total amount of time when the acceleration is below $0.0m/s^2$, for a driving through a signalised intersection (300m).
High Acceleration Duration	Total amount of time when the acceleration exceeds $1.5m/s^2$, for a driving through a signalised intersection (300m).
Braking Duration	Total amount of braking time for a driving through a signalised intersection (300m).
Idling Duration	Total idling time for a driving through a signalised intersection (300m).
Low Gear Duration	Total amount of time when the gear engaged is between gear one and gear three, for a driving through a signalised intersection (300m).

6.2 Cluster Analysis Methods

Cluster analysis methods can be divided into two types, i.e., partition and hierarchical. The partition method assigns data under a predefined number of clusters, whilst the hierarchical method agglomerates data into bigger groups iteratively. Both hierarchical and partition methods have their own advantages and disadvantages (Table 6-2). A combined approach using the hierarchical method followed by the partition method is believed to be able to provide the best overall approach (Hair, Black et al. 2006). In this study, the combined approach was adopted, in which the hierarchical method provided the cluster solution, which is the number of clusters. Then, the partition method was used to generate the clusters. The partition method was used because the data size was bigger than 400 and the method is less susceptible to the effect of outliers (Hair, Black et al. 2006; Hamilton 2009). The K-means method, one of the most common clustering techniques under the partition method was used. This method calculates the cluster mean iteratively and assigns each data to the cluster with the closest mean.

Table 6-2: Advantages and disadvantages of cluster analysis methods

	Advantages	Disadvantaged
Hierarchical Method	• Simple yet comprehensive method that provides the entire range of clustering solutions. • Use the measures of similarity concept that can be applied to almost any type of clustering variables. • Fast method to deliver solutions.	• Outliers could potentially lead to artificial result. • Removal of cases includes outliers and non-outliers could potentially distort the results. • Not amenable to analyse a large sample size. Only good for the sample size under 300-400.
Partition Method	• Less susceptible to the outliers, distance measured and the inclusion of irrelevant or inappropriate variables. • Able to analyse extremely large datasets.	• Used of non-random seed point could jeopardise the results. • Unsuitable for any cluster solution that is potentially large.

Source: Summarised from page 590-591, (Hair, Black et al. 2006)

6.3 Algorithms for Clustering

The hierarchical method offers several cluster analysis algorithms to determine the similarity between data before agglomerating the data into the same cluster. Commonly used algorithms are the Single Linkage, Complete Linkage, Weighted Average Linkage, Centroid Linkage and the Ward's Linkage. All algorithms are based on the same concept, which is the smallest similarity measurement. The summary of the algorithms and their suitability for this study is given in Table 6-3. Average Linkage and Ward's Linkage are the most popular algorithms (Hair, Black et al. 2006). Therefore, these two algorithms were prioritised during the selection of the suitable algorithm. Other algorithms were found unsuitable for the data in this study. Considering the possibility that the cluster sizes may not be equal, Ward's Linkage algorithm was also discarded. Weighted Average Linkage, an enhanced Average Linkage algorithm, was selected because of its resistance to outliers and unequal cluster sizes.

Table 6-3: Summary of cluster algorithms and its suitability

Algorithm	Characteristics	Suitability to This Study
Single Linkage • Measure the shortest distance from any data in one cluster to any other data in the other clusters.	• 1st pro: Able to define a wide range of clustering patterns including concentric circles and bull-eye-ring. • 1st con: May produce loose clusters with long snakelike chain patterns with great dissimilarity. • 2nd con: Low resistance to the effect of outliers.	• Not suitable • Potential problems of chain-pattern clusters. • Potential problem due to outliers.
Complete Linkage • Measure the maximum distance between the data in each cluster.	• 1st pro: Eliminate the chaining problem in single-linkage method. • 2nd pro: Less sensitive to outlier effect. • 1st con: Tendency of produce tight, spatially compact clusters.	• Unsuitable. • Potential problem of over compact clusters.
Weighted Average Linkage • Measure the average distance between any pairs of members in two clusters, and weighted by respective clusters.	• 1st pro: Not affected by the outliers. • 2nd pro: Small variation within the cluster. • 3rd pro: Less affected by clusters with unequal sizes because each cluster carries the same weight regardless of the cluster size.	• Suitable. • Not affected by outliers. • Apply weighted measures to clusters with different sizes.
Centroid Linkage • Measure the distance between the cluster centroids.	• 1st pro: Less affected by outliers. • 1st con: Renewable cluster centroid because every step of agglomeration may lead to unstable cluster structure and confusing result.	• Unsuitable. • Potential problem of unstable cluster structure.
Ward's Linkage • Measure the minimum sum of squares of all variables' distances within the clusters.	• 1st pro: Suitable for cluster that is multivariate, normal and spherical. • 1st con: Easily affected by outliers. • 2nd con: Unsuitable for clusters with unequal sizes.	• Unsuitable. • Potential problem due to unequal cluster sizes and outliers.

Source: Summarised from pages 586-588 (Hair, Black et al. 2006), pages 48-49 (Wedel and Kamakura 1999), and pages 80-162 (StataCorp 2007).

6.4 Cluster Analysis Variables

Choosing the suitable cluster analysis variables are crucial in clustering driving behaviour correctly. The variables should be highly correlated with carbon emissions so that different driving behaviour clusters could reflect the difference in carbon emissions. A number of variables were selected for the cluster analysis based on the Pearson Correlation analysis, Multicollinearity analysis and theoretical understanding from literature reviews. The variables considered in the clustering include average speed, average acceleration, non-optimum-speed duration, high acceleration duration, low gear duration, braking duration, idling duration and positive acceleration duration (refer Table 6-1 for the definitions of the variables).

The Pearson Correlation analysis evaluates the strength of association between dependent and independent variables. Since the objective of cluster analysis was to group driving behaviour according to CO_2 emission levels, the cumulative CO_2 emission was selected as the dependent variable, and other variables as independent variables. Correlation coefficient, $|r|$ given by the Pearson Correlation analysis indicates whether the emission variables are significant to the cluster analysis. The sign before Correlation Coefficient denotes directions of the relationship, with +1 showing a perfect positive relationship, -1 showing a perfect negative relationship, and 0 indicating no relationship. Values of $|r|$ indicate the strength of the relationship between the dependent and independent variables, where 0.1 indicates weak, 0.3 indicates moderate and 0.5 indicates strong (Acock 2008). Variables with moderate to strong strength are considered significant to the cluster analysis.

Not all emission variables should be used for the cluster analysis, even if their Correlation Coefficients are high. This is because some variables have strong multicollinearity with others that may induce a redundancy effect on the cluster analysis. Therefore, Multicollinearity analysis was used to produce a set of independent variables (emission variables) with the least correlation and interference among themselves. The emission variables were regressed against cumulative CO_2 emissions, and variance inflation factor (VIF) was calculated. A VIF value above ten suggests evidence of collinearity [Section 3.3, (Acock 2008)].

In this study, variables that had low correlation coefficients or high multicollinearity were excluded to avoid misleading results. The average acceleration was removed because of a weak correlation with CO_2 emissions in the Pearson Correlation analysis (Table 6-4). Besides, among two durational acceleration variables, the positive acceleration duration was also discarded due to a poorer Correlation Coefficient value (Table 6-4). Other variables that had strong and significant correlations ($|r| > 0.5$ and $p = 0.0000$) with the cumulative CO_2 emissions were retained. The non-optimum-speed duration was discarded during the Multicollinearity analysis because of a high VIF value (Table 6-5). This removal eliminated the multicollinearity problem and produced a set of independent variables suitable for the cluster analysis (Table 6-6).

The final set of independent variables consisted of the low gear duration, average speed, idling duration, braking duration and high acceleration duration.

Table 6-4: Correlation Coefficient of emission variables with cumulative CO_2 emissions

Independent Variable	Pearson Correlation Coefficient with cumulative CO_2 Emissions, $\|r\|$
Average Speed	-0.8012
Non-optimum-speed Duration	0.8299
Average Acceleration	-0.0048
Positive Acceleration Duration	0.5970
High Acceleration Duration	0.7761
Braking Duration	0.7302
Idling Duration	0.7904
Low Gear Duration	0.7997

Table 6-5: Variance Inflation Factor (VIF) for the initial set of independent variables

Variable	VIF
Non-optimum-speed Duration	47.48
Average Speed	17.56
Idling Duration	17.1
Low Gear Duration	5.49
Braking Duration	3.04
High Acceleration Duration	2.64

Table 6-6: Variance Inflation Factor (VIF) for the final set of independent variables

Variable	VIF
Low Gear Duration	5.33
Average Speed	4.24
Idling Duration	3.36
Braking Duration	3.04
High Acceleration Duration	2.29

6.5 Initial Cluster Analysis

A combination of two cluster analysis methods was adopted in this study: the hierarchical method followed by the partition method.

Hierarchical Method

The cluster analysis inherently lies between art and science as there is no definite solution. Different clustering methods might provide different results, especially in determining the number of clusters (Hair, Black et al. 2006). However, it was recommended that the cluster solution, which determines the number of clusters, should be made by comparing cluster solutions based on the priori criteria, practical judgement, common sense and theoretical foundation (Hair, Black et al. 2006; Joseph F. Hair 2006). Driving behaviour has often been divided into two or three categories, namely, aggressive driving, normal driving and economical driving. Although driving behaviour can possibly be categorised into more than three clusters, in this study the number of clusters was limited to three. Grouping driving behaviour to more than three clusters might not produce meaningful findings because there could be no/negligible difference between the clusters in terms of carbon emissions.

A stopping rule is required in Hierarchical analysis to produce the cluster solution. In addition, a Dendrogram can be used as a visual check for the right cluster solution. Two stopping rules can be used in the hierarchical analysis to produce the cluster solution, namely Calinski-Harabasz and Duda-Hart rules. The cluster solution is selected based on indices generated from these rules. Distinct clustering is indicated by high Calinski-Harabasz Pseudo-F and Duda-Hart Je(2)/Je(1) indices, but a low Pseudo-T-Squared index.

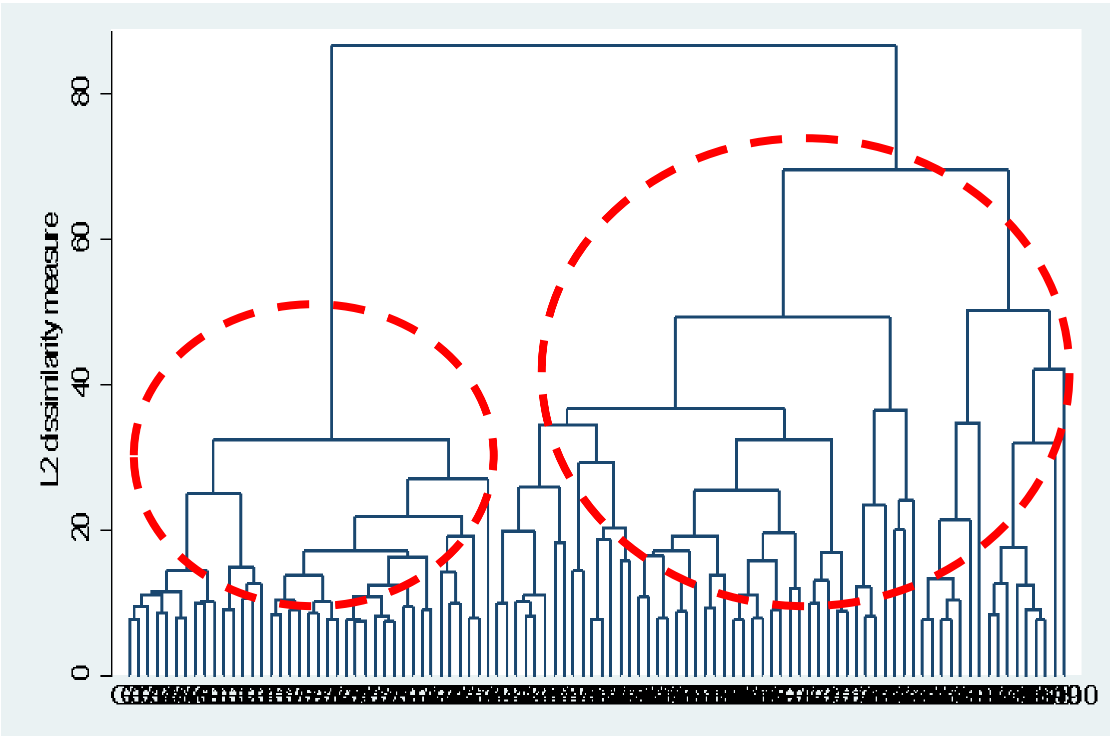
Based on the stopping rules (refer Table 6-7), only two clusters of driving behaviour were found. A solution with the highest Calinski-Harabasz and Duda-Hart values and the lowest Pseudo-T-Squared value was selected as the most appropriate cluster solution, which is a two-cluster solution. The Dendrogram produced based on the Weighted Average Linkage algorithm also indicated the same (Figure 6-1). The Dendrogram showed a small dissimilarity within the key cluster but a large dissimilarity between key clusters. Different sizes of the key clusters suggested that the Weighted Average Linkage algorithm is a suitable algorithm for this analysis, as it could handle unequal cluster sizes well.

Table 6-7: Index of stopping rule

Number of Cluster	Calinski-Harabasz Pseudo-F	Duda-Hart	
		Je(2)/Je(1)	Pseudo-T-Squared
1	NA	0.3729	923.42
2	923.42	0.659	58.46
3	605.43	0.2473	70.01

NA: Not applicable

Figure 6-1: Dendogram based on Weighted Average Linkage algorithm



Partition Method

The partition method using the Kmeans algorithm was cross examined with the cluster solution obtained from the hierarchical method. The overall clustering solution was found to be quite similar, with only 5% difference (Table 6-8).

Table 6-8: Cluster size for partition and hierarchical methods

		Hierarchical Method	
		Cluster 1	Cluster 2
Partition Method	Cluster 1	406	-
	Cluster 2	30	115

Comparing Clusters

It was found that the clustering was based on the driving condition, i.e., interrupted or uninterrupted driving. Ninety-two percent of the clustered data matched the two driving conditions. This indicates that interruption in driving is the dominant factor which contributed to the difference in driving behaviour.

Clusters were compared in terms of emission variables (Table 6-9). Cluster 1 denotes low carbon driving where driving is uninterrupted and Cluster 2 represents high carbon driving where driving is interrupted. It was found that low carbon driving produced only 49% of the CO_2 emission of high carbon driving. The reduction in carbon emissions was associated with a 28kph reduction in the average speed, 24s increase in the braking duration and 32s increase in the idling duration. All variables exhibited substantial differences between the two clusters, except for high acceleration duration (Table 6-9).

Table 6-9: Average value of variables for Cluster 1 and Cluster 2

Variable	Cluster 1: Low Carbon Driving	Cluster 2: High Carbon Driving
Average Speed (kph)	45.28	17.55
High Acceleration Duration (s)	0.6	3.2
Braking Duration (s)	4.0	27.6
Low Gear Duration (s)	4.5	42.6
Idling Duration (s)	0.6	32.6
Cumulative CO_2 Emissions (g)	67.33	137.73

Summary

The initial cluster analysis grouped driving behaviour into two clusters. The difference in driving behaviour was well captured by the selected variables, i.e., the idling duration, braking duration, high acceleration duration, low gear duration and average speed. It was found that driving behaviour at the signalised intersections was mainly governed by the interruption in driving. Since drivers often have little control over the interruption, a cluster analysis was further conducted in the following section to produce the true clusters of driving behaviour. However, the situation is not clear cut, as more aggressive drivers may be more likely to have to stop, by not anticipating signal changes.

6.6 Further Cluster Analysis

Cluster analyses were performed for two driving conditions, i.e., interrupted and uninterrupted driving. This is to investigate the true difference in driving behaviour without the effect of the interruption. Cluster analyses in this section had excluded the idling duration variable because uninterrupted driving does not involve idling.

6.6.1 Cluster Analysis for Interrupted Driving

The cluster analysis suggested a three-cluster solution based on the two stopping rules discussed earlier. The three-cluster solution was recommended based on high Je(2)/Je(1) and Pseudo-F indices, and low Pseudo-T-Squared index (Table 6-10). The solution consisted of one big cluster and two small clusters (Figure 6-2). Cluster 1 is the largest cluster which represents low carbon driving behaviour. This cluster is characterised by the highest average speed and the shortest of high acceleration duration, low gear duration and braking duration. Vice versa, Cluster 3 denotes high carbon driving with the lowest average speed and the greatest high acceleration duration, low gear duration and braking duration. Cluster 2 is a group between clusters 1 and 3 (Table 6-11). However, no significant difference in cumulative CO_2 emissions can be observed between clusters 2 and 3.

Table 6-10: Stopping rule index for interrupted driving

Number of Cluster	Calinski-Harabasz Pseudo-F	Duda-Hart	
		Je(2)/Je(1)	Pseudo-T-Squared
1	NA	0.5181	173.02
2	173.02	0.2766	78.48
3	137.21	0.8805	20.89
4	109.11	0.6099	11.51
5	86.74	0.5306	130.03

NA: Not applicable

Figure 6-2: Dendrogram for interrupted driving

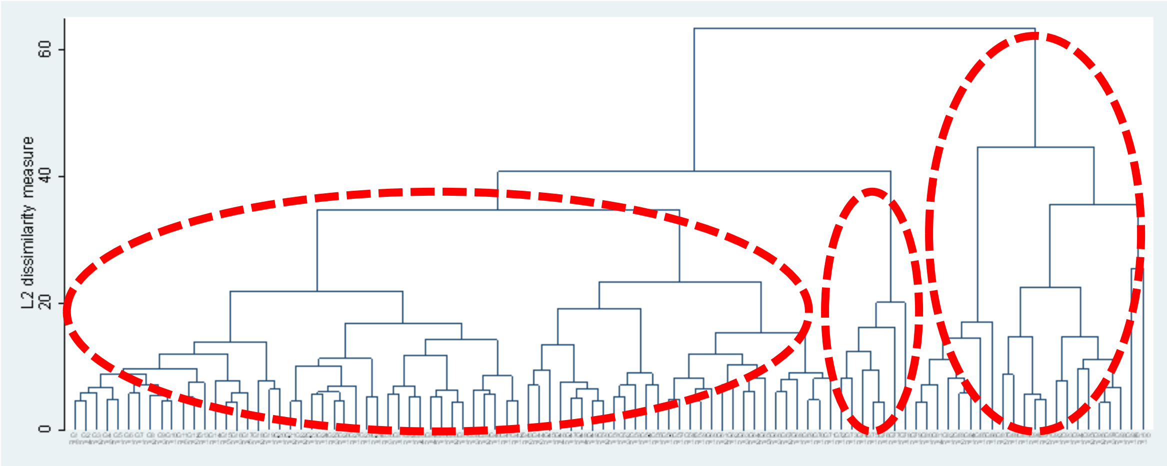


Table 6-11: Average values of cluster variables for interrupted driving

Variable	Cluster 1: Low Carbon Driving	Cluster 2: Medium Carbon Driving	Cluster 3: High Carbon Driving
Average Speed (kph)	24.08	17.82	12.54
High Acceleration Duration (s)	2.9	3.5	3.4
Braking Duration (s)	15.8	31.3	38.0
Low Gear Duration (s)	24.3	39.1	70.6
Cumulative CO_2 Emissions (g)	113.92	141.81	156.42

6.6.2 Cluster Analysis for Uninterrupted Driving

The cluster analysis suggested a three-cluster solution for uninterrupted driving based on Calinski-Harabasz and Duda-Hart stopping rules (Table 6-12). Dendrogram also suggested the same (Figure 6-3). Similar to interrupted driving, the cluster with the highest average speed and the shortest in high acceleration duration, low gear duration and braking duration produced the lowest cumulative CO_2 emissions (Table 6-13). However, no significant difference in CO_2 emissions between clusters 2 and 3 was found using the Kruskal Wallis Rank test ($p=0.4373$). Therefore, driving behaviour was clustered into two groups only, i.e., high carbon driving and low carbon driving.

Table 6-12: Stopping rule index for uninterrupted driving

Number of Cluster	Calinski-Harabasz Pseudo-F	Duda-Hart	
		Je(2)/Je(1)	Pseudo-T-Squared
1	NA	0.6094	231.36
2	231.36	0.4786	366.11
3	394.14	0.805	5.57
4	272.25	0.7551	7.14
5	211.78	0.649	10.27

NA: Not applicable

Figure 6-3: Dendrogram for uninterrupted driving

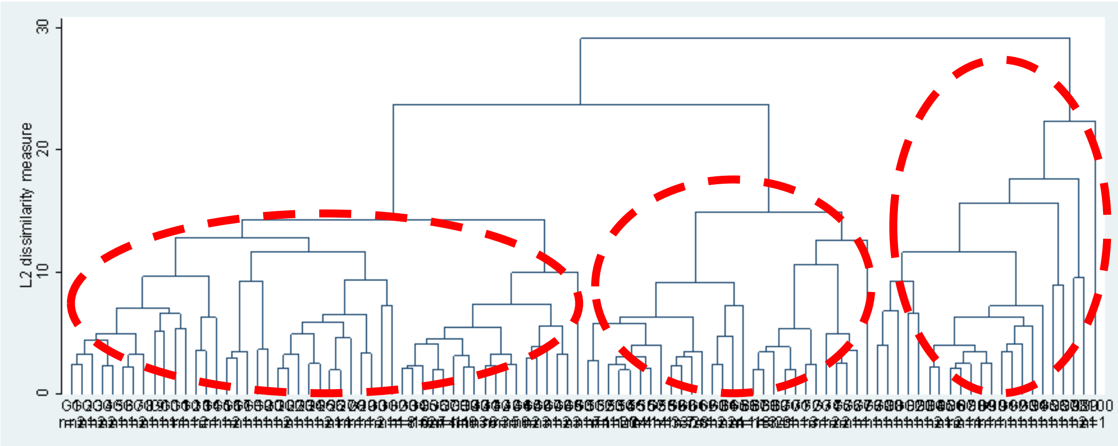


Table 6-13: Average values of cluster variables for uninterrupted driving

Variable	Cluster 1: Low Carbon Driving	Cluster 2: High Carbon Driving	Cluster 3: Low Carbon Driving
Average Speed (kph)	44.38	32.12	55.60
High Acceleration Duration (s)	0.05	1.45	0.04
Braking Duration (s)	2.80	10.13	0.53
Low Gear Duration (s)	0.36	16.31	0.022
Cumulative CO_2 Emissions (g)	59.06	86.41	59.00

6.6.3 Analysis on Two-Cluster Solution

Despite three clusters of driving behaviour having been found only two clusters of driving behaviour had distinct differences in carbon emissions, i.e., high carbon and low carbon driving. Therefore, cluster analyses were performed to generate two clusters of driving behaviour for each of the interrupted and uninterrupted driving. Low carbon driving and high carbon driving were denoted by Cluster 1 and Cluster 2, respectively in Table 6-14. For both interrupted and uninterrupted driving, increased average speed, reduced braking and low-gear durations decreased carbon emissions. Positive acceleration duration increased carbon emissions during uninterrupted driving but not for interrupted driving. No significant difference in the positive acceleration duration was found between high carbon and low carbon driving.

Based on Table 6-14, low carbon driving reduced the average cumulative CO_2 emissions by 27%-30% and the average cumulative fuel by 26-30% compared with high carbon driving. This reduction was found to be related to average speed of 23kph for interrupted driving and 50kph for uninterrupted driving.

Table 6-14: Average values of variables for two clusters solution

	Interrupted		Uninterrupted	
Variable	**Cluster 1**	**Cluster 2**	**Cluster 1**	**Cluster 2**
Cumulative CO_2 Emissions (g)	115.62	158.09	58.84	84.25
Cumulative Fuel (l)	0.048	0.065	0.026	0.037
Average Speed (kph)	23.69	12.95	50.20	32.74
Positive Acceleration Duration (s)	15.68	15.92	10.96	15.71
Braking Duration (s)	18.45	36.04	1.58	9.65
Low-Gear Duration (s)	27.89	56.83	0.08	15.04

6.7 Summary

Two different driving behaviours that produced distinct carbon emissions were found, i.e., high carbon and low carbon driving behaviours. Carbon emission variables that can be used to define driving behaviour at signalized intersections are the average speed, acceleration duration, braking duration and low-gear duration. These factors were adequate for clustering driving behaviour. The percentage of difference in CO_2 emissions between two clusters was found to be identical to the findings in the instructed driving test (preliminary data).

Differences in the average cumulative carbon emissions between the two driving behaviour clusters were found to be 27% and 30% for interrupted and uninterrupted driving, respectively. This indicates a significant yet potential carbon saving opportunity by changing high carbon driving to low carbon driving at signalised intersections. The characteristics of low carbon and high carbon driving were summarised in Table 6-14.

Chapter 7 Analysis and Results

7.1 Introduction

There are two distinct clusters of driving behaviour at signalised intersections (refer Chapter 6). The average differences in fuel and CO_2 between the clusters were between 27% and 30%. Therefore, this chapter investigated the effect of different driving behaviours on CO_2 emissions.

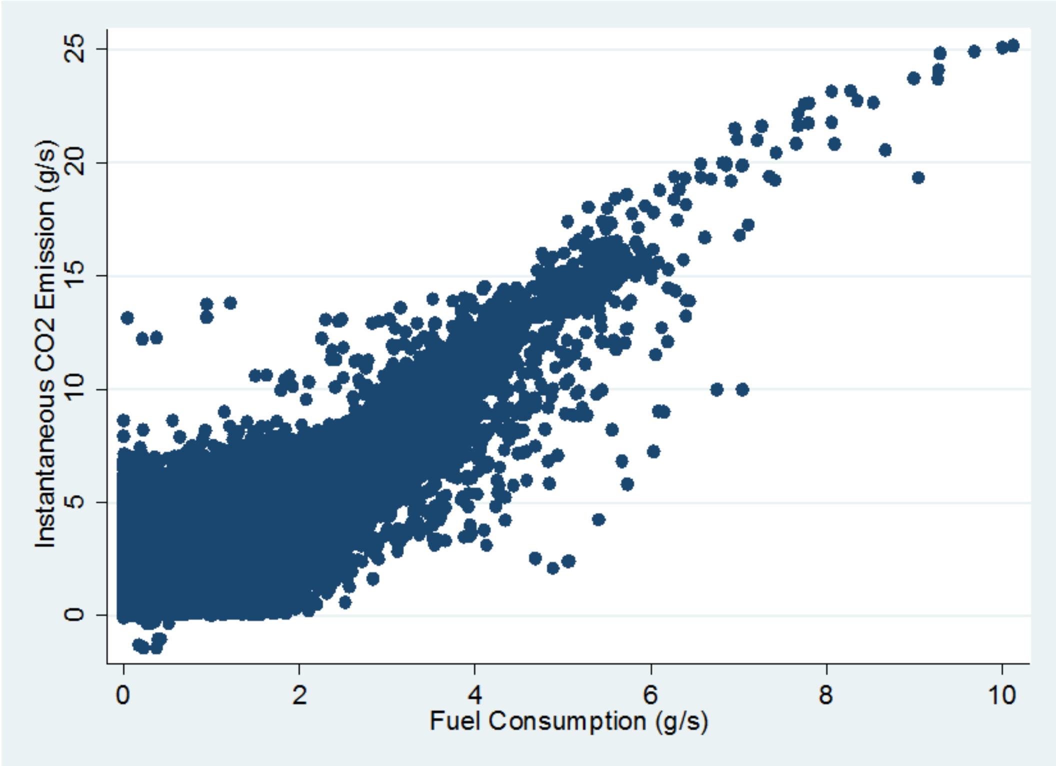
The analysis in this chapter is divided into the following sections. Section 7.2: Verification of the relationship between fuel consumption and CO_2 emissions. Section 7.3: Investigation of the effects of individual emission variables on carbon emissions. Section 7.4: Investigation of the combined impact of instantaneous speed and the instantaneous acceleration on instantaneous CO_2 emissions, by using binned variables. Section 7.5: Investigation of the impacts of interruption, driving mode and driving behaviour on CO_2 emissions. Section 7.6: The analysis of the effects of driving behaviour on CO_2 emissions for each driving modes, i.e., acceleration, idle, deceleration and cruise. Section 7.7: Comparison of different speed profiles over 300m long intersections. Section 7.8: Summary of CO_2 emission rates and maximum CO_2 variations for different cases of driving. Section 7.9: Investigation on the applicability of CO_2 savings that was demonstrated by the instrumented vehicle to other vehicle types. Definitions of the variables used in this chapter are given in Table 6-1.

7.2 CO_2 Emissions vs. Fuel Consumption at Signalised Intersections

Carbon emissions were assumed to be directly proportional to the fuel consumption. This would be true for driving that has little/no incomplete combustion events. Therefore, the purpose of this analysis was threefold: 1) to investigate whether this assumption can be applied to driving at signalised intersections that was dominated by extreme combustion events, 2) to demonstrate that findings of the preliminary analysis, which are based on fuel consumption, have the same impact on carbon emissions, and 3) to show that CO_2 savings concluded in this study are proportional to savings in fuel consumption.

A linear function between instantaneous CO_2 emissions and instantaneous fuel consumption was established from driving data collected at signalised intersections in this study (Figure 7-1). Some scattered data points were observed at lower values of the axes due to the sensitivity of the OBS equipment. Based on observations during the field tests, CO_2 emission concentration fluctuated at low engine load, which may cause by the dilution of gases at the exhaust pipe and/or change in exhaust flow. From the aspect of statistics, massive data concentrated at lower values may increase noise in data.

Figure 7-1: Instantaneous CO_2 emission vs. instantaneous fuel consumption at signalised intersections



Pairwise and linear regression analyses were performed on instantaneous fuel consumption and instantaneous CO_2 emission data using STATA, a statistical software package developed by StataCorp. A strong correlation between these two variables was reported from the Pairwise Correlation analysis, with a correlation coefficient of 0.9159, which implied that these two variables were strongly correlated. Then, a robust linear equation with a high coefficient of determination (R^2) and a low Root Mean-Square-Error (Root-MSE) was established using the linear regression analysis (Table 7-1). An R^2 value of 0.9199 indicated that the relationship between CO_2 emissions and fuel consumption was linear. The instantaneous CO_2 emission in g/s, *IC* can be expressed by instantaneous fuel consumption, *IF* in g/s as Equation 7-1.

$$IC = 2.799IF$$

Equation 7-1

Comparing this linear equation with Equation 4-1, CO_2 produced from one gram of petrol using Equation 7-1 were 11% different from the prediction of Equation 4-1. Equation 7-1 confirmed the linear dependency of carbon emissions on fuel consumption at signalised intersections. However, impacts demonstrated by either one variable shall be applicable to others only if an adjustment is made according to Equation 7-1.

Table 7-1: Linear regression between CO_2 emissions and fuel consumption at signalised intersections

```
. regress co2_obs fuel_canbus, noconstant beta

      Source |       SS        df        MS             Number of obs =  200742
-------------+------------------------------            F(  1,200741) =       .
       Model |  1633677.99      1  1633677.99           Prob > F      =  0.0000
    Residual |  142299.484200741  .708871052            R-squared     =  0.9199
-------------+------------------------------            Adj R-squared =  0.9199
       Total |  1775977.47200742  8.84706475            Root MSE      =  .84194

------------------------------------------------------------------------------
     co2_obs |      Coef.   Std. Err.      t    P>|t|                     Beta
-------------+----------------------------------------------------------------
 fuel_canbus |   2.799071   .0018438  1518.10   0.000                 1.082363
```

7.3 Relationships between Emission variables and Carbon Emissions

Carbon emissions were found to be highly correlated with the average speed, positive acceleration duration, low gear duration and braking duration at signalised intersections (refer Chapter 6). Increase in the positive acceleration duration, low gear duration and braking duration increased CO_2 emissions, but increases in the average speed reduced CO_2 emissions (Table 6-14). Therefore, the dependencies of CO_2 emissions on each of the emission variables were investigated separately in the following sections, and carbon emission equations were established for each of these variables for signalised intersections. Carbon emissions were presented in two formats, i.e., cumulative CO_2 emissions for entire driving over a 300m long signalised intersection and cumulative CO_2 emissions under particular driving situations, such as positive acceleration, braking or low gear.

7.3.1 Positive Acceleration Duration

CO_2 emissions produced during positive acceleration were the main source of CO_2 emissions at intersections (Table 7-7). An increase in positive acceleration duration increased cumulative CO_2 emissions (Figure 7-2). A linear relationship can be observed between these two variables (Figure 7-3), which can be expressed as Equation 7-2. The constant was discarded because it was statistically insignificant (Table 7-2).

$$CC = 4PA$$

Equation 7-2

- *CC* is the cumulative CO_2 emissions during positive acceleration in grams.
- *PA* is the positive acceleration duration in seconds.

Figure 7-2: Cumulative CO_2 emissions vs. positive acceleration duration

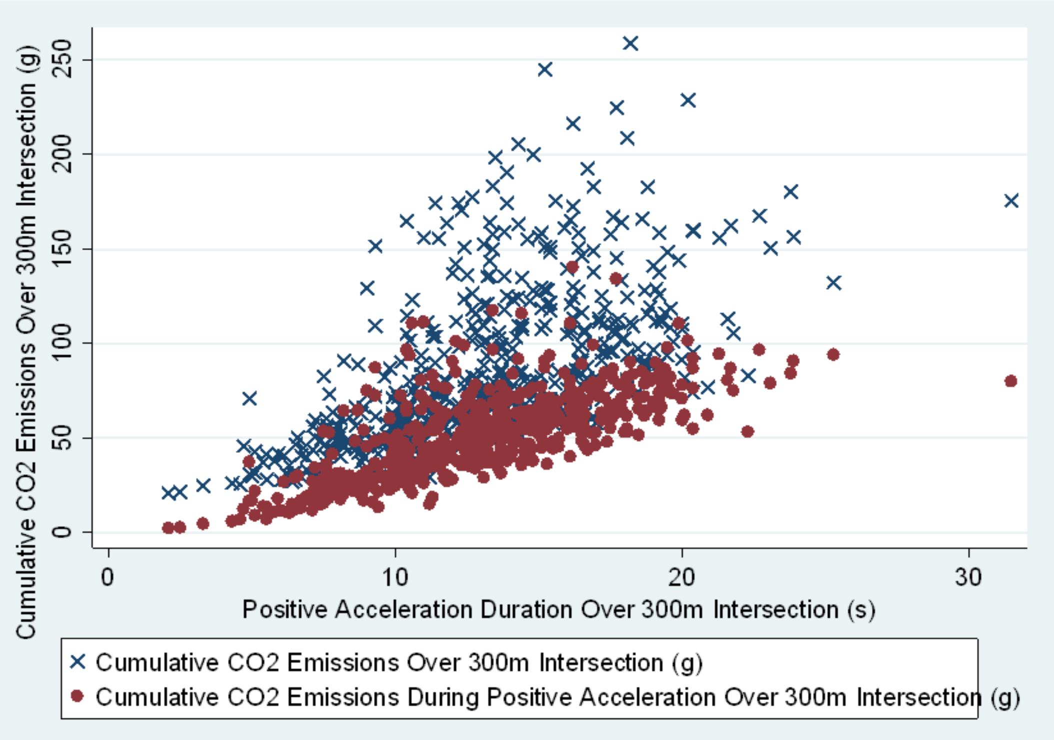


Figure 7-3: Cumulative CO_2 emissions during positive acceleration vs. positive acceleration duration for 300m intersection

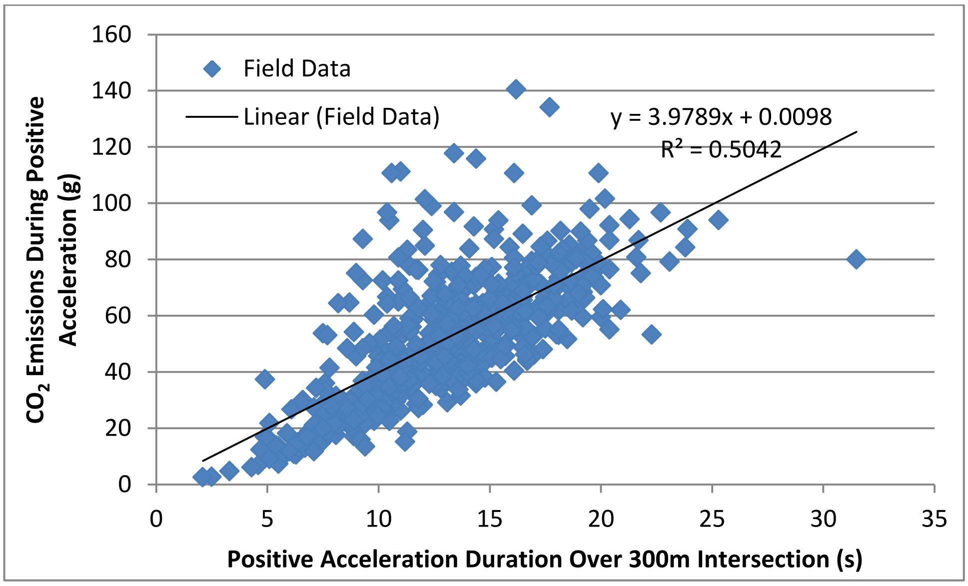


Table 7-2: Linear fitting equation for cumulative CO_2 during positive acceleration and positive acceleration duration

Source	SS	df	MS		
				Number of obs	= 550
				F(1, 548)	= 557.36
Model	135676.524	1	135676.524	Prob > F	= 0.0000
Residual	133398.818	548	243.428501	R-squared	= 0.5042
				Adj R-squared	= 0.5033
Total	269075.343	549	490.119022	Root MSE	= 15.602

co2_acc_po~g	Coef.	Std. Err.	t	P>|t|	Beta
acc_positi~n	3.978877	.1685365	23.61	0.000	.7100933
_cons	.0098018	2.311576	0.00	0.997	.

7.3.2 Braking Duration

An increase in the braking duration increased the cumulative CO_2 emissions (Figure 7-4). However, the braking duration was found to be highly correlated to the idling duration. A plot of the braking duration vs. idling duration showed two trends. One increased corresponding to the idling duration and the other remained constant (Figure 7-5). The former might be due to drivers pressing the brake pedal during idling mode, which increased the total braking duration. Therefore, an actual braking duration was obtained by subtracting braking-duration-during-idling from the total braking duration.

Figure 7-4: Cumulative CO_2 emissions vs. actual braking duration

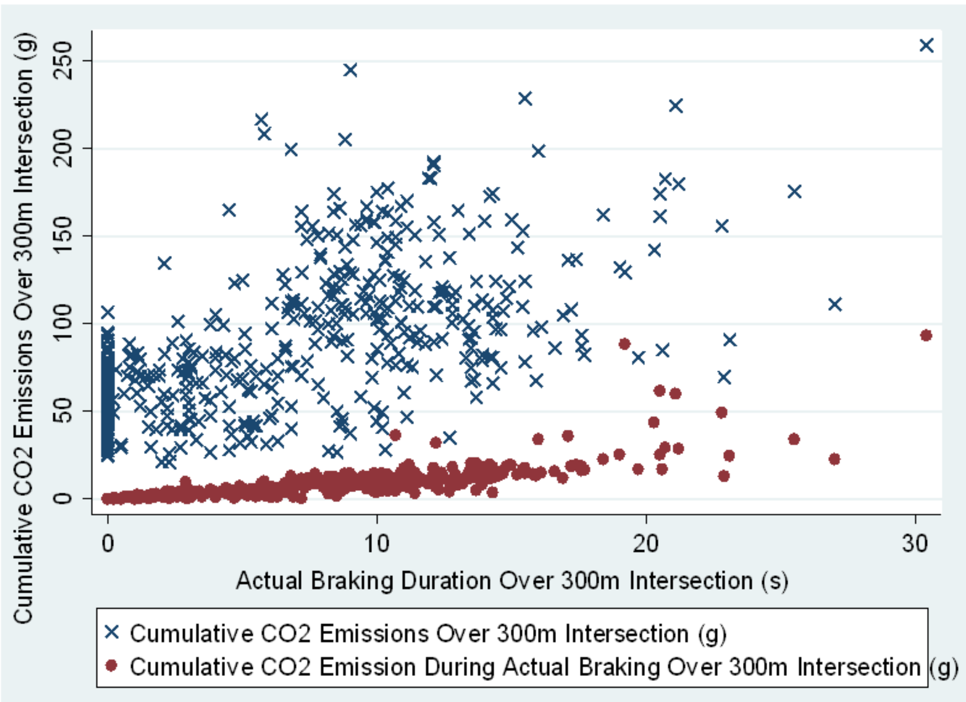
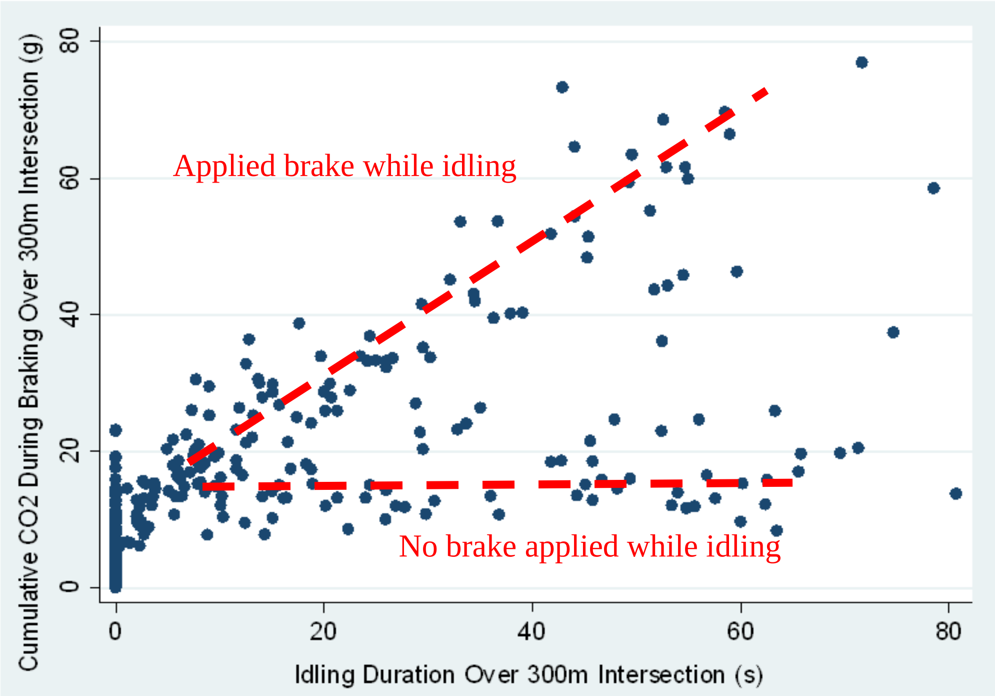


Figure 7-5: Braking duration vs. idling duration



Cumulative CO_2 emissions during actual braking were found to increase with the actual braking duration (Figure 7-4). A linear fitting equation (Figure 7-6, Table 7-3) for the cumulative CO_2 emissions during actual braking can be expressed as:

$$CC = 1.28\,BD - 1.0$$

Equation 7-3

- CC is the cumulative CO_2 emissions during actual braking in grams.
- BD is the actual braking duration in seconds.

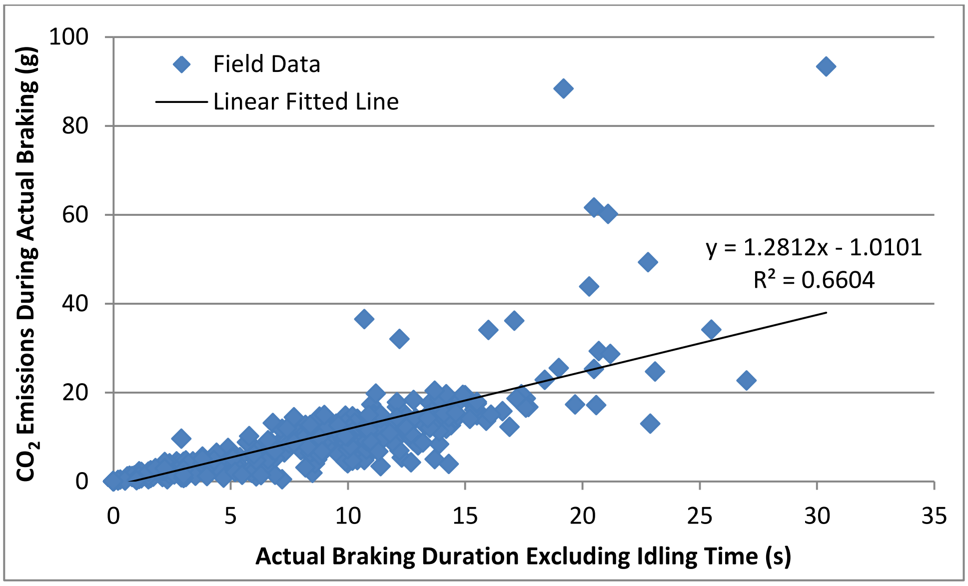
CO_2 emissions from the actual braking were relatively small compared with total CO_2 emissions at an intersection (Figure 7-4). Although braking had little effect on total CO_2 emissions, the action itself could induce higher cumulative CO_2 emissions because of the subsequent acceleration effort required to regain the desired speed.

Table 7-3: Linear fitting for cumulative CO_2 emissions during actual braking based on actual braking duration

Source	SS	df	MS		
				Number of obs =	550
				F(1, 548) =	1065.51
Model	31528.2569	1	31528.2569	Prob > F =	0.0000
Residual	16215.1726	548	29.5897309	R-squared =	0.6604
				Adj R-squared =	0.6597
Total	47743.4294	549	86.9643523	Root MSE =	5.4396

braking_ex~g	Coef.	Std. Err.	t	P>|t|	Beta
braking_ex~e	1.281206	.03925	32.64	0.000	.8126306
_cons	-1.01009	.3264012	-3.09	0.002	.

Figure 7-6: Cumulative CO_2 emissions during actual braking vs. actual braking duration for 300m intersection



7.3.3 Low Gear Duration

Field tests in this study were conducted using a car with an automatic transmission. The observed driving behaviour reflected more on drivers' aggressiveness instead of their gear changing skills. The most significant proportion of cumulative CO_2 emissions at signalised intersections was produced in low gears (Figure 7-7). CO_2 emitted during low gears increased with the increase in the low gear duration (Figure 7-8). A linear relationship between the variables was established using STATA statistical software (Table 7-4).

$$CC = 1.95LG + 6$$

Equation 7-4

- CC is the cumulative CO_2 emissions during the low gear in grams.
- LG is the low gear duration in seconds.

Table 7-4: Linear fitting equation for cumulative CO_2 emissions during low gear vs. low gear duration

Source	SS	df	MS
Model	898022.864	1	898022.864
Residual	202913.794	548	370.280646
Total	1100936.66	549	2005.3491

Number of obs	= 550
F(1, 548)	= 2425.25
Prob > F	= 0.0000
R-squared	= 0.8157
Adj R-squared	= 0.8154
Root MSE	= 19.243

low_gear_c~g	Coef.	Std. Err.	t	P>|t|	Beta
gear_low_d~n	1.948691	.0395699	49.25	0.000	.9031555
_cons	5.837966	1.000882	5.83	0.000	.

Figure 7-7: Cumulative CO_2 emissions vs. low gear duration

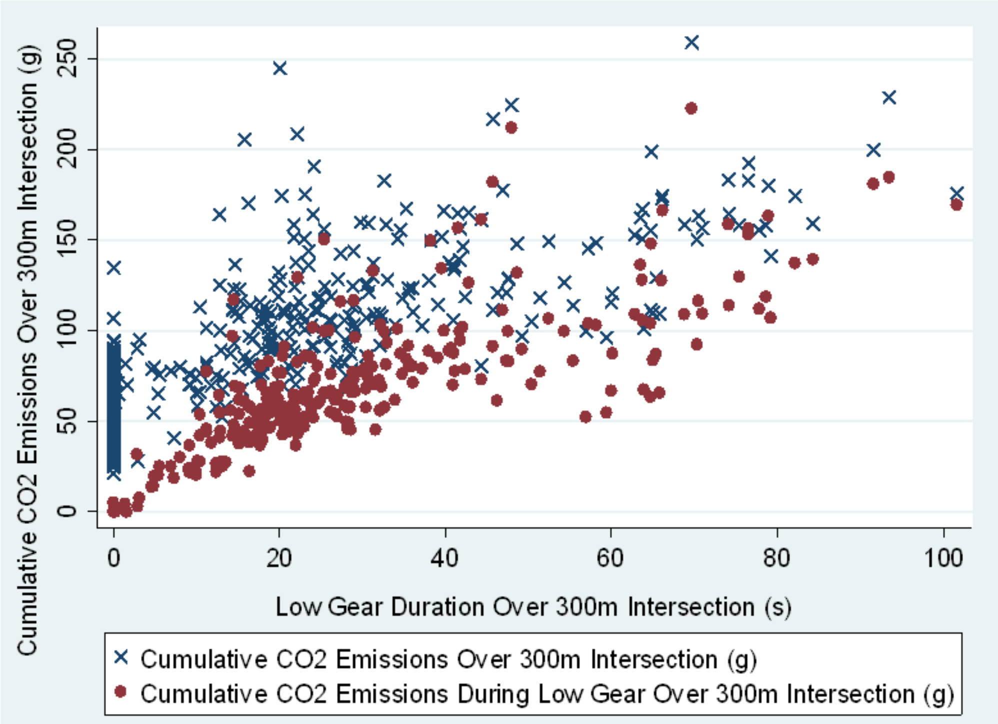
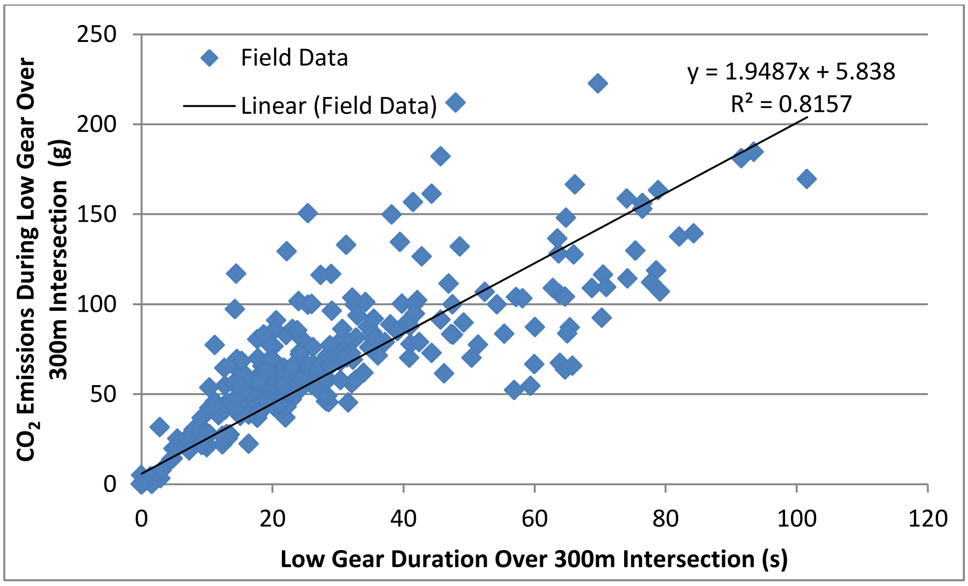


Figure 7-8: Cumulative CO_2 emissions during low gear vs. low gear duration



7.3.4 Average Speed

The relationship between average speed and cumulative CO_2 emissions was found to be a convex curve (Figure 7-9), similar to findings reported by Barth and Boriboonsomsin, 2008 (Barth and Boriboonsomsin 2008). The majority of average speeds obtained from in this study lay in between 10kph and 60kph because of the 40mph (64kph) speed limit. This small range of speed covered only half of the convex curve (Figure 7-9).

The optimum average speed for low emissions was found to be between 50kph-60kph for signalised intersections. This range of optimum speeds was found to be lower than the range of optimum speeds for links. An optimum speed between 72kph-90kph for links was reported by Barth and Boriboonsomsin, 2008, Rakha and Ding, 2003, and El-Shawarby et al., 2005 (Rakha and Ding 2003; El-Shawarby, Ahn et al. 2005; Barth and Boriboonsomsin 2008). This indicated that driving attributes at intersections was different from links, in which driving at intersections were characterised by more extreme events, i.e., deceleration and acceleration. The optimum average speed for intersection segments could only be achieved during uninterrupted driving where speed is high. For interrupted driving, increasing speed reduced CO_2 emissions but the speed was not sufficiently high to achieve the optimum speed (Figure 7-10).

A comparison of the result in this section with the result reported by Barth and Boriboonsomsin, 2008, showed that overall CO_2 emissions at signalised intersections were similar to CO_2 emissions on links (Figure 7-11, (Barth and Boriboonsomsin 2008)). However, below 40kph speed, signalised intersections had higher CO_2 emissions than the links, which might be caused by the use of low gears and more frequent acceleration events.

Figure 7-9: Cumulative CO_2 emissions vs. average speed

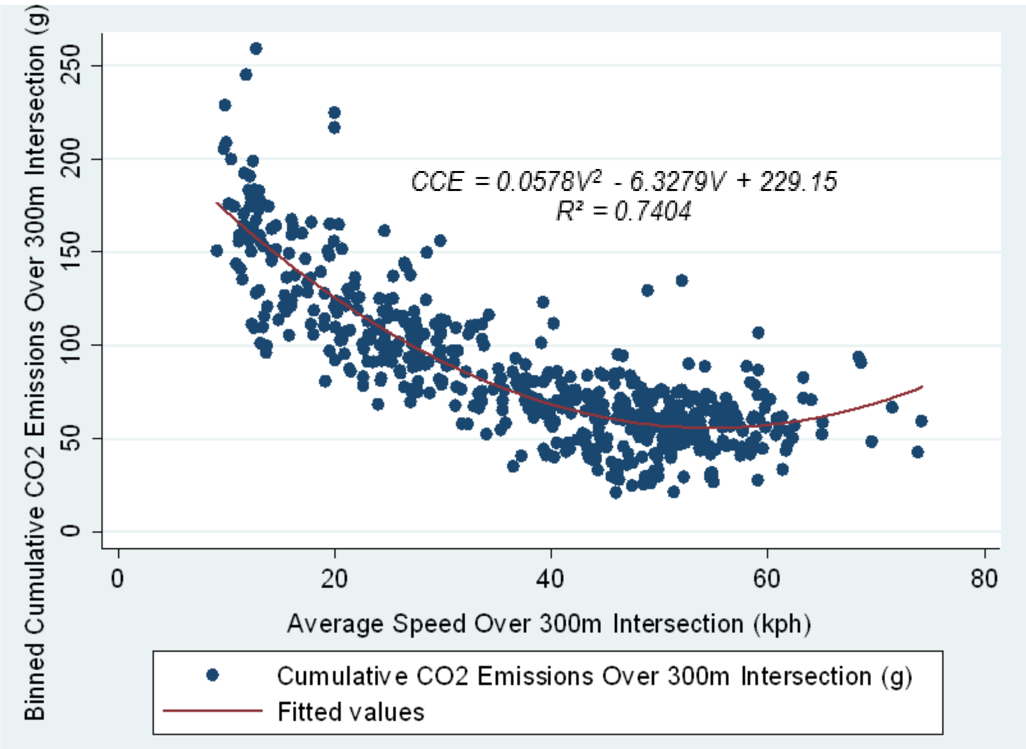


Figure 7-10: Cumulative CO_2 emissions vs. average speed over 300m long intersections

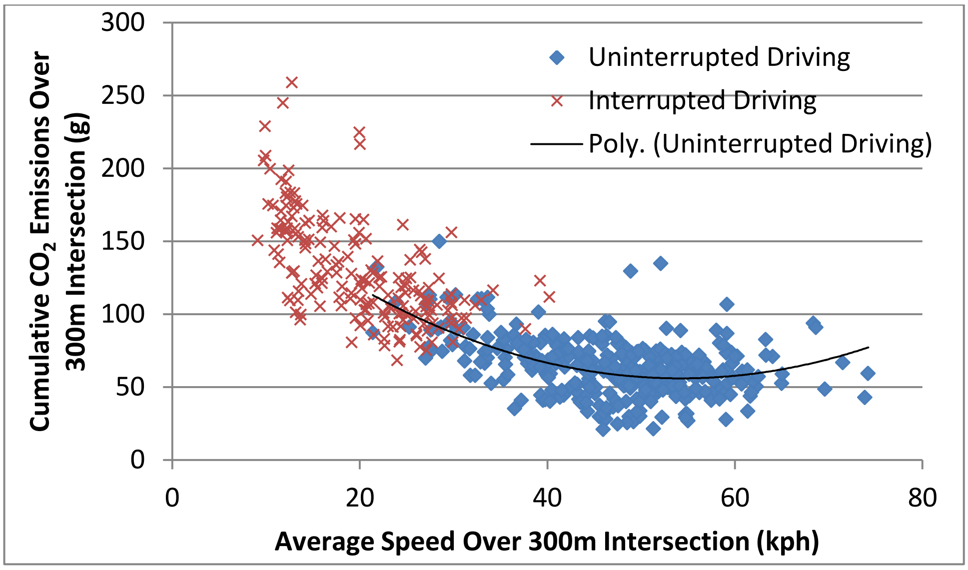
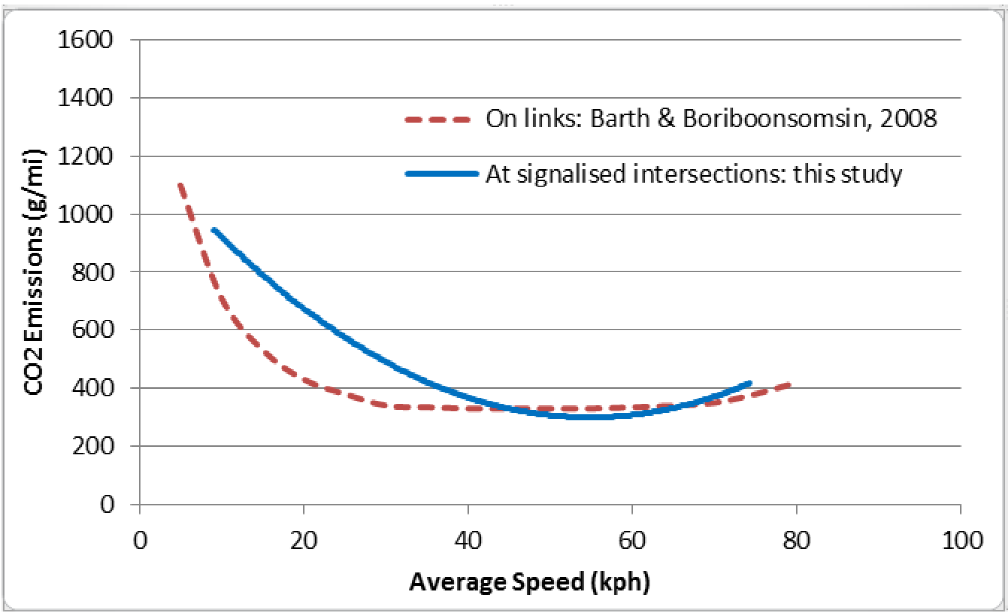


Figure 7-11: Comparison of CO_2 emissions with other study



7.3.5 Instantaneous Speed and Acceleration

Three impact zones were found in the preliminary analysis, based on the impact of acceleration levels on fuel consumption 1) the low-impact zone, where acceleration and speed had insignificant impact on fuel consumption, 2) the intermediate-impact zone, where increases in fuel consumption were essentially affected by the acceleration and 3) the high-impact zone, where both acceleration and speed had significant impacts on fuel consumption (refer Section 5.8.2 Instantaneous Acceleration). CO_2 emissions in the larger study (main field test) showed similar impact zones as in the preliminary analysis, in which three impact zones were observed (Figure 7-12). The values of acceleration corresponding to low, intermediate and high impact zones were given in Table 7-5. In the low-impact zone, CO_2 emission rates were insensitive to acceleration and speed for all driving modes. Carbon emissions in the intermediate-impact zone were highly sensitive to acceleration, but less sensitive to speed. For high-impact zone, both acceleration and speed had substantial effects on CO_2 emissions..

A fitted equation for overall CO_2 emissions vs. acceleration was given in Figure 7-13. However, its coefficient of correlation, R^2, was found to be relatively low because there was variation in driving behaviour between drivers and CO_2 emissions cannot be described by acceleration alone. Fitted equations for individual drivers were found to be better in strength, with maximum Coefficient of Correlation of 0.4647.

Extreme acceleration was observed for both negative and positive acceleration in this study (Figure 7-14). Some were greater than the standard acceleration (-3.41m/s^2) recommended by American Association of State Highway and Transportation Officials (AASHTO). The extreme acceleration might indicate that 1) acceleration in real-world driving could be much higher than those used in design, 2) data collected in this study was comprehensive and covered a wide range of driving behaviour, including extreme events and minute changes in driving and 3) acceleration calculated from speed based on 0.1s intervals were higher than when 1s interval was used.

Figure 7-12: Impact zones

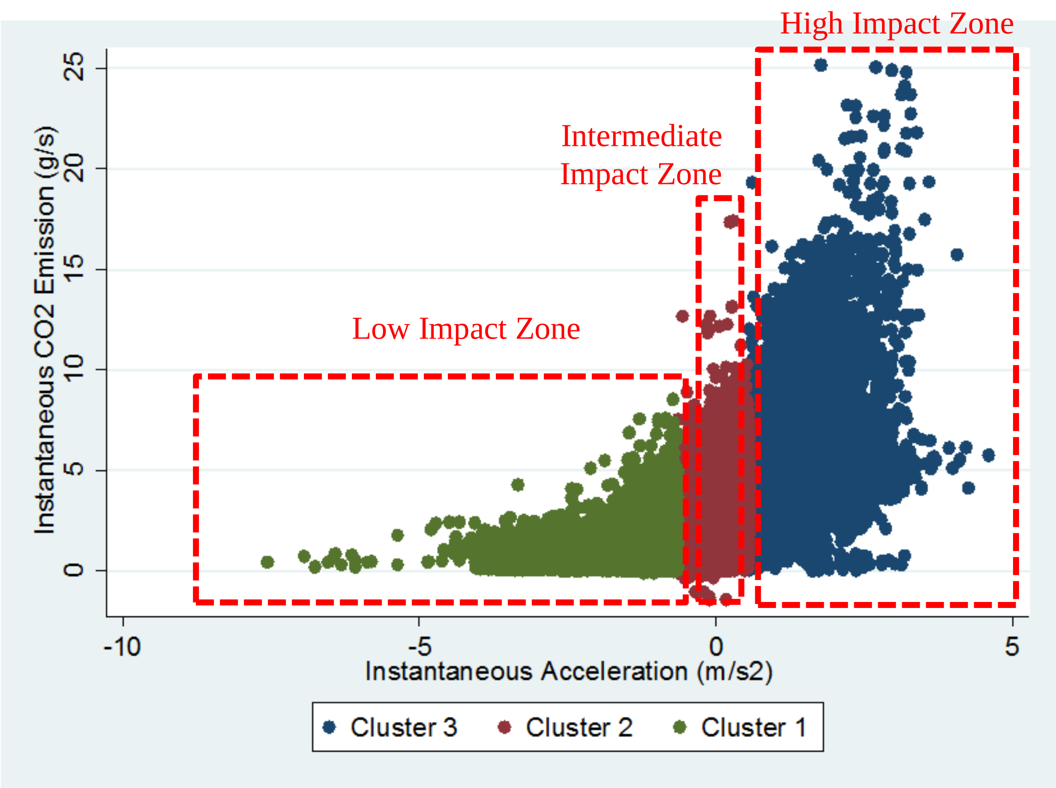
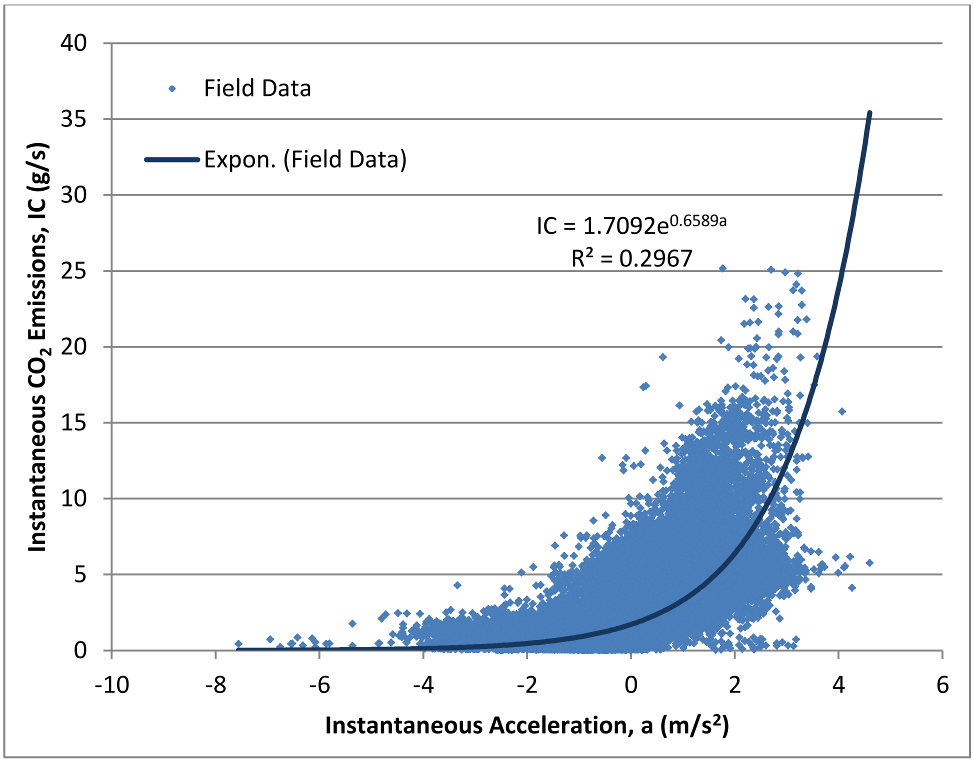


Table 7-5: Maximum and minimum acceleration values for each cluster

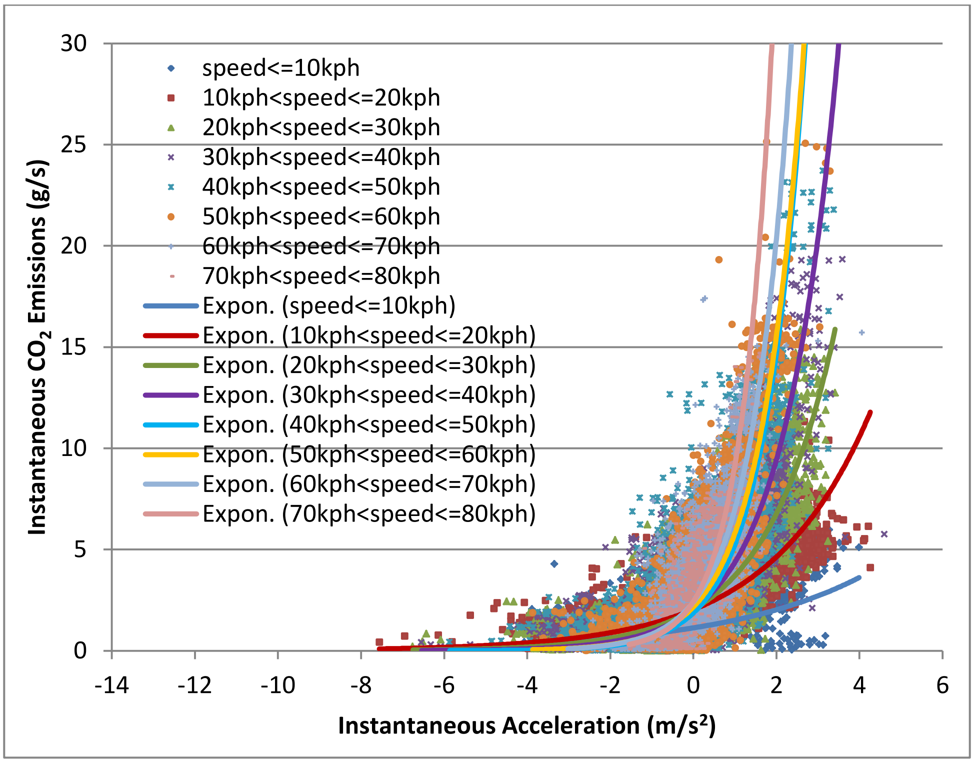
Cluster	Observation	Variable	Min	Max
1	25320	CO_2 (g/s)	-0.1	8.5
		Acceleration (m/s^2)	-7.6	-0.6
		Speed (kph)	0.0	79.6
2	144368	CO_2 (g/s)	-1.4	17.4
		Acceleration (m/s^2)	-0.6	0.6
		Speed (kph)	0.0	79.4
3	31054	CO_2 (g/s)	0.0	25.2
		Acceleration (m/s^2)	0.6	4.6
		Speed (kph)	0.2	80.9

Figure 7-13: CO_2 emission function



Note: For CO_2 emissions > 0g/s

Figure 7-14: Instantaneous CO_2 emissions vs. instantaneous acceleration at different speeds



7.3.6 Summary

The increase in positive acceleration and low gear duration positive acceleration and low gear duration has a strong correlation with the increase in CO_2 emissions at signalised intersections. However, CO_2 emissions during the actual braking were relatively small when compared with the others.

The average intersection speed for optimum CO_2 output was between 50-60kph under uninterrupted driving. An increase in average speed reduces CO_2 emissions for interrupted driving. CO_2 emissions vs. average speed trends were similar between signalised intersections and links. However, the optimum average speed at signalised intersections is different from links, which might be caused by greater usages in low gear and positive acceleration at intersections.

Effects of changes in acceleration and speed on CO_2 emissions are small/negligible for acceleration below -0.6 m/s^2. Beyond 0.6 m/s^2, both acceleration and speed had significant effects on CO_2 emissions. Therefore, the effect of low acceleration and soft acceleration was investigated in Section 7.6.1 Analysis for Acceleration Mode.

7.4 Impacts of Interruption, Driving Mode and Behaviour on Carbon Emissions

Carbon emissions at signalised intersections are highly correlated to the emission variables discussed in previous sections. Impacts of these factors on CO_2 emissions vary depending on: 1) driving conditions, i.e., interrupted and uninterrupted driving, 2) driving modes, i.e., acceleration, idle and deceleration and 3) driving behaviour, i.e., high carbon driving (aggressive) and low carbon driving (economical). This section investigates and quantifies the differences between each case in terms of the average speed, average acceleration, average travel duration and CO_2 emissions. This provides information on the maximum savings that can be achieved if conditions change, for example, if the interruption is prevented. The average speed and average acceleration were compared to see the influence of each factor on CO_2 emissions.

7.4.1 Interruption

In this study, interrupted driving refers to driving where a driver encounters at least one stop at an intersection. Vice versa, uninterrupted driving represents a situation where a driver crosses an intersection without stopping.

The interruption doubled the average cumulative CO_2 emissions (Table 7-6). In the preliminary analysis, fuel consumption of interrupted driving was 2.8 times of uninterrupted driving at a signalised intersection, which was greater than the increase in CO_2 due to the interruption (Section 5.8.1 Stop/Interruption). This could be because the main field tests collected more natural and normal driving, which tend to show smaller deviation than the rather artificial instructed driving, i.e., aggressive vs. economical, used in the preliminary field test. The large increase in cumulative CO_2 emissions was found to be highly correlated to the significant reduction in average speed, change in positive acceleration and increase in the travel duration.

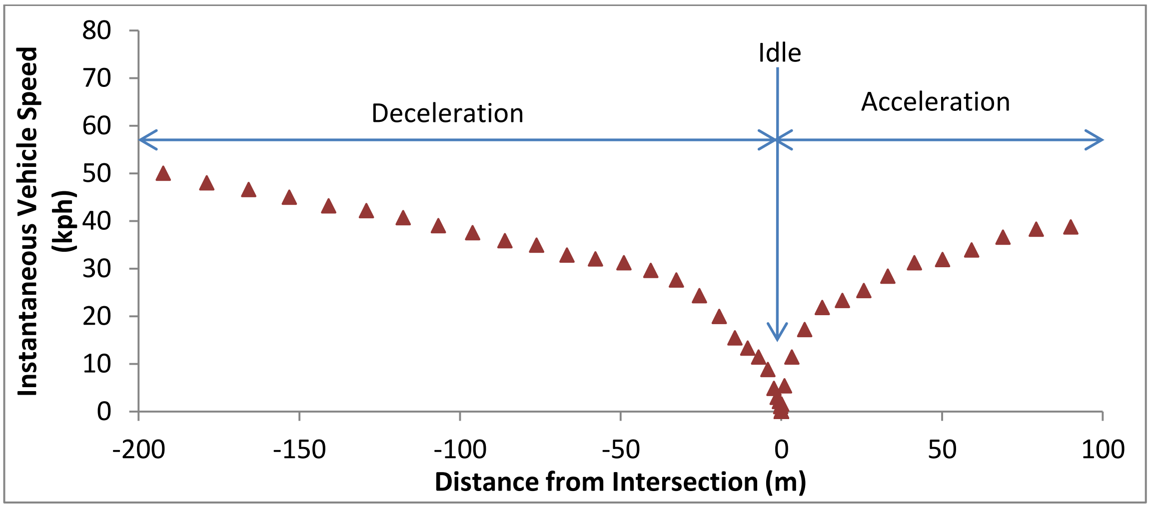
Table 7-6: Mean of variables for driving on 300m intersections

Variable	Uninterrupted Driving [A]	Interrupted Driving [B]	Difference (%) [(A-B)/A]
Cumulative Fuel (g)	20.5	39.4	92
Cumulative CO_2 (g)	63.2	129.6	105
Average Speed (kph)	47.2	20.1	-57
Average Positive Acceleration (m/s^2)	0.432	0.955	121
Average Negative Acceleration (m/s^2)	-0.387	-0.911	136
Average Acceleration (m/s^2)	0.041	-0.018	-143
Duration (s)	23.9	60.8	154

7.4.2 Driving Mode

Three driving modes involved in interrupted driving are deceleration, idle and acceleration (Figure 7-15). Cruising is the only mode involved in uninterrupted driving.

Figure 7-15: Modes involved in interrupted driving at the intersection



Of all driving modes, acceleration produced the highest cumulative CO_2 emissions over a 300m intersection (Table 7-7). Even though the instrumented vehicle spent the least time under the acceleration mode (27%), 55% of the CO_2 was emitted during this mode. 20% of the CO_2 was emitted during deceleration and the remaining 25% of the CO_2 came from idling with an average idling duration of 26s (Table 7-7). The average instantaneous CO_2 emission rate (g/s) during acceleration was the highest among four driving modes. The rate was found to be 3.5 times of the idle mode, 3.0 times of the deceleration mode and 1.6 times of the cruise mode. The difference in CO_2 emissions between acceleration and deceleration was largely because of the variation in acceleration, as average speeds were almost identical. For the idle mode, CO_2 emissions were not affected by speed nor the acceleration but the idling duration (Section 7.5.1.2).

Table 7-7: Average values of the variables by driving mode

Variable	Interrupted			Uninterrupted
	Deceleration	Idle	Acceleration	Cruise
Cumulative CO2 (g)	7.1	8.0	24.2	20.5
Cumulative Fuel (g)	26.5	32.3	70.8	63.2
Average Speed (kph)	32.5	0.0	32.1	47.2
Average Positive Acceleration (m/s^2)	0.323	0.0	1.030	0.432
Average Negative Acceleration (m/s^2)	-0.994	0.0	-0.309	-0.387
Average Acceleration (m/s^2)	-0.812	0.0	0.822	0.041
Duration (s)	18.5	26.0	16.3	23.9
Cumulative CO_2 (g)	7.1	8.0	24.2	20.5

7.4.3 Driving Behaviour

Traffic control such as traffic signal affects driving at signalised intersections. In order to prevent conflicts, traffic lights assign exclusive rights of way to certain intersection approaches and stop traffic on other approaches. This resulted in four driving modes, i.e., deceleration, idle, acceleration and cruise modes at intersections. Eliminating the effect from traffic control by studying the individual driving mode, CO_2 emissions from driving are then assumed to be mainly governed by decisions made by drivers and thus their driving behaviour. The decisions made by drivers relating to aggressiveness in the acceleration, deceleration, speed and gear change could affect the total CO_2 emissions at intersections. The decision may vary between drivers and within the same driver on different trips.

In the preliminary analysis, a significant difference in fuel consumption was found between the instructed aggressive driving and instructed economical driving (Section 5.6.1 Difference in Driving Behaviour). In this section, variations in carbon emissions due to driving behaviour were investigated for deceleration, idle, acceleration and cruising modes. CO_2 variations during idling were not considered. Excluding the outliers, the boxplot in Figure 7-16 showed that CO_2 variations between drivers were 45g during deceleration, 93g during idling, 67g during acceleration and 88g during cruising, respectively. Such great variations in CO_2 emissions indicated a good opportunity of reducing carbon emissions through changing driving behaviour. CO_2

variations within a driver were found to be relatively smaller than variations between drivers. There were a few exceptions where CO_2 variations within a driver were considerably large, for example, drivers 16, 17 and 27 during deceleration, and drivers 6, 16 and 23 during acceleration (Figure 7-17). These were observable from the field tests, where these drivers were found driving rather inconsistently. They appeared to be less calm or little flurried and tended to drive more aggressively at some locations. However, more consistent driving could be expected if the drivers were driving their own vehicles, and therefore, producing smaller within-driver CO_2 variations. CO_2 variations were found to be more uniform during the cruising mode.

These findings implied that although there was some degree of CO_2 variation within a driver, an average CO_2 saving of 30g and 35g of CO_2 for acceleration and cruising modes, respectively, could be achieved if the driving of an average driver was to change (Table 7-8). This estimation was rather conservative as it is based on the average savings of 29 drivers, which consisted of both aggressive and non-aggressive drivers. The saving might be less if the driver is already an economical driver, but larger CO_2 savings shall be expected from more aggressive drivers.

Figure 7-16: CO_2 variation between drivers

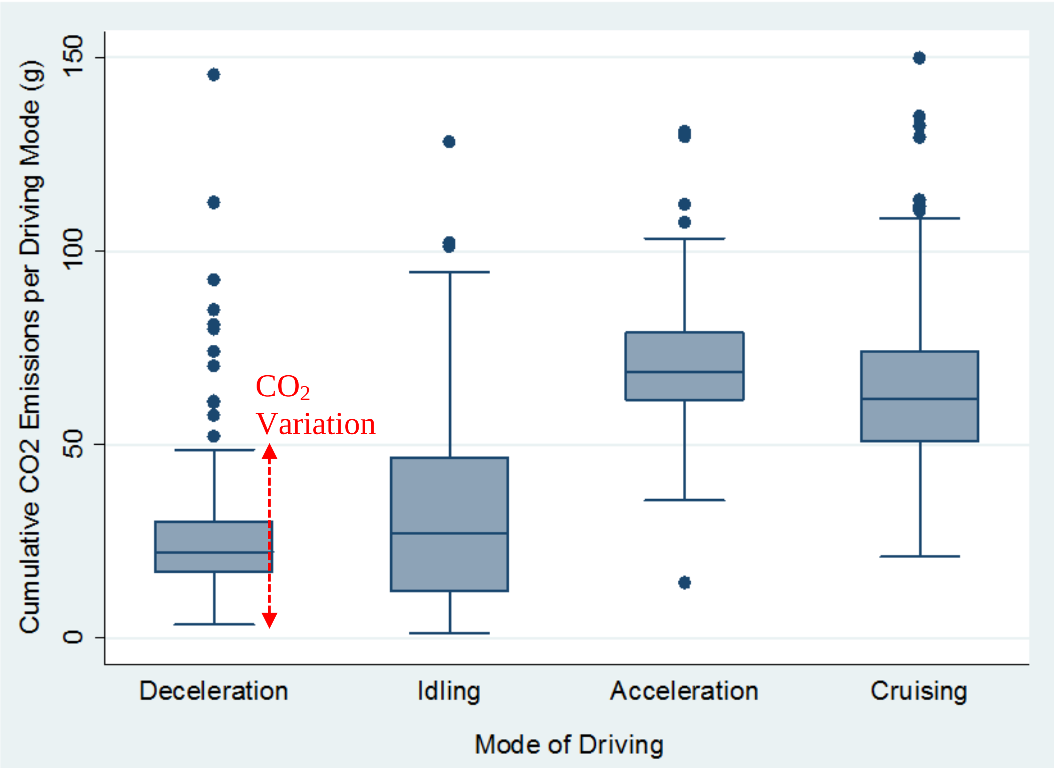


Figure 7-17: CO_2 variation within driver

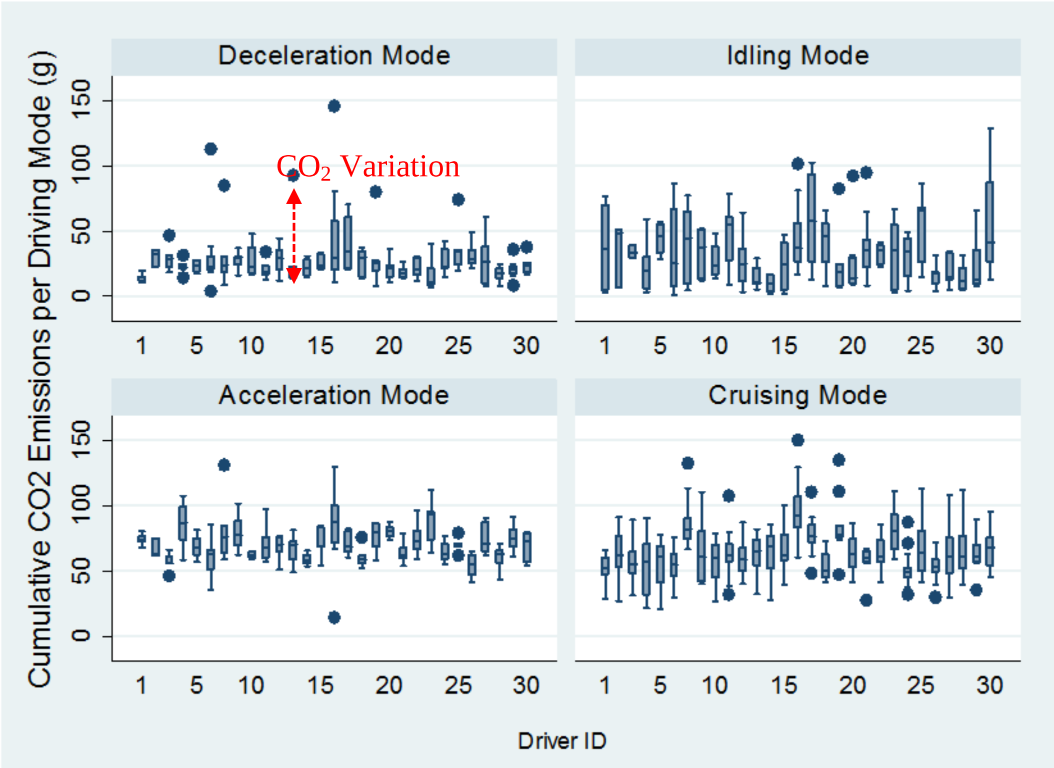


Table 7-8: CO_2 savings by an average driver through changing driving behaviour

Mode	Average CO_2 Variation Within Driver (g)	Maximum CO_2 Variation Between Drivers (g)	Average CO_2 Saving by individual driver (g)
	[A]	**[B]**	**[B]-[A]**
Deceleration	37	45	8
Acceleration	32	67	35
Cruising	58	88	30

7.4.4 Summary

In summary, an interruption in driving could double the average CO_2 emissions of an uninterrupted driving. CO_2 emissions for the acceleration mode were 1.6 times of the cruise mode. This demonstrates that interruptions and driving modes have significant effects on carbon emissions at intersections. Therefore, later analyses were focused on the four main driving modes.

Substantial CO_2 variations between drivers indicated that changing driving behaviour could significantly reduce CO_2 emissions. Although some degrees of variation existed within the driver, the real CO_2 reduction after taking into account the within-driver variation would still be significant enough if driving behaviour were to change. Considering the substantial impact and low cost involved in changing driving behaviour, next section investigated possible changes in driving behaviour/practices to achieve carbon reductions at signalised intersections.

7.5 CO_2 Emission Models

Since the majority of carbon emission models were based on standard driving cycles and there were no carbon emission models that focused at the intersection segments which involved vehicle operations at the transient stage. Existing models generalised the vehicle emissions on any type of roads. This might bias the prediction result of the carbon emission model if a significant amount of CO_2 emissions comes from signalised intersections.

CO_2 emission models were established in this study to provide an insight into the relationships between emission variables and carbon emissions at signalised intersections. These linear regression models were generated using STATA statistical software (refer Nomenclature). These models could still be improved. For instances, more efforts are required to check requirements and assumptions of the regression in future research. The models used in this study, however, could provide rough estimation of 1) cumulative CO_2 emissions based on average trip variables and 2) instantaneous CO_2 emissions based on instantaneous speed and acceleration.

7.5.1 Cumulative CO_2 Emissions

The models developed in this section estimate cumulative CO_2 emissions for particular driving modes, which include acceleration, idling, deceleration and cruising modes.

7.5.1.1 For Acceleration Mode

A number of factors could influence cumulative CO_2 emissions during the acceleration mode at intersections. These factors include the average acceleration, average speed, positive acceleration duration, low gear duration, negative acceleration and braking acceleration. It was found that these factors were statistically significant in the estimation of the cumulative CO_2 emissions at 95% confidence level (Table 7-9). The β values in the table indicated the influence of each variable on CO_2 emissions, in which the strongest influence came from positive acceleration duration, average acceleration and average speed variables. Relationships between cumulative CO_2 emissions and the six emission variables are depicted in Figure 7-18 where CO_2

emissions were found to increase as the average speed and average acceleration increased. CO_2 emissions were less sensitive to the other emission variables.

A linear regression model established from 551 driving cases was given as below (Table 7-9). A model specification test conducted on the regression model indicating no variables have been omitted (Table 7-10).

$$CCA = 3.4PA+2.3SA+28AA+1.9LA+2.2NA + 2.5BA - 100$$

Equation 7-5

- *CCA* is cumulative CO_2 during the acceleration mode (g).
- *PA* is the positive acceleration duration during the acceleration mode (s).
- *SA* is the average speed during the acceleration mode (kph).
- *AA* is the average acceleration during the acceleration mode (m/s^2).
- *LA* is the low gear duration during the acceleration mode (s).
- *NA* is the negative acceleration duration during the acceleration mode (s).
- *BA* is the braking duration during the acceleration mode (s).

Figure 7-18: Matrix scatterplot for cumulative CO_2 and emission variables for Acceleration Mode

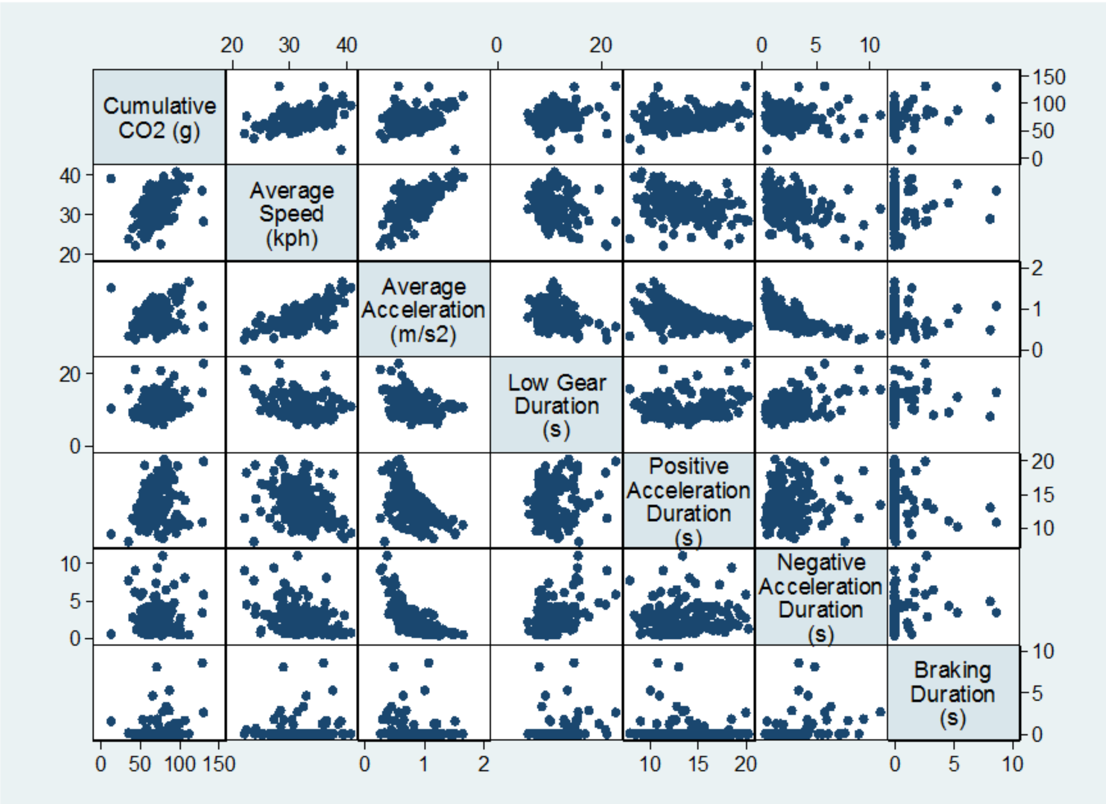


Table 7-9: Linear regression for cumulative CO_2 emissions during acceleration

```
. regress co2_mode_3_g mode3_mean_speed mode3_mean_acc  mode3_lowgear_s    mode
> 3_postive_acc_s   mode3_neg_acc_s mode3_braking_s, beta

      Source |       SS       df       MS              Number of obs =     188
-------------+------------------------------           F(  6,   181) =   50.89
       Model |  27383.7773     6  4563.96288           Prob > F      =  0.0000
    Residual |  16233.5525   181  89.6881356           R-squared     =  0.6278
-------------+------------------------------           Adj R-squared =  0.6155
       Total |  43617.3298   187  233.247753           Root MSE      =  9.4704

------------------------------------------------------------------------------
co2_mode_3_g |      Coef.   Std. Err.      t    P>|t|                     Beta
-------------+----------------------------------------------------------------
mode3_mean~d |   2.276154   .3436406     6.62   0.000                 .5024361
mode3_mean~c |   28.47049   7.686048     3.70   0.000                 .4761033
mode3_lowg~s |   1.894166   .3373568     5.61   0.000                 .3486149
mode3_post~s |   3.429303   .4336505     7.91   0.000                 .5958371
mode3_neg_~s |   2.194307   .7911757     2.77   0.006                 .2643504
mode3_brak~s |   2.513533   .6870812     3.66   0.000                 .1814858
       _cons |  -97.40124   10.75901    -9.05   0.000                        .
```

Table 7-10: Model specification test

```
. linktest

      Source |       SS       df       MS              Number of obs =     188
-------------+------------------------------           F(  2,   185) =  159.88
       Model |  27630.9645     2  13815.4823           Prob > F      =  0.0000
    Residual |  15986.3653   185  86.4127855           R-squared     =  0.6335
-------------+------------------------------           Adj R-squared =  0.6295
       Total |  43617.3298   187  233.247753           Root MSE      =  9.2958

------------------------------------------------------------------------------
co2_mode_3_g |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        _hat |   .2619836   .4399584     0.60   0.552     -.605997    1.129964
      _hatsq |   .0049791   .0029439     1.69   0.092    -.0008289    .0107871
       _cons |   26.56898   16.21943     1.64   0.103    -5.429841     58.5678
------------------------------------------------------------------------------

. ovtest

Ramsey RESET test using powers of the fitted values of co2_mode_3_g
       Ho:  model has no omitted variables
                  F(3, 178) =      2.88
                  Prob > F =      0.0372
```

7.5.1.2 For Idle Mode

The idling duration was found to be the dominant factor that affected carbon emissions during idling mode. No speed or acceleration effects on carbon emissions were observed for idling mode. Therefore, cumulative CO_2 emissions can be expressed by the idling duration (Figure 7-19, Table 7-11):

$$CCI = 1.16\ I$$

Equation 7-6

- *CCI* is the CO_2 emitted during the idling mode in grams.
- *I* is the idling duration in seconds.

Figure 7-19: Cumulative CO_2 emissions during idling vs. idling duration

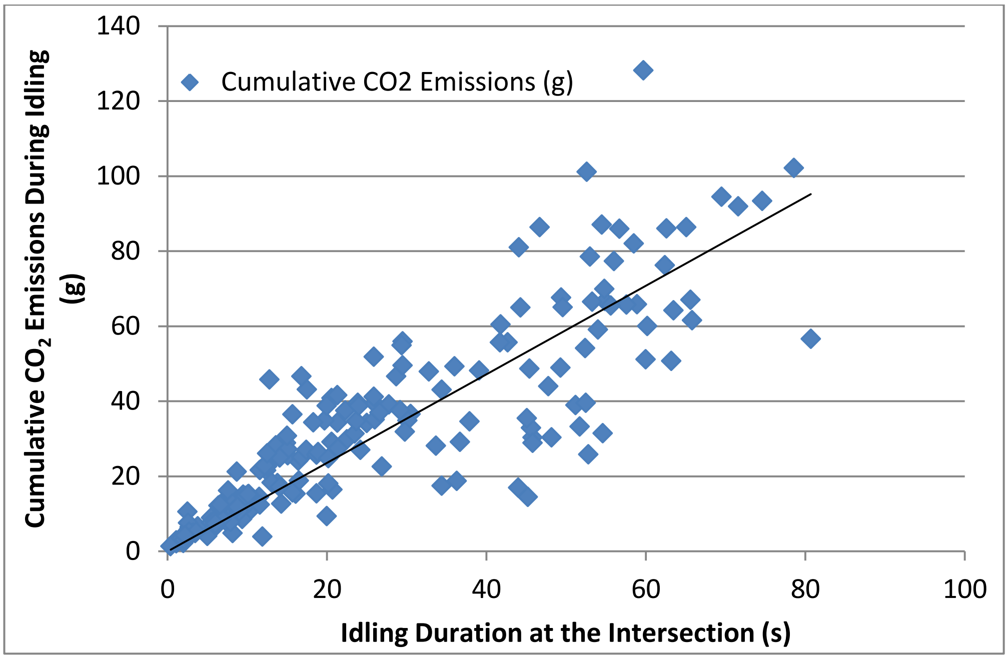


Table 7-11: Linear regression for cumulative CO_2 emissions during idling

Source	SS	df	MS		
Model	242352.413	1	242352.413	Number of obs =	924
Residual	34019.0734	922	36.8970428	F(1, 922) =	6568.34
Total	276371.487	923	299.427396	Prob > F =	0.0000
				R-squared =	0.8769
				Adj R-squared =	0.8768
				Root MSE =	6.0743

co2_mode_2_g	Coef.	Std. Err.	t	P>|t|	Beta
idling_dur~n	1.162261	.0143409	81.05	0.000	.9364337
_cons	.3292049	.2140178	1.54	0.124	.

7.5.1.3 For Deceleration Mode

The linear regression analysis of the cumulative CO_2 emissions adopted the same six emission variables used in Section 7.5.1.1. The cumulative CO_2 emission was found to increase with the increase in all dependent variables, except for average speed (Figure 7-20).

The cumulative carbon emissions can be estimated using the following linear equation (Table 7-12).

$$CCD = LD+25AD+2PD+BD+0.7SD-ND+18$$

Equation 7-7

- *CCD* is cumulative CO_2 during the deceleration mode (g).
- *LD* is the low gear duration during the deceleration mode (s).
- *AD* is the average acceleration during the deceleration mode (m/s^2).
- *PD* is the positive acceleration duration during the deceleration mode (s).

- *BD* is the braking duration during the deceleration mode (s).
- *SD* is the average speed during the deceleration mode (kph).
- *ND* is the negative acceleration duration during the deceleration mode (s).

Figure 7-20: Matrix scatterplot for cumulative CO_2 and emission variables for deceleration mode

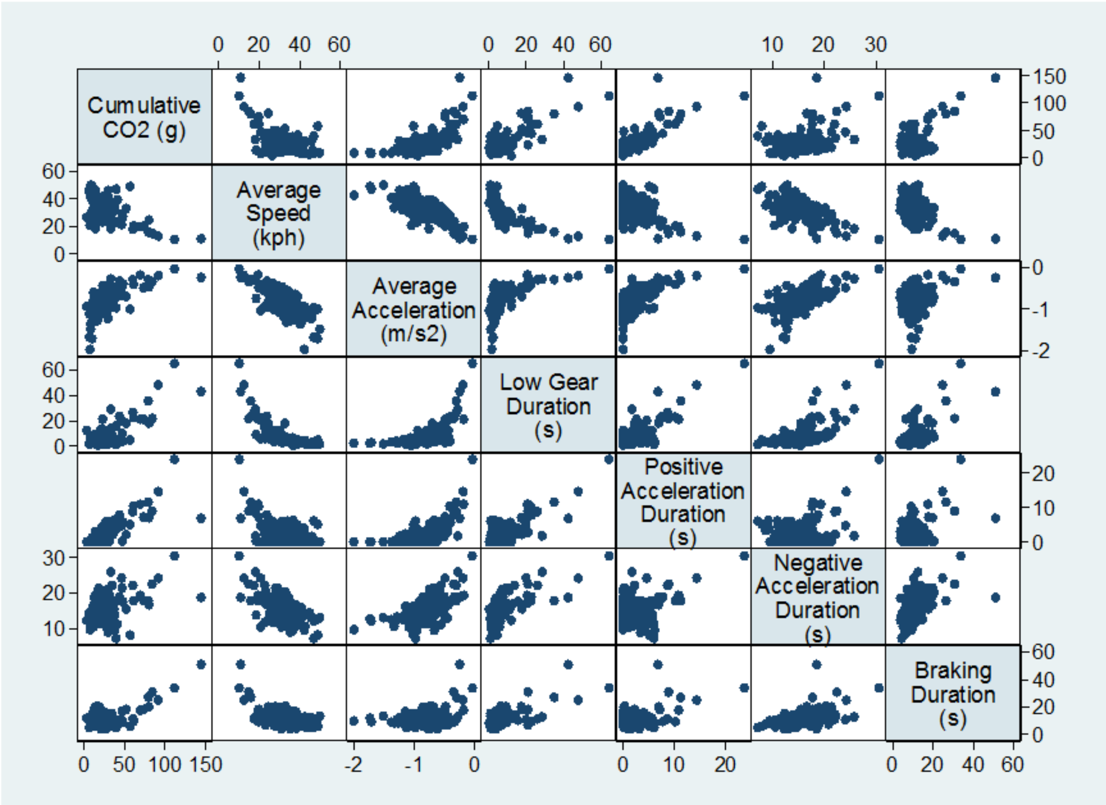


Table 7-12: Linear regression for cumulative CO_2 emissions during deceleration

```
. regress co2_mode_1_g gear_low_duration acceleration_mean acc_positive_duratio
> n braking_duration speed_mean acc_negative_duration if mode==1, beta

      Source |       SS       df       MS              Number of obs =     188
-------------+------------------------------           F(  6,   181) =  120.86
       Model |  47510.3356     6  7918.38927           Prob > F      =  0.0000
    Residual |   11858.403   181  65.5160386           R-squared     =  0.8003
-------------+------------------------------           Adj R-squared =  0.7936
       Total |  59368.7386   187  317.479885           Root MSE      =  8.0942

------------------------------------------------------------------------------
co2_mode_1_g |      Coef.   Std. Err.      t    P>|t|                     Beta
-------------+----------------------------------------------------------------
gear_low_d~n |   1.003483   .2178348     4.61   0.000                 .4355625
accelerati~n |   24.91501   4.641294     5.37   0.000                 .3768282
acc_positi~n |   1.955348   .4472652     4.37   0.000                 .3207825
braking_du~n |   .9661149   .1581175     6.11   0.000                 .2786545
  speed_mean |   .6859095   .1741109     3.94   0.000                  .260794
acc_negati~n |  -1.047657   .3143433    -3.33   0.001                -.1876955
       _cons |   18.32545   6.944302     2.64   0.009                        .
```

7.5.1.4 For Cruising/Uninterrupted Mode

The CO_2 emission model for uninterrupted driving was established using the same six emission variables. Increases in the average acceleration, low gear duration and positive acceleration duration aggravated cumulative CO_2 emissions during the uninterrupted driving mode (Figure 7-21). However, increases in average speed reduced CO_2 emissions. CO_2 emissions were insensitive to changes in negative acceleration and braking durations. Therefore, the cumulative CO_2 emission model can be expressed as Equation 7-8 (Table 7-13). A model specification test performed on the model showed that neither relevant variable had been omitted nor irrelevant variable had been included (Table 7-14).

$$CCU = 1.1\ SU + 94\ AU + 0.5\ LU + 2.7\ PU + 2.3\ NU + 0.80\ BU - 50$$

Equation 7-8

- *CCU* is the cumulative CO_2 during uninterrupted driving in grams.
- *SU* is the average speed during uninterrupted driving in kilometres per hour, kph.
- *AU* is the average acceleration during uninterrupted driving in m/s^2.
- *PU* is the positive acceleration duration during uninterrupted driving in seconds.
- *LU* is the low gear duration during uninterrupted driving in seconds.
- *NU* is the negative acceleration duration during uninterrupted driving in seconds.
- *BU* is the braking duration during uninterrupted driving in seconds.

Figure 7-21: Matrix scatterplot for cumulative CO_2 and emission variables for cruising/uninterrupted driving mode

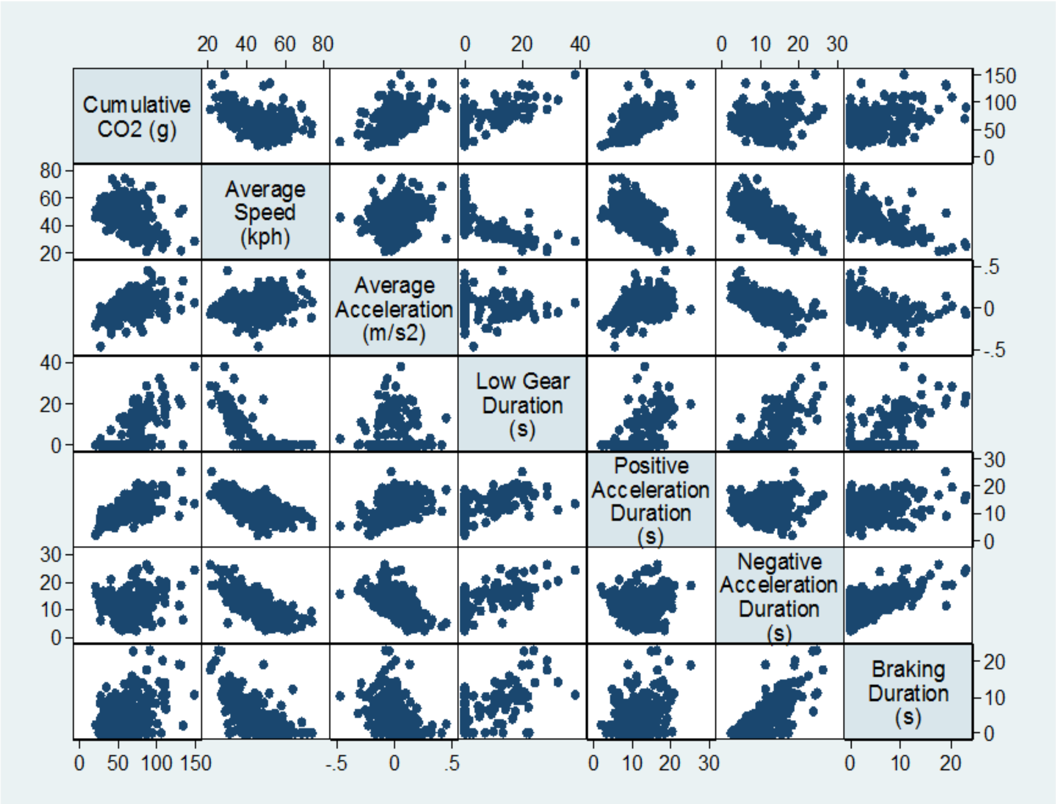


Table 7-13: Linear regression for cumulative CO_2 emissions during uninterrupted driving

```
. regress co2_sum_g speed_mean acceleration_mean low_gear_dur_s positive_acc_du
> r_s negative_acc_dur_s braking_dur_s, beta

      Source |       SS       df       MS              Number of obs =     363
-------------+------------------------------           F(  6,   356) =  126.73
       Model |  95570.7923     6  15928.4654           Prob > F      =  0.0000
    Residual |  44746.4819   356  125.692365           R-squared     =  0.6811
-------------+------------------------------           Adj R-squared =  0.6757
       Total |  140317.274   362  387.616779           Root MSE      =  11.211

------------------------------------------------------------------------------
   co2_sum_g |      Coef.   Std. Err.      t    P>|t|                     Beta
-------------+----------------------------------------------------------------
  speed_mean |   1.084975   .1862345     5.83   0.000                 .5149949
accelerati~n |    94.3509   9.270908    10.18   0.000                 .5632613
low_gear_d~s |   .4944915   .1063493     4.65   0.000                 .3002698
positive_a~s |   2.671305   .4232941     6.31   0.000                 .4902462
negative_a~s |   2.347385   .3873571     6.06   0.000                 .5389602
braking_du~s |   .8020959   .2286754     3.51   0.001                  .179733
       _cons |  -54.75359   15.44989    -3.54   0.000                        .
```

Table 7-14: Model specification test

```
. linktest

      Source |       SS       df       MS              Number of obs =     363
-------------+------------------------------           F(  2,   360) =  384.45
       Model |  95571.0161     2   47785.508           Prob > F      =  0.0000
    Residual |  44746.2581   360  124.295161           R-squared     =  0.6811
-------------+------------------------------           Adj R-squared =  0.6793
       Total |  140317.274   362  387.616779           Root MSE      =  11.149

------------------------------------------------------------------------------
   co2_sum_g |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        _hat |   .9913524   .2068309     4.79   0.000     .5846038    1.398101
      _hatsq |   .0000659   .0015513     0.04   0.966    -.0029849    .0031167
       _cons |   .2660773   6.693452     0.04   0.968     -12.8971    13.42926
------------------------------------------------------------------------------

. ovtest

Ramsey RESET test using powers of the fitted values of co2_sum_g
       Ho:  model has no omitted variables
                 F(3, 353) =      0.64
                  Prob > F =      0.5921
```

7.5.2 Instantaneous CO_2 Emissions

Two CO_2 emission models were established in this section, which can be used to predict instantaneous CO_2 emissions for acceleration and deceleration modes. Two emission variables were considered, namely instantaneous speed and instantaneous acceleration. Considering instantaneous CO_2 emissions were insensitive to the instantaneous acceleration and instantaneous speed if the acceleration was zero or negative, CO_2 emission models were developed for acceleration greater than 0 m/s^2.

7.5.2.1 For Acceleration Mode

The instantaneous carbon emission rate during the acceleration mode can be estimated using instantaneous speed and instantaneous acceleration, which are referred to as independent variables. CO_2 emissions for acceleration smaller or equal to zero were quite constant, which showed an average value of 2.3g/s. For acceleration greater than zero, instantaneous CO_2 emissions can be estimated using Equation 7-9 (Table 7-15). With a coefficient of determination, R^2 of 0.7, the linear regression model was considered strong in terms of strength. The instantaneous acceleration had the largest impact to the model.

$$ICA = 2.1a + 0.12v$$

Equation 7-9

- *ICA* is the instantaneous CO_2 emissions in g/s.
- *a* represents the instantaneous acceleration in m/s^2.
- *v* is the instantaneous speed in kph.

In Figure 7-22, instantaneous CO_2 emissions were found to be linearly proportionate to instantaneous acceleration, where increases in the instantaneous acceleration increased CO_2 emissions. The relationship between the instantaneous CO_2 emissions and instantaneous speed was represented by a polynomial function, in which case the values of instantaneous CO_2 emissions can be both high and low at the same speed.

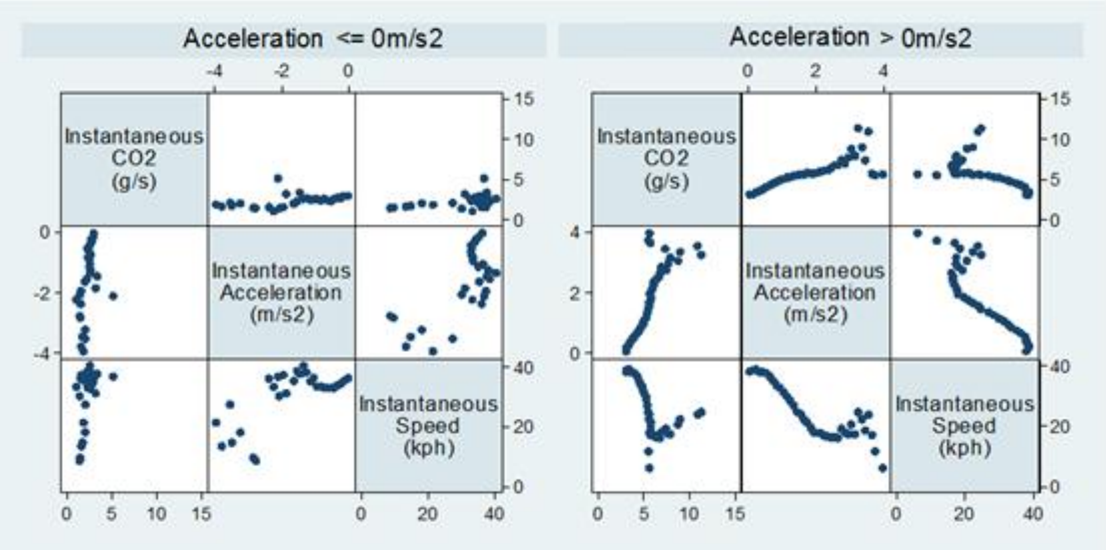
Table 7-15: Linear regression model for instantaneous CO_2 emissions during the acceleration mode

Source	SS	df	MS
Model	92.7705705	2	46.3852853
Residual	40.3659782	36	1.12127717
Total	133.136549	38	3.50359339

Number of obs	39
F(2, 36)	41.37
Prob > F	0.0000
R-squared	0.6968
Adj R-squared	0.6800
Root MSE	1.0589

co2_obs	Coef.	Std. Err.	t	P>|t|	Beta
acceleration	2.115206	.3100655	6.82	0.000	1.290929
speed_canbus	.1236058	.0405515	3.05	0.004	.5768131
_cons	-1.178467	1.54942	-0.76	0.452	.

Figure 7-22: A matrix of scatter plots between instantaneous CO_2 emissions, instantaneous acceleration and instantaneous speed during the acceleration mode



7.5.2.2 For Deceleration Mode

The instantaneous CO_2 emission model for the deceleration mode was established using the same independent variables. Similar to the earlier section, instantaneous CO_2 emission were regressed to instantaneous speed and instantaneous acceleration. For acceleration equals or below zero, the average CO_2 emission was rather constant, with an average rate of 1.1g/s. For acceleration greater than zero, instantaneous CO_2 emissions can be expressed as Equation 7-10 (Table 7-16). Acceleration was found to have a bigger impact on instantaneous CO_2 emissions for both acceleration and deceleration modes. Reducing the instantaneous acceleration reduced instantaneous CO_2, but reducing instantaneous speed increases the instantaneous CO_2 emissions. However, the instantaneous speed parameter was excluded from the model because the variable was found to be insignificant, with a probability of 0.901 (Table 7-16).

$$\boldsymbol{ICD = 0.8a + 3}$$

Equation 7-10

- *ICD* is the instantaneous CO_2 emission rate in g/s.
- *a* represents the instantaneous acceleration in m/s^2.
- *v* is the instantaneous speed in kph.

Relationships between these instantaneous variables were depicted in the matrix scatterplot (Figure 7-23). Instantaneous CO_2 emission rates increased as acceleration increased. However, instantaneous CO_2 emission rates reduced as instantaneous speed increased.

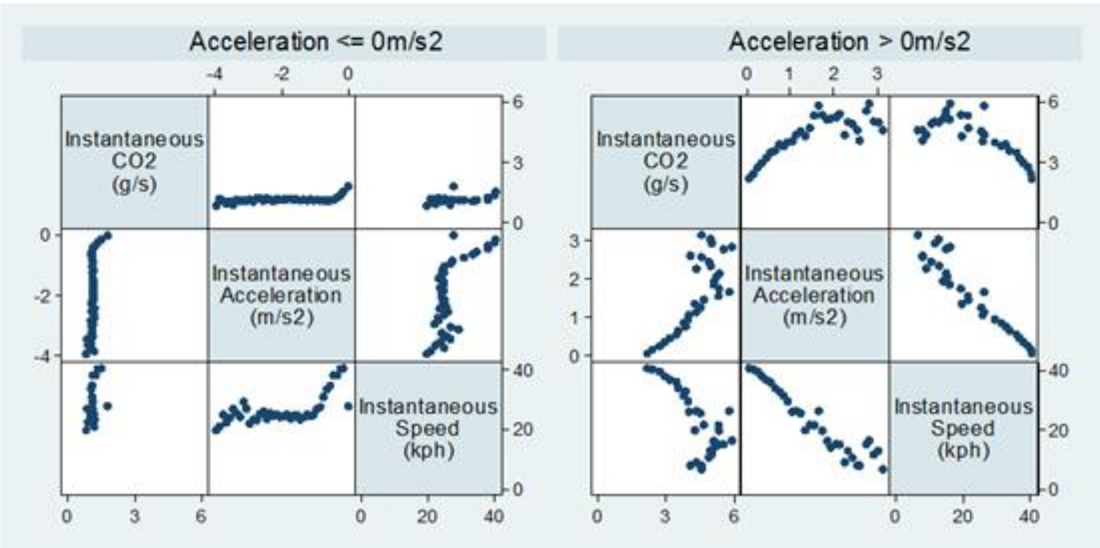
Table 7-16: Linear regression model for instantaneous CO_2 emissions during the deceleration mode

Source	SS	df	MS
Model	18.1499836	2	9.07499178
Residual	11.2099213	29	.386549009
Total	29.3599048	31	.947093704

Number of obs =	32
F(2, 29) =	23.48
Prob > F =	0.0000
R-squared =	0.6182
Adj R-squared =	0.5919
Root MSE =	.62173

co2_obs	Coef.	Std. Err.	t	P>|t|	Beta
acceleration	.7732667	.3876566	1.99	0.056	.7419091
speed_canbus	-.0041757	.0334161	-0.12	0.901	-.0464774
_cons	3.239249	1.357285	2.39	0.024	.

Figure 7-23: Matrix scatterplot between instantaneous CO_2 emissions, instantaneous speed and instantaneous acceleration during the deceleration mode



7.6 Analysis by Driving Mode

Findings discussed in previous sections showed that CO_2 emissions were significantly different between the driving modes, and there could be substantial savings in CO_2 if driving behaviour was to change. Therefore, separate investigations on CO_2 emissions for every individual driving mode are necessary in order to understand the true difference in driving behaviour for each driving mode, and to suggest driving practices that help in CO_2 reductions.

A total of 138 cases of driving was extracted from Intersection 10. Each case represented a driving over 300m long distance at the intersection. A total of 138 cases was categorised into interrupted driving (110 cases) and uninterrupted driving (28 cases). Data from only one intersection (Intersection 10) was used in order to remove potential variations in CO_2 emissions caused by different intersection attributes. Intersection 10 was selected because it provided a larger number of interrupted driving cases (80%) as compared with other intersections (Table 7-17).

Table 7-17: Number of interrupted and uninterrupted driving cases at every intersection

Intersection	Number of Uninterrupted Driving Case	Number of Interrupted Driving Case	Total Number of Driving Case	% of Interrupted Driving Case
5	100	38	138	28
9	107	31	138	22
10	28	110	138	80
11	128	9	137	7

7.6.1 Analysis for Acceleration Mode

It is important to understand that data used in this section, and its results are limited to the acceleration mode (refer Figure 7-15 for definition of acceleration mode). For example, cumulative CO_2 emissions were referred to the aggregated CO_2 emissions during the acceleration mode only.

7.6.1.1 Effect of Acceleration Distance

Acceleration distances varied between the different interrupted driving cases. Therefore, it is important to investigate whether differences in the acceleration distance have a significant impact on the cumulative CO_2 emissions, which could affect the comparison of driving behaviour.

In order to investigate the effect of the acceleration distance on CO_2 emissions, all interrupted driving cases under the acceleration mode at Intersection 10 were divided into five groups according to 20m acceleration distance intervals (Table 7-18). The acceleration distance was plotted against cumulative CO_2 emissions for all cases (Figure 7-24). It was found that cumulative CO_2 emissions increased as the acceleration distance increased. A check of normality on acceleration distance data showed that the data was not normally distributed, which prompted for the use of Kruskal Wallis Rank test. The Kruskal Wallis Rank test was performed on different lengths of intervals of acceleration distance. For instance, 20m-range consisted of driving with acceleration distance between 120m and 140m, 40m-range consisted of acceleration distance between 120m and 160m, etc. The result of Kruskal Wallis Rank test showed no significant difference in cumulative CO_2 emissions if the range of acceleration distance was less than 60m (p=0.0641, Table 7-19). This indicated that the effect of acceleration distance is negligible if difference in acceleration distance between the different cases is less than 60m.

Based on this finding, 110 cases of driving were divided into two groups, where the maximum difference in acceleration distance between the different cases was kept to less than 60m in each group. Thus, first group represented 94 runs with acceleration distance between 120m-170m (50m range). Second group consisted of 16 runs with acceleration distance ranging between 170m-220m (50m range). First group was used for later analyses. But second group was discarded because of limited driving cases.

Table 7-18: Grouping of driving cases at Intersection 10 based on acceleration distance

Distance Group	Acceleration Distance	Total Number of Runs
1	200-220	4
2	180-200	9
3	160-180	10
4	140-160	34
5	120-140	53

Figure 7-24: Cumulative CO_2 emissions during acceleration vs. acceleration distance

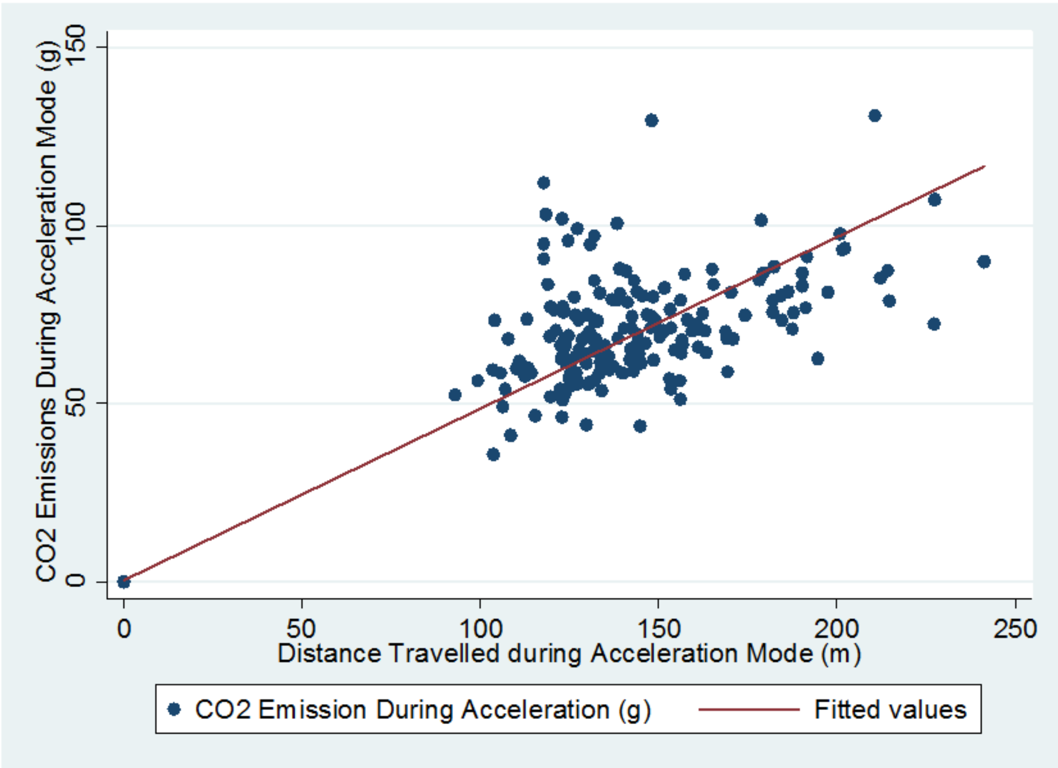


Table 7-19: Kruskal Wallis Equality-of-population Rank test on cumulative CO_2 emission for different distance groups

Distance Group	Probability of Equality
1,2,3,4,5	0.0005
1,2,3,4	0.0476
1,2,3	0.0641

7.6.1.2 Effect of Vehicle Position in the Queue

Ability of a vehicle to accelerate to the desired speed might be limited by vehicles in front. A total of 94 cases selected in the previous section was used to study the effects of the car-following and vehicle position in a queue on acceleration and CO_2 emissions (Table 7-20). Comparisons were made based on the vehicle position in the queue, i.e., first in the queue (non-following) and other positions in the queue (following). Positions of the test vehicle were obtained from video images recorded during the field test.

Table 7-20: Number of runs by position of the vehicle in queue

Position in Queue	Number of Runs
1^{st}	19
2^{nd}	22
3^{rd}	12
4^{th}	17
5^{th}	24

Normality tests conducted on the average acceleration and cumulative CO_2 emissions during the acceleration mode showed that neither variable met the normality requirement for ANOVA test ($p<0.05$, Table 7-21, Table 7-22). Therefore, the nonparametric test, Kruskal Wallis Equality-of-Populations Rank test, was used. Average acceleration during the acceleration mode was found to be significantly different, subjected to the position of the instrumented vehicle in the queue. Three distinctive groups of positions were formed 1) 1^{st} in the queue and not following other vehicles, 2) 2^{nd}, 3^{rd} or 4^{th} position in the queue and 3) 5^{th} position in the queue (Figure 7-25). There was a significant difference in terms of acceleration between these three groups (Figure 7-25, Table 7-23), but no significant differences in terms of cumulative CO_2 emissions were found (Figure 7-26, Table 7-24). This indicates that although the position in a queue affected the average acceleration, the effect was not strong enough to influence the cumulative CO_2 emissions.

Table 7-21: Normality test (Shapiro-Wilk) for average acceleration

Shapiro-Wilk W test for normal data

Variable	Obs	W	V	z	Prob>z
mode3_mean~c	110	0.95082	4.398	3.303	0.00048

Table 7-22: Normality test (Shapiro-Wilk) for cumulative CO_2 emissions during acceleration

Shapiro-Wilk W test for normal data

Variable	Obs	W	V	z	Prob>z
co2_accele~n	110	0.96886	2.785	2.284	0.01119

Figure 7-25: Boxplot for average acceleration based on the position in the queue

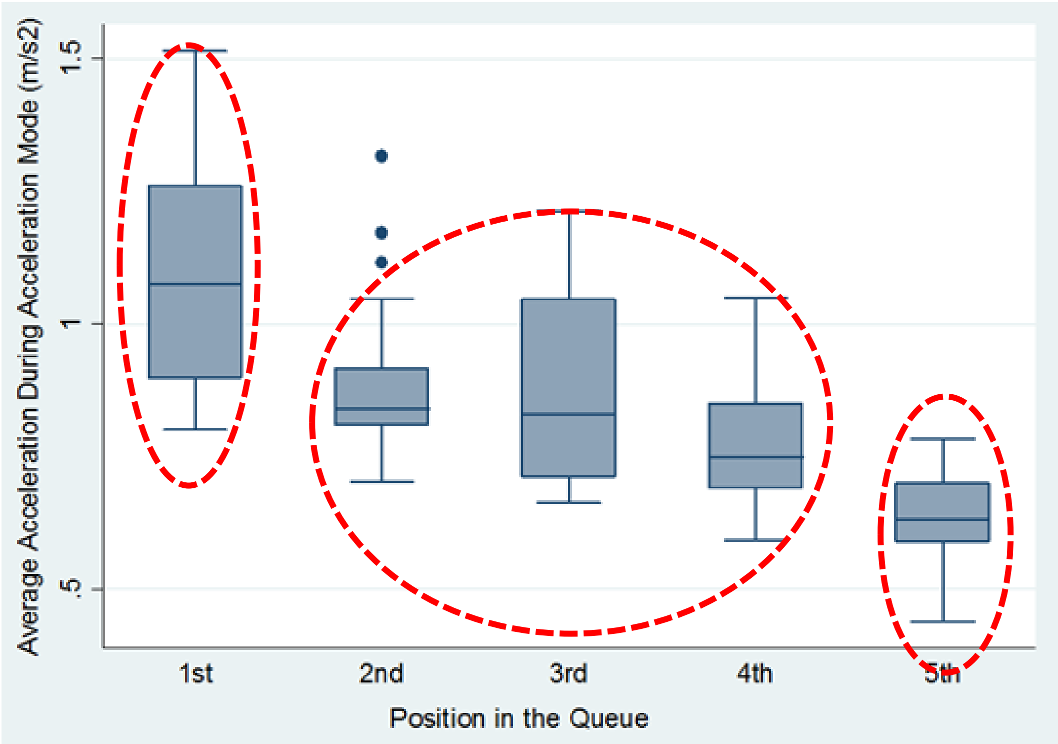


Table 7-23: Kruskal Wallis Rank test on average acceleration

Kruskal-Wallis equality-of-populations rank test

position	Obs	Rank Sum
1	19	1462.00
2	22	1350.00
3	12	662.00
4	17	716.00
5	26	466.00

chi-squared = 57.411 with 4 d.f.
probability = 0.0001

chi-squared with ties = 57.411 with 4 d.f.
probability = 0.0001

Figure 7-26: Boxplot for cumulative CO_2 emissions based on the position in the queue

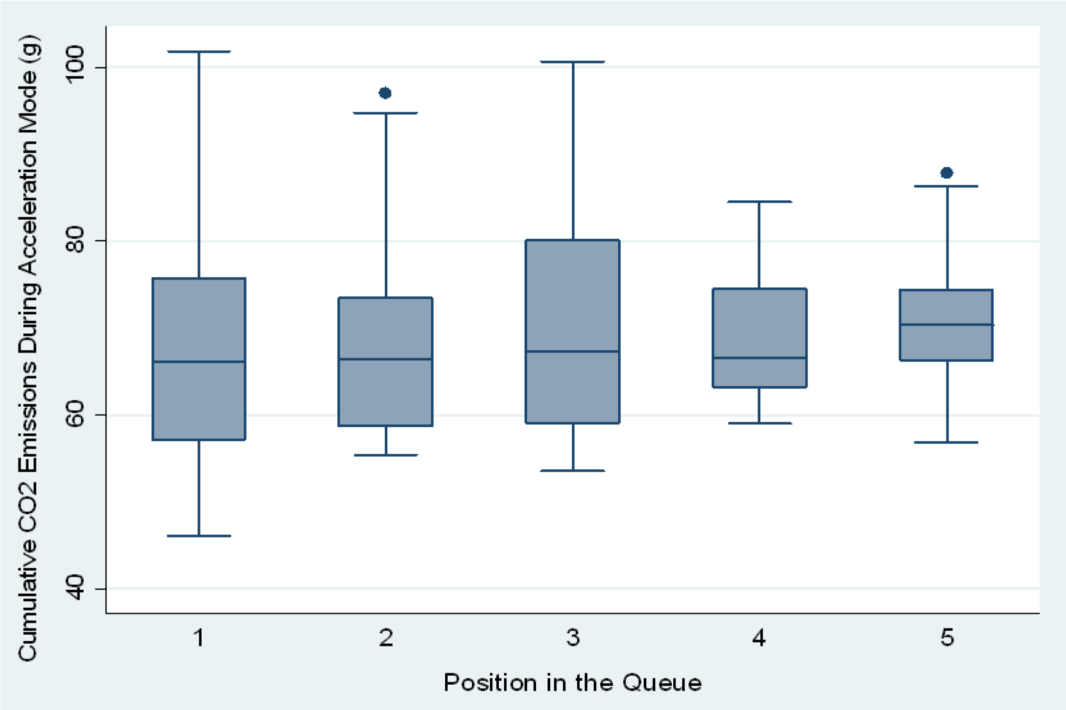


Table 7-24 Kruskal Wallis Rank test on cumulative CO_2 emissions

Kruskal-Wallis equality-of-populations rank test

position	Obs	Rank Sum
1	19	807.50
2	22	931.00
3	12	586.00
4	17	823.00
5	26	1508.50

chi-squared = 5.003 with 4 d.f.
probability = 0.2870

chi-squared with ties = 5.004 with 4 d.f.
probability = 0.2869

7.6.1.3 Effect of Leaving Speed

Leaving speed refers to the speed when the vehicle leaves the intersection, which was measured at 200m distance downstream from the intersection.

From the 94 driving cases, driving with higher leaving speed was found to produce higher cumulative CO_2 emissions compared with that of lower leaving speed (Figure 7-30). This could be because a stronger and longer acceleration was required to reach the higher speed, which produced more CO_2 emissions. However, driving with the lowest leaving speed did not guarantee the lowest CO_2 emissions. A polynomial fitted curve in Figure 7-27 and Figure 7-28 suggested that reducing the leaving speed to 45kph cut carbon emissions to its lowest. Further reduction in leaving speed below the optimum leaving speed could increase the cumulative CO_2 emissions again. However, the fitting curve was not strong enough to accurately predict the effects of changing leaving speed considering the coefficient of determination was less than 0.4. A strong fitting curve was obtained for the situation where the instrumented vehicle was first in the queue (Top of Figure 7-28). Compared with other positions, CO_2 emissions for the first vehicle in a queue clearly increased as leaving speed increased. Based on the equation of the fitting curve in Figure 7-28, reducing leaving speed of the first vehicle in a queue from 60kph to 45kph could lower cumulative CO_2 during the acceleration mode by 35% (31g CO_2).

Figure 7-27: Cumulative CO_2 emissions vs. leaving speed for 1^{st} to 5^{th} queue positions

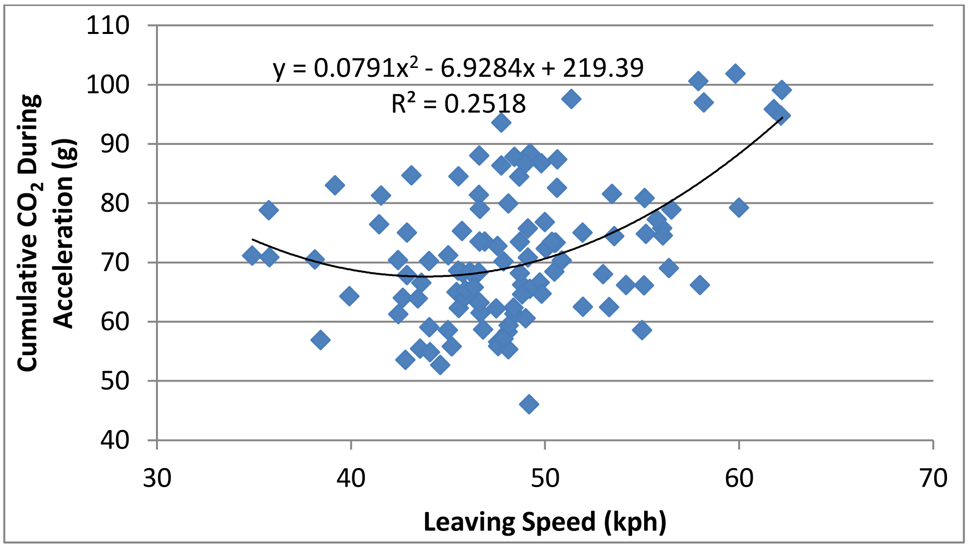
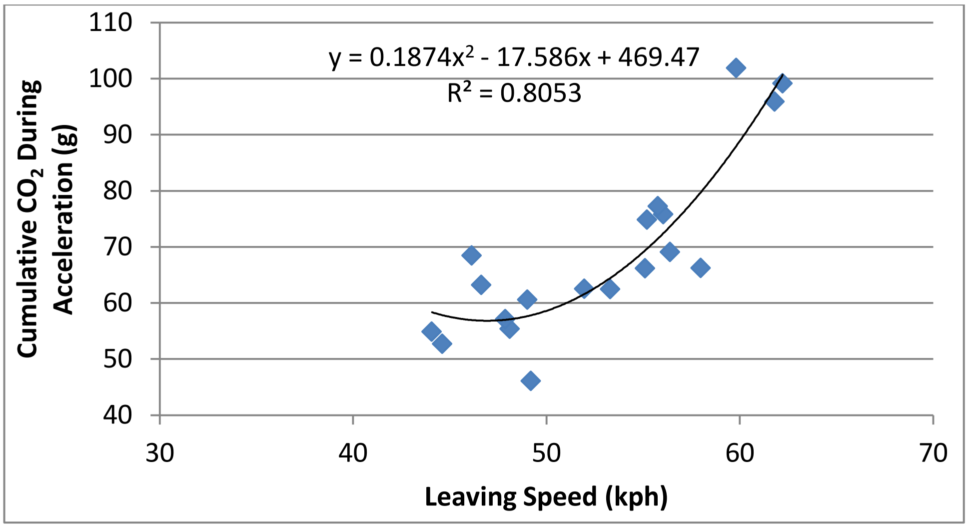
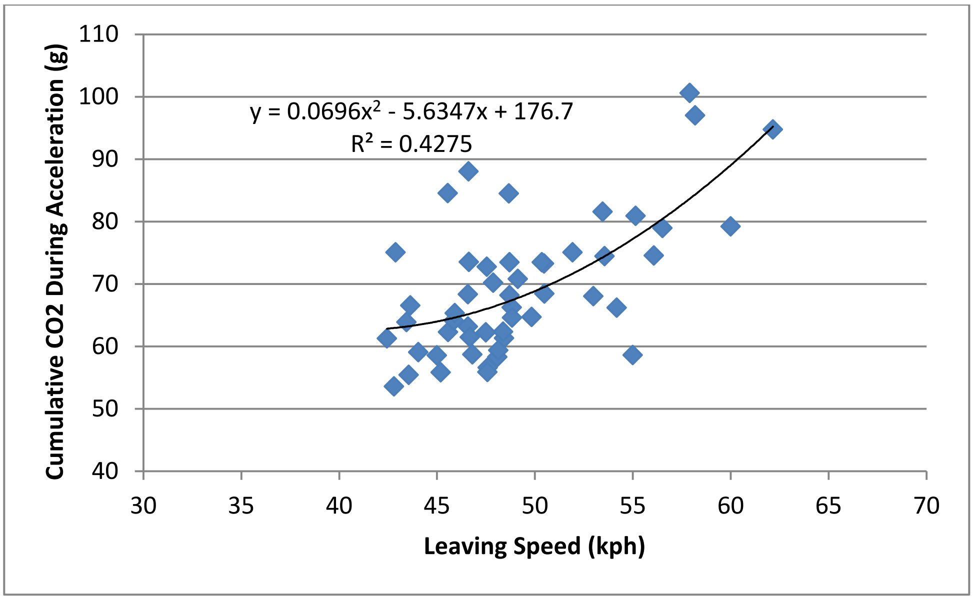
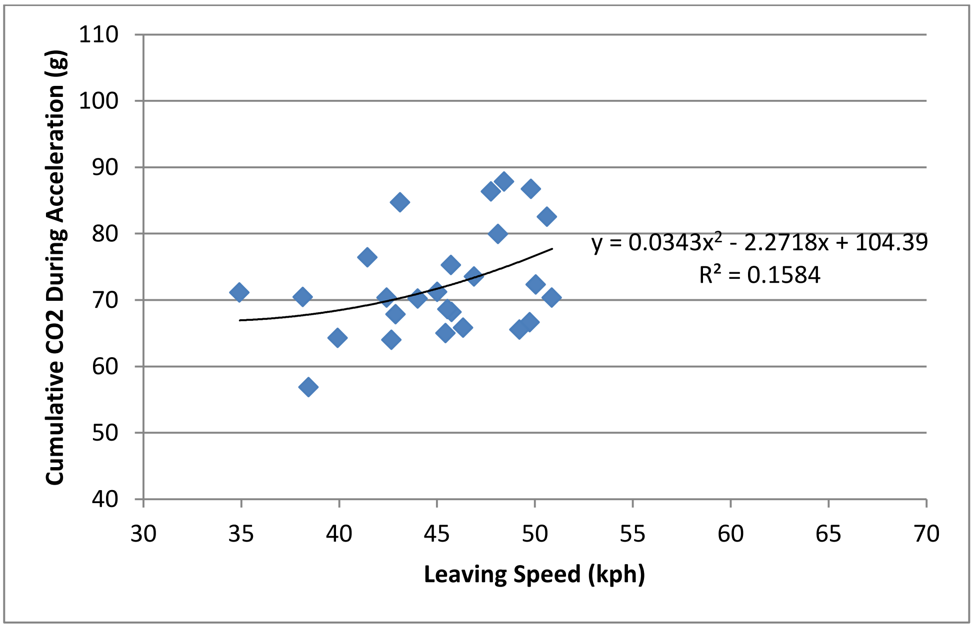


Figure 7-28: Cumulative CO_2 emissions vs. leaving speed for (Top) 1^{st} (Middle) 2^{nd}, 3^{rd}, 4^{th} and (Bottom) 5^{th} queue positions







7.6.1.4 Effect of Soft Acceleration

During the acceleration mode, differences in driving behaviour between low carbon driving and high carbon driving was found to be mainly governed by the acceleration style, which included the positive acceleration duration, average acceleration and average speed (refer Section 7.5.1.1). Variables such as the acceleration distance, position in the queue and leaving speed were controlled at the constant level so that the change in CO_2 emissions is solely due to the acceleration style. This was done by comparing driving cases that had the same acceleration distance, queue position and leaving speed.

Of the selected two driving cases that had the same acceleration distance, queue position, leaving speed and travel duration, Case 1 showed 35% lower cumulative CO_2

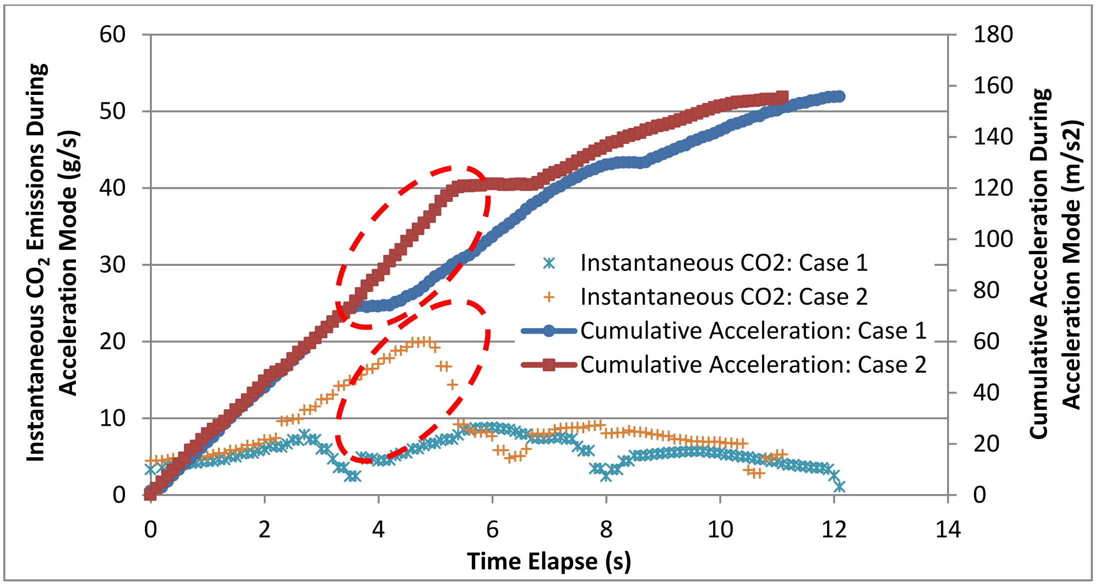
emissions as compared with Case 2 (Table 7-25). Variations in CO_2 emissions between the two cases were highly correlated with the difference in average acceleration. This could be observed from Figure 7-29 that Case-1 had softer acceleration and lower acceleration than Case 2. Although the result may not be conclusive as only two cases were compared. However, it provided an insight on the effect of different acceleration styles on CO_2 emissions.

Table 7-25: Comparison of two acceleration patterns

Variable	Case 1	Case 2
Position in the Queue*	First	First
Acceleration Distance (m)*	121.0	121.8
Leaving speed (kph)*	58.0	59.8
Cumulative CO_2 During Acceleration Mode (g)	66.2	101.8
Duration of Acceleration Mode (s)	12.1	11.2
Average Speed of Acceleration Mode (kph)	36.5	39.5
Average Acceleration of Acceleration Mode (m/s^2)	1.286	1.416
Positive Acceleration Duration During Acceleration Mode (s)	11.6	10.4
Braking Duration During Acceleration Mode (s)	0	0
Low Gear Duration During Acceleration Mode (s)	8.5	10.8
Negative Acceleration Duration During Acceleration Mode (s)	0.5	0.8
Driver	6	23
Lap	1	4

* Controlled variables.

Figure 7-29: Speed and carbon emission profiles



7.6.1.5 Effect of Maintaining Acceleration Below 0.6 m/s²

Acceleration and speed had greater impact on CO_2 emissions when acceleration exceeded 0.6m/s^2 (refer Section 7.3.5 Instantaneous Speed and Acceleration). Applying soft acceleration and reducing average acceleration was also found to reduce CO_2 emissions (refer Table 7-25). Therefore, in this section, the impact of maintaining acceleration below 0.6m/s^2, and impact of increasing acceleration by 1m/s^2 (from 0.6m/s^2 to 1.6m/s^2) were investigated.

Equation 7-9 was used to predict CO_2 emissions for the above scenarios. Acceleration and speed profiles of five high carbon driving cases (refer Section 7.6.1.6) were used as the input to the equation to determine its accuracy. The prediction was found to be accurate with a maximum deviation of 15%.

Results in Table 7-26 showed reductions between 14% and 25% if acceleration was maintained below 0.6m/s^2. The result might underestimate the cumulative CO_2 emissions for the 0.6m/s^2 scenario because the increase in travel time due to reduced acceleration had not been considered in this analysis. Nonetheless, the result confirmed that advantage of reducing acceleration is significant for CO_2 reduction at signalised intersections.

Table 7-26: Effects of maintaining acceleration below 0.6m/s^2

Case	Measured CO_2	Predicted CO_2	Accuracy	Predicted CO_2 for a<0.6m/s^2	Reduction	Remarks
	[A]	[B]	[B]/[A]	[C]	(1-[C]/[B])	
1	99.1	91.5	92%	68.9	25%	4-2
2	97.0	90.1	93%	74.3	18%	16-1
3	100.6	92.9	92%	80.3	14%	16-3
4	95.9	89.2	93%	71.0	20%	22-5
5	101.8	86.7	85%	66.7	23%	23-4

Second scenario was also investigated using Equation 7-9. Effects of increasing acceleration from 0.6m/s^2 to 1.6m/s^2 at different speed were investigated. The range of speed considered was between 10kph and 60kph only. This is because it was unlikely that vehicle speed at intersections exceeded 60kph. Instantaneous CO_2 emissions were found to increase by 20% at the speed of 60kph if acceleration was to increase by 1m/s^2 (Table 7-27). The relative increase in CO_2 emissions became larger as the speed reduced from 60kph to 10kph.

Table 7-27: Difference in CO_2 emissions due to changes in acceleration

Speed (kph)	CO_2 Emissions (g/s)		Increase in CO_2 Emissions	
	Acceleration ($0.6 m/s^2$)	Acceleration ($1.6 m/s^2$)	g/s	%
10	2.5	4.6	2.1	46
20	3.7	5.8	2.1	37
30	4.9	7.0	2.1	30
40	6.1	8.2	2.1	26
50	7.3	9.4	2.1	23
60	8.5	10.6	2.1	20

7.6.1.6 Characteristics of High Carbon Driving and Low Carbon Driving Under Acceleration Mode

The work described in this section investigated the difference between high carbon and low carbon driving. This was achieved by comparing the high carbon driving group with the low carbon driving group. Ninety four driving cases were ranked according to the cumulative CO_2 emissions. Two groups were formed, which consisted of 1) five driving cases with the highest cumulative CO_2 emissions 2) five driving cases with the lowest cumulative CO_2 emissions (Figure 7-30).

An average difference of 46.4g CO_2 (47%) was found between the two groups despite the duration and distance of driving were almost the same (Table 7-28). High carbon driving was characterised by high average acceleration and average speed. Vice versa, low carbon driving had relatively lower average acceleration and average speed. Therefore, an increase in average acceleration and average speed of the acceleration mode increased cumulative CO_2 emissions (Figure 7-31).

Differences in CO_2 emissions between two groups were highly correlated with the positive acceleration duration, average acceleration and low gear duration (refer highlighted rows in Table 7-28). The major CO_2 variations between high carbon and low carbon groups were 48.9g CO_2 and 45.8g CO_2 for low-gear and positive acceleration, respectively (Table 7-28).

Figure 7-30: Speed profiles for high carbon and low carbon driving during acceleration

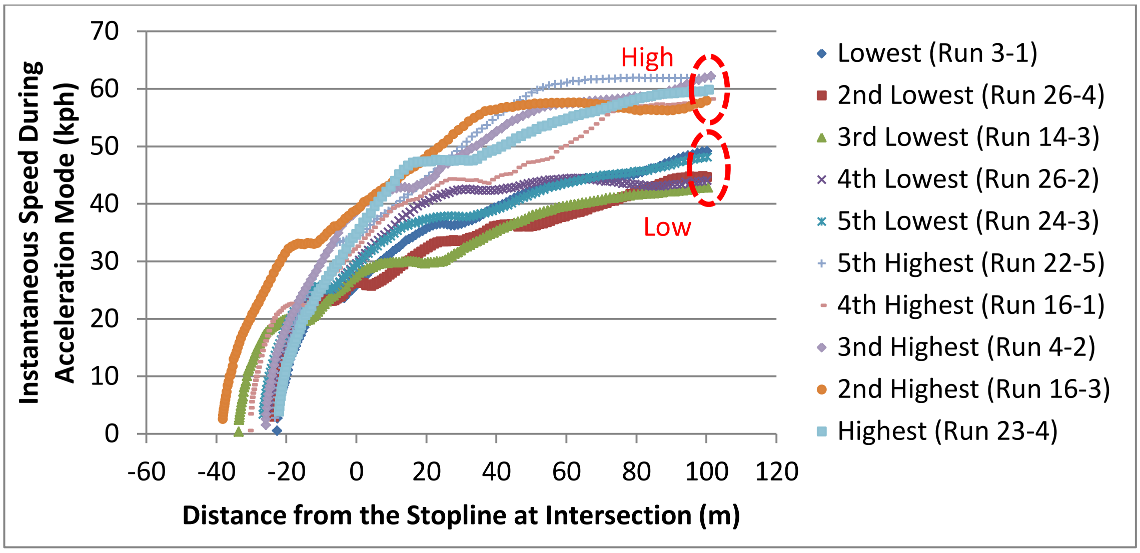
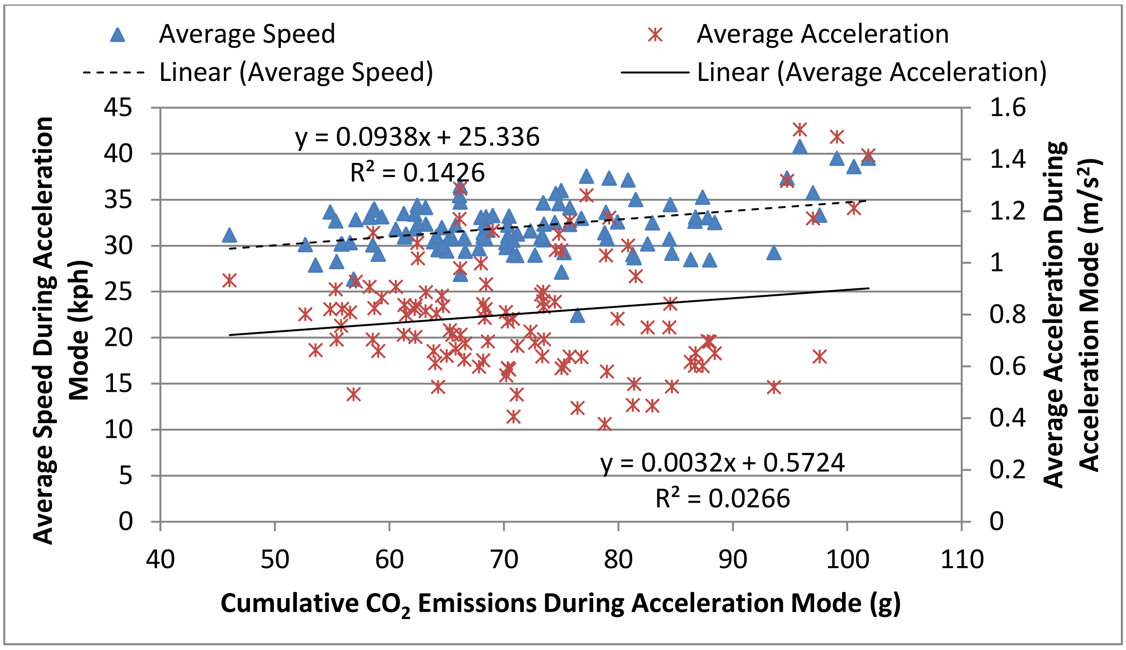


Table 7-28: Average values for high carbon and low carbon groups

Average Variable Value	Low Carbon Group	High Carbon Group
Cumulative CO_2 Emissions (g)	52.49	98.88
Cumulative Fuel Consumption (g)	20.10	33.31
Total Duration (s)	14.74	12.00
Total Distance (m)	126.58	129.00
Average Speed (kph)	31.09	38.82
Average acceleration (m/s^2)	0.823	1.360
Cumulative CO_2 During Negative Acceleration (g)	4.64	4.94
Duration of Negative Acceleration (s)	1.44	0.98
Cumulative CO_2 During Zero Acceleration (g)	1.22	1.48
Duration of Zero Acceleration (s)	0.42	0.32
Cumulative CO_2 During Positive Acceleration (g)	46.64	92.47
Duration of Positive Acceleration (s)	12.88	10.70
Distance of Positive Acceleration (m)	109.18	110.81
Average Acceleration During Positive Acceleration (m/s^2)	0.96	1.54
Cumulative CO_2 During Low Gear (g)	49.95	98.88
Duration of Low Gear (s)	8.36	11.66
Distance of Low Gear (m)	115.96	129.00
Cumulative CO_2 During Braking (g)	0.00	2.62
Braking Duration (s)	0.0	4.2
Distance of Braking (m)	0.00	4.23

Figure 7-31: CO_2 vs. average speed and average acceleration during acceleration mode



7.6.1.7 Summary

- The vehicle position in a queue at intersections could significantly affect its acceleration capability, but not the cumulative CO_2 emissions.
- The leaving speed has a significant effect on cumulative CO_2 emissions. The optimum leaving speed at 100m downstream of an intersection is 45kph in order to achieve the lowest carbon emissions. Reducing the leaving speed of the first vehicle in the queue from 60kph to 45kph could reduce cumulative CO_2 emissions of the acceleration mode by 35% (31g CO_2).
- Applying soft acceleration without exerting prolonged positive acceleration could cause 35% CO_2 reduction (35.6g CO_2) during the acceleration mode.
- Reducing acceleration from 1.6m/s^2 to 0.6m/s^2 may reduce CO_2 emissions by 2.1g/s. On the other hand, keeping acceleration below 0.6m/s^2 was found to reduce CO_2 emissions during the acceleration mode by 14-25% as compared with CO_2 emissions produced by from the original high carbon driving in this study.

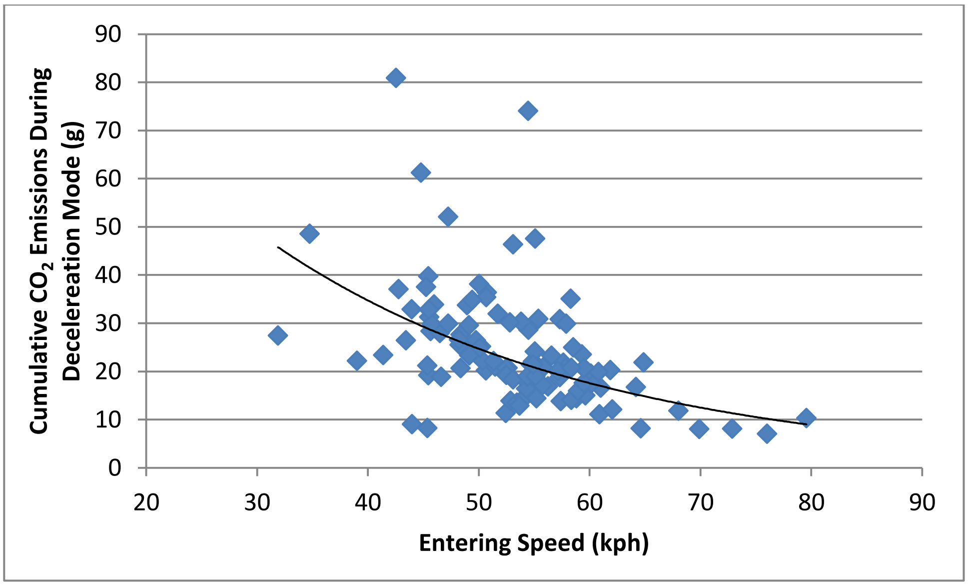
7.6.2 Analysis for Deceleration Mode

Results and data in this section were limited to the deceleration mode only. For instance, average acceleration is referred to as the arithmetic mean of the acceleration during the deceleration mode only.

7.6.2.1 Effect of Entering Speed

The entering speed is a speed at the point a vehicle first enters signalised intersections, which is measured at 200m distance upstream of the intersections. Comparing driving cases between the five lowest carbon emissions and the five highest carbon emissions, it was found that the former had a higher entering speed than the latter (Figure 7-35). Low entering speed can be caused by many reasons, such as slow moving traffic and drivers' response to the traffic signal. Regardless of the causes, cumulative CO_2 emissions increased as the entering speed reduced (Figure 7-32). However, high carbon driving was not only featured by the low entering speed, but also the occurrence of acceleration events during the deceleration mode.

Figure 7-32: Cumulative CO_2 emissions vs. average entering speed



7.6.2.2 Effect of Smooth Deceleration

Carbon emissions were found to be higher during rough deceleration compared with smooth deceleration (Figure 7-33). Rough deceleration is characterised as deceleration with unstable speed and/or deceleration that consists of acceleration events. Comparing two driving cases with the same entering speed and deceleration distance but different deceleration styles, smooth deceleration (Case 1) was found to produce 54% lower CO_2 emissions compared with rough deceleration (Case 2) (Table 7-29). The smooth deceleration showed more uniform CO_2 emission rates while the rough deceleration had a spike in its CO_2 emission profile (Figure 7-34). The difference in carbon emissions was most likely caused by the positive acceleration, low gear and braking durations. This is evident by significant differences between these two cases in terms of cumulative CO_2.

Figure 7-33: Smooth deceleration (Case 1) vs. rough deceleration (Case 2)

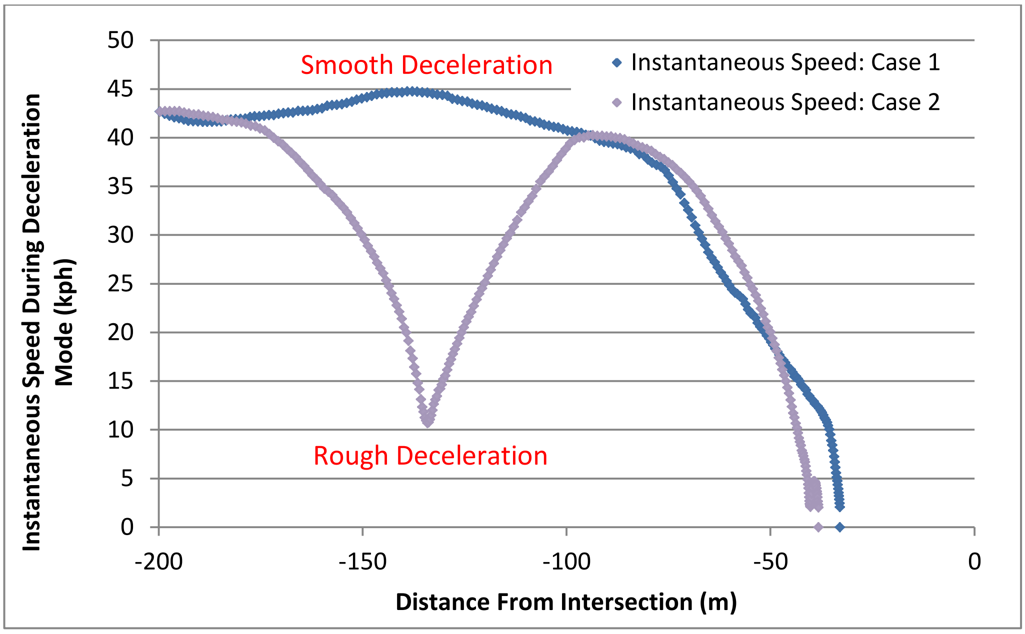
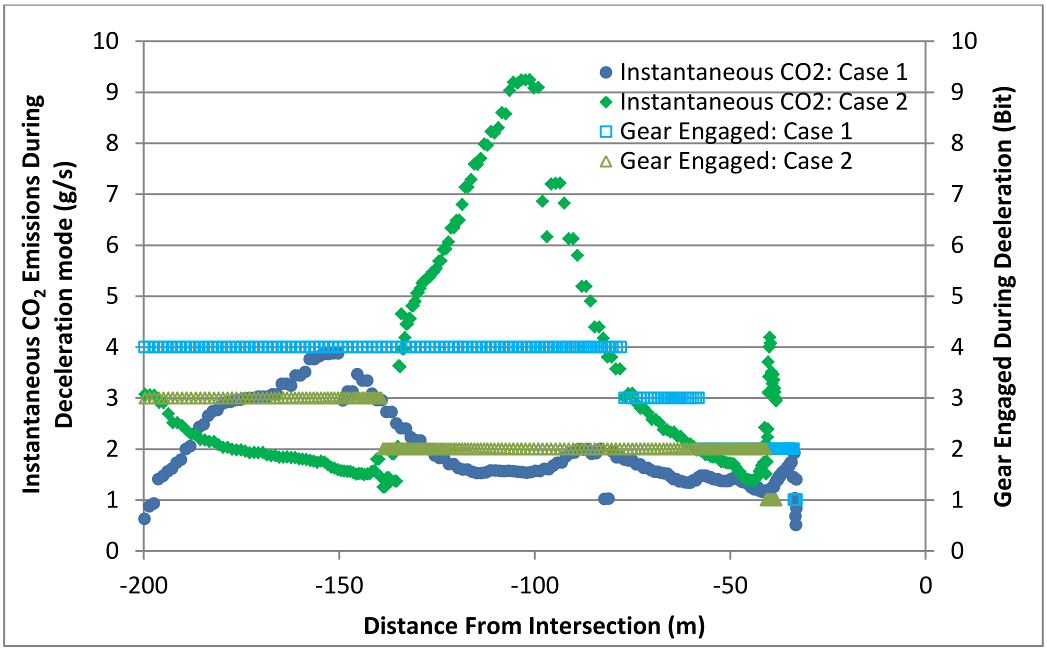


Table 7-29: Comparison on two deceleration patterns

Variable	Case 1	Case 2
Deceleration Distance (m)*	168.1	163.2
Entering Speed (kph)*	42.8	42.6
Cumulative CO_2 During Deceleration Mode (g)	37.0	80.9
Following Other Vehicles*	Yes	Yes
Duration of Deceleration Mode (s)	19.8	24.0
Average Speed of Deceleration Mode (kph)	30.7	24.6
Average Acceleration of Deceleration Mode (m/s^2)	-0.6	-0.5
Positive Acceleration Duration During Deceleration Mode (s)	3.7	7.0
CO_2 From Positive Acceleration During Deceleration Mode (g)	11.7	42.1
Braking Duration During Deceleration Mode (s)	10.3	20.0
CO_2 From Braking During Deceleration Mode (g)	14.7	55.3
Low Gear Duration During Deceleration Mode (s)	6.8	17.6
CO_2 From Low Gear During Deceleration Mode (g)	9.2	68.3
Driver	18	16
Lap	5	3

*Controlled variables

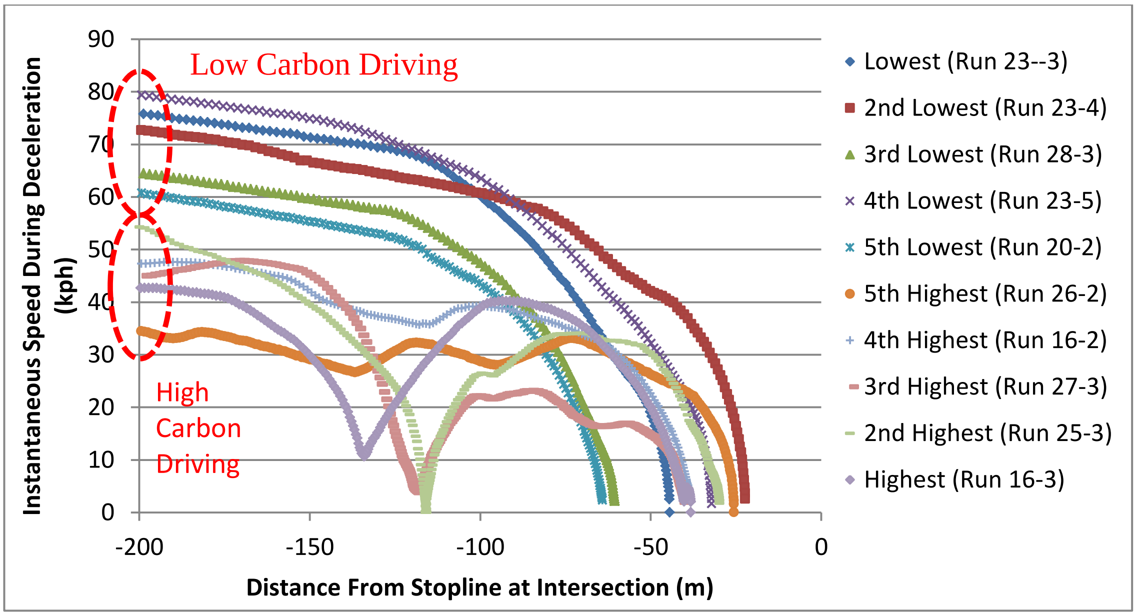
Figure 7-34: CO_2 emissions and gear engaged for Case 1 and Case 2



7.6.2.3 Characteristics of High Carbon Driving and Low Carbon Driving under Deceleration Mode

This section investigated the difference between the emission variables by comparing two driving groups, i.e., high carbon driving and low carbon driving. The cases of driving were ranked from the lowest to the highest based on cumulative CO_2 emissions. Five cases with the highest cumulative CO_2 emissions formed the high carbon group, and five cases with the lowest cumulative CO_2 emissions formed the low carbon group (Figure 7-35).

Figure 7-35: Speed profiles for high carbon and low carbon driving during deceleration



CO_2 variation between these two groups was 55g (86%), which was highly correlated with durations spent during low gear, positive acceleration, negative acceleration and braking (refer highlighted rows in Table 7-30). CO_2 emissions were also affected by the average acceleration and average speed (Figure 7-36). The low carbon group was characterised by higher average speed and average deceleration compared with the high carbon group (Table 7-30). The effects of the average speed on CO_2 emissions were contrasted between acceleration and deceleration modes, where it is essential to keep the average speed low during acceleration but maintain a high speed during the deceleration mode to lower CO_2 emissions (Figure 7-36).

The high carbon group was characterised by unstable speed and more acceleration events, while the low carbon group was characterised by smooth deceleration (Figure 7-35). Unstable speed and re-acceleration events during the deceleration mode would, therefore, aggravate CO_2 emissions.

Figure 7-36: Cumulative CO_2 vs. average speed and average acceleration during deceleration mode

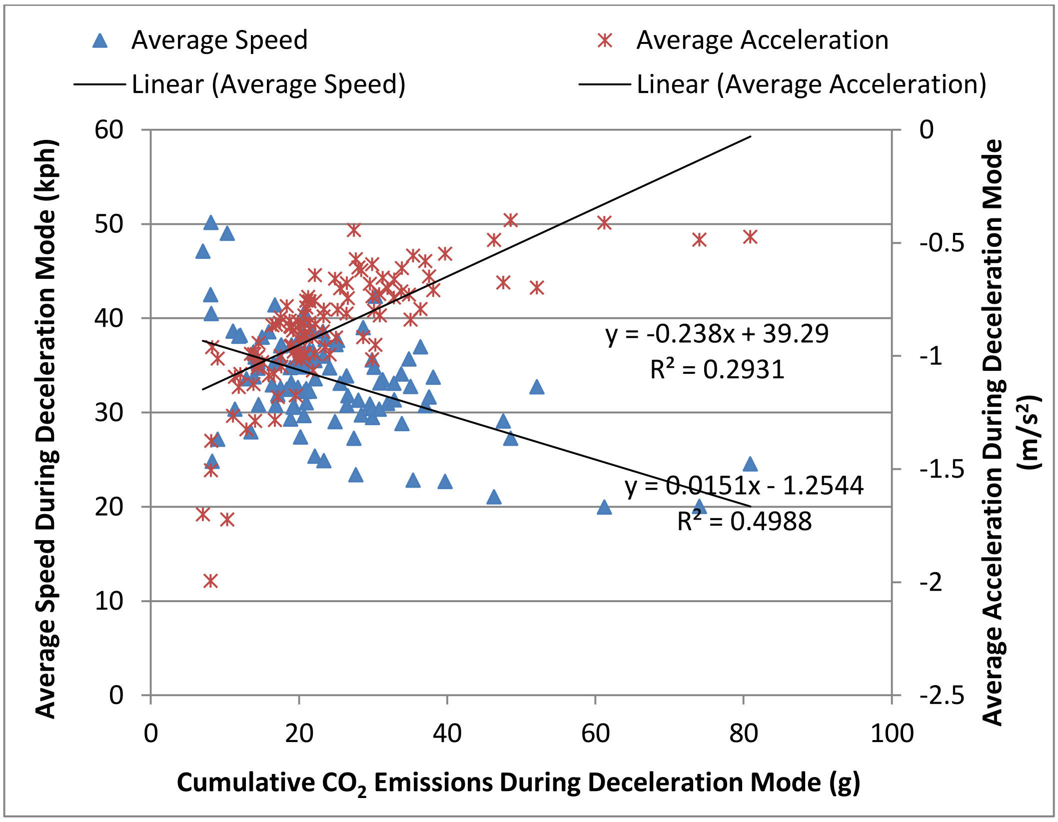


Table 7-30: Average Characteristics for high carbon and low carbon groups during deceleration mode

Average Variable Values	Low Carbon Group	High Carbon Group
Cumulative CO_2 Emissions (g)	8.95	63.38
Cumulative Fuel Consumption (g)	2.36	18.42
Instantaneous CO_2 Emission Rate (g/s)	0.71	2.57
Total Duration (s)	12.64	25.04
Total Distance (m)	158.29	167.30
Average Speed (kph)	45.10	24.91
Average acceleration (m/s^2)	-1.514	-0.494
Cumulative CO_2 During Negative Acceleration (g)	8.94	32.88
Duration of Negative Acceleration (s)	12.60	16.98
Cumulative CO_2 During Zero Acceleration (g)	0.01	3.36
Duration of Zero Acceleration (s)	0.02	1.60
Cumulative CO_2 During Positive Acceleration (g)	0.01	27.14
Duration of Positive Acceleration (s)	0.02	6.46
Distance of Positive Acceleration (m)	0.36	45.37
Cumulative CO_2 During Low Gear (g)	5.44	60.49
Duration of Low Gear (s)	2.50	16.62
Distance of Low Gear (m)	24.28	144.12
Cumulative CO_2 During Braking (g)	8.01	30.70
Braking Duration (s)	10.16	14.78
Distance of Braking (m)	114.11	99.47

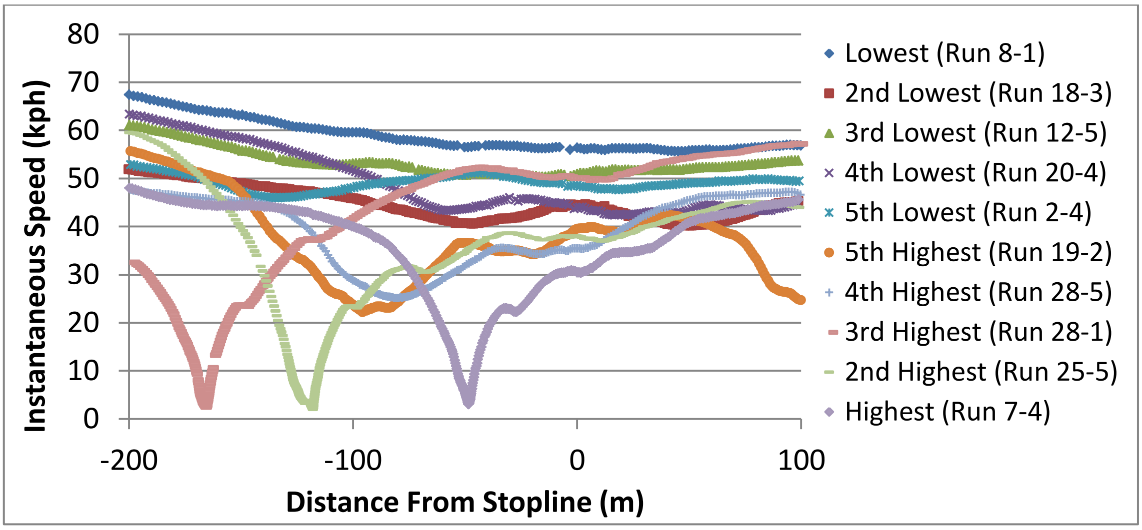
7.6.2.4 Summary

- An increase in entering speed was correlated with the reduction in cumulative CO_2 emissions during deceleration.
- A smooth deceleration could reduce as much as 54% of the cumulative CO_2 emission during deceleration compared with a rough deceleration.
- High carbon driving was characterised by unstable speed, more acceleration events, low average speed and high average negative acceleration (deceleration) as compared with the low carbon group.

7.6.3 Uninterrupted Driving

High carbon and low carbon groups showed a substantial difference in terms of speed profiles under the uninterrupted driving mode. Although the instrumented vehicle had not come to a halt, the speed profile of high carbon driving under the uninterrupted mode was similar to that of interrupted driving. Carbon emissions were aggravated by rough deceleration and high acceleration (Figure 7-37). Ranking the driving cases according to cumulative CO_2 emissions, the highest three cases were found to be different from the 4^{th} and 5^{th} cases (Figure 7-37). Therefore, only the top three and bottom three cases were considered in this section.

Figure 7-37: Speed profiles for high carbon and low carbon groups at Intersection 10



On average, the high carbon group spent 1.7 times longer than the low carbon group to cross a 300m signalised intersection (Table 7-31). A CO_2 variation of 64g (56%) was found between the high carbon group and the low carbon group. The low carbon group was characterised by higher average acceleration and average speed, as well as shorter positive acceleration duration and low gear duration. The variation in CO_2 between two groups could be correlated to large differences in CO_2 during positive acceleration and low gear, and differences in average speed and acceleration (refer highlighted rows in Table 7-31).

Table 7-31: Average variable values for high carbon and low carbon groups under uninterrupted driving

Variable	Low Carbon Group	High Carbon Group
Cumulative CO_2 Emissions (g)	48.69	112.59
Cumulative Fuel Consumption (g)	14.83	34.23
Instantaneous CO_2 Emission Rate (g/s)	2.38	3.16
Total Duration (s)	20.73	35.90
Average Speed (kph)	52.23	30.45
Average acceleration (m/s^2)	-0.109	0.025
CO_2 Emissions During Negative Acceleration (g)	26.05	29.77
Duration of Negative Acceleration (s)	12.43	16.63
Distance of Negative Acceleration (m)	181.44	124.69
CO_2 Emissions During Zero Acceleration (g)	4.62	2.42
Duration of Zero Acceleration (s)	1.73	0.77
Distance of Zero Acceleration (m)	24.99	8.25
CO_2 Emissions During Positive Acceleration (g)	18.02	80.40
Duration of Positive Acceleration (s)	6.57	18.50
Distance of Positive Acceleration (m)	90.21	168.50
CO_2 Emissions During Low Gear (g)	0.00	45.35
Duration of Low Gear (s)	0.0	14.3
Distance of Low Gear (m)	0.00	59.00
CO_2 Emissions During Braking (g)	0.83	10.65
Braking Duration (s)	0.53	8.13
Distance of Braking (m)	6.33	50.41

7.7 Comparison of Speed Profiles Over 300m Intersections

The speed profile of driving could reflect a driver's aggressiveness and his/her driving behaviour. Different speed profiles were found to produce different cumulative carbon emissions at signalised intersections, especially between interrupted and uninterrupted driving. In order to compare the speed profiles, driving cases were categorised into groups, where similar speed profiles were placed under one group. Data of one intersection, which was Intersection 10, was used to eliminate intersection variability. Speed profiles with similar entering and leaving speeds were selected to allow a comparison without the effect of leaving and entering speeds. A total of 57 cases was selected based on two criteria: 1) leaving speed range of 10kph (41-51kph) and 2) entering speed range of 10kph (48-58kph). These speed ranges were chosen to provide the maximum number of case studies but limited to 10kph speed range. The idling mode was excluded in this analysis. CO_2 emissions in grams per meter were used to compare the cases.

Five types of speed profiles were found (Table 7-32, Figure 7-38). Type 1 had the highest CO_2 emissions per meter distance, apparently due to more stops. Previous analysis showed that interruptions/stops increased CO_2 emissions. Therefore, it is reasonable to expect high cumulative CO_2 emissions if more stops were involved. Based on the average CO_2 emissions in Table 7-32, changing no-stop driving (Type 5) to one-stop driving (Type 2) increased 58% of the total CO_2 emissions. Changing no-stop driving (Type 5) to two-stop driving (Type 1) increased 113% of the total CO_2 emissions.

Type 2 speed profiles had large deviations in terms of total CO_2 emissions. However, CO_2 emissions for these driving were not sensitive to entering and leaving speeds (Figure 7-39) as well as deceleration/acceleration distances (Figure 7-40). This is because appropriate criteria were used to limit the range of leaving and entering speeds to 10kph. A difference in CO_2 emissions would be expected if the speed range was greater, as earlier analyses demonstrated that different leaving and entering speeds had different impacts on CO_2 emissions (refer Section 7.6 Analysis by Driving Mode). The governing factor of CO_2 emissions for Type 2 speed profiles would be the aggressiveness of drivers during acceleration/deceleration, which depends on whether smooth/rough deceleration or soft/hard acceleration is applied.

Type 3 speed profiles had speed values closed to zero (lowest speed was 3kph), indicating the instrumented vehicle had almost come to a stop at the intersection. This type of driving was very similar to the Type 2, although the vehicle did not stop. Therefore, it is not surprising that the CO_2 emissions per meter distance for Type 3 speed profiles lay within the CO_2 emission range of Type 2.

Type 4 speed profiles involved some degrees of disturbance in driving but did not come to a stop. The disturbance was smaller compared with Type 3 speed profiles, which may come from the impeding traffic at intersections or changes in traffic signals that reduced speed of the vehicle. As a consequence, short acceleration was observed as the vehicle attempted to resume the desired speed. The average CO_2 emission per meter distance for Type 4 was between Type 3 and Type 5.

Type 5 speed profiles were considered the "best" in terms of CO_2 emissions. This type of driving was neither affected by the traffic light nor traffic conditions. This type of speed profile showed that the signalised intersections were not saturated by traffic and the green light was long enough to clear the queued traffic before the vehicle arrived at the intersections.

Table 7-32: Comparison on five driving profiles at signalised intersections

Profile Type	Description	CO_2 Emissions (g/m)		No. of Cases
		Range	Average	
1	Interrupted driving with more than one stops.	0.34-0.47	0.405	2
2	Interrupted driving with only one stop.	0.22-0.38	0.300	43
3	Uninterrupted driving that decelerated to almost zero speed but no idling.	-	0.370	1
4	Uninterrupted driving involved deceleration and acceleration but no stopping.	0.22-0.27	0.245	4
5	Uninterrupted driving with smooth and uniform speed.	0.17-0.21	0.193	7

Figure 7-38: Speed profiles for five types of driving

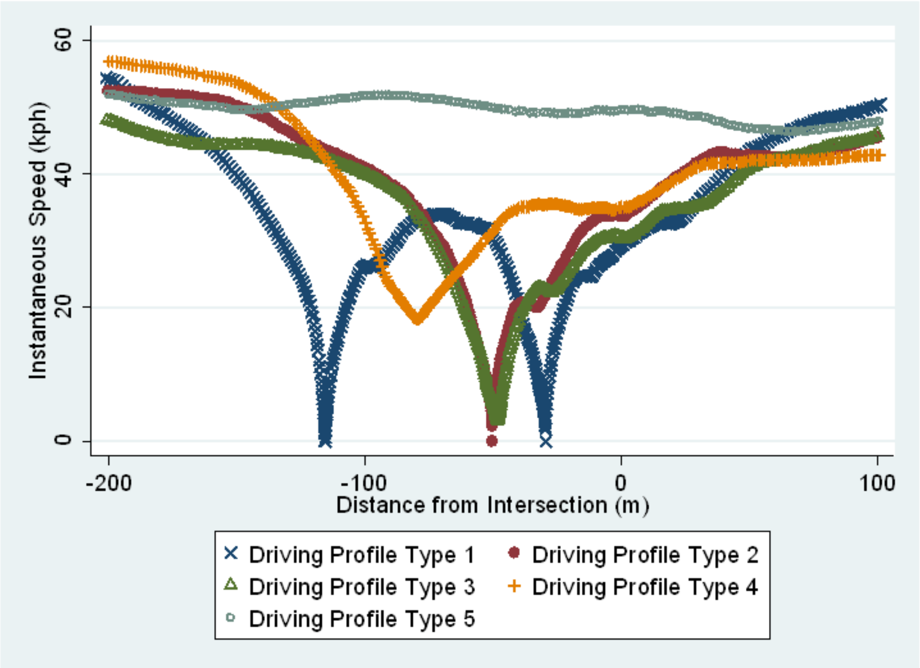


Figure 7-39: Effects of entering and leaving speeds at Intersection 10

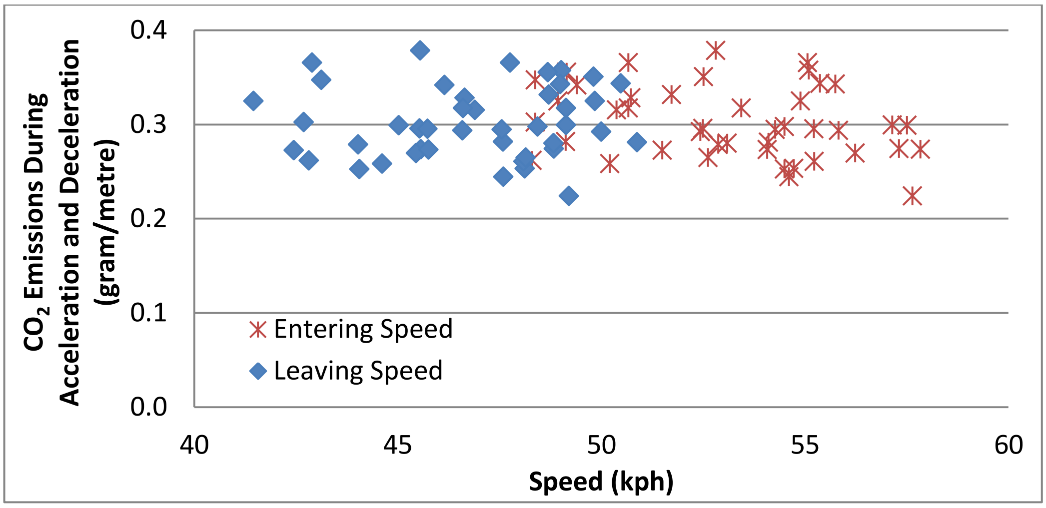
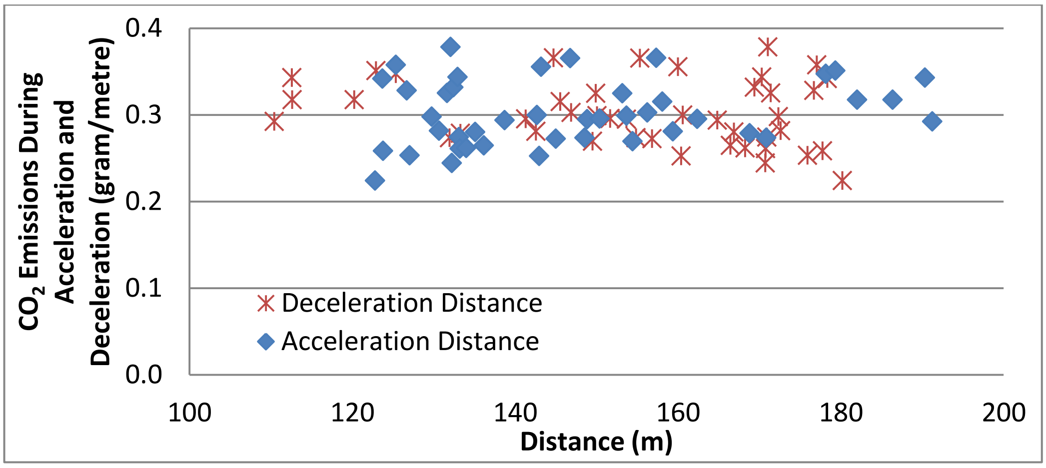


Figure 7-40: Effects of deceleration and acceleration distances at Intersection 10



7.8 CO_2 Emissions per Meter Distance and Maximum CO_2 Variation

This section presented the average CO_2 emission rate and maximum CO_2 variation over a 300m segment at signalised intersections for different types of driving conditions, driving modes, intersections, acceleration types and road types. The average emission rates were expressed in grams per meter (g/m) because it was an appropriate unit for comparisons of different cases of driving.

Based on average CO_2 emission rates (g/m) in Table 7-33, the lowest average emission rate was found on links, followed by the deceleration mode at intersections. Vice versa, the highest average CO_2 emission rate was produced at the intersections and during the acceleration mode. Interrupted driving at a signalised intersection doubled the CO_2 emissions of uninterrupted driving (refer Section 7.4.1 Interruption), and increased 2.7 times the CO_2 emissions of driving at links. The average CO_2 emission rate of acceleration was 3 times higher than deceleration (refer Section 7.4.2 Driving Mode). Average CO_2 emission rates were different between the intersections, which were largely affected by the ratio of interrupted driving vs. uninterrupted driving (Table 7-17). On average, adding an intersection increased CO_2 emissions tremendously, where cumulative CO_2 emissions at a signalised intersection could be 2.6 times of that on a link road.

Table 7-33: Average CO_2 emission rate and CO_2 variation

Case No.	Category	Sub-Category	Average Cumulative CO_2 over 300m Segment (g)	Average CO_2 Emission (g/m)	Maximum CO_2 Variation	
					grams	%^
1	Driving Condition	Uninterrupted	63.2	0.211	128.9	86
2		Interrupted	129.6	0.428	190.6	73.6
3	Driving Mode	Deceleration	26.5	0.165	145.5	97.6
4		Idle	32.3	1.244*	128.1	99
5		Acceleration	70.8	0.500	130.8	89.1
6	Intersection	Intersection 5	67.6	0.225	238.0	91.9
7		Intersection 9	85.2	0.284	167.4	77.3
8		Intersection 10	125.0	0.417	199.3	81.4
9		Intersection 11	65.4	0.218	101.4	75.2
10	Acceleration Type	Negative	18.7	0.139	48.4	90.0
11		Zero	14.9	NA	129.2	100.0
12		Positive	52.2	0.358	138.0	98.2
13	Road Type	Links	47.4	0.158	78.5	78.1
14		Intersections	125.0	0.417	199.3	81.4

*CO_2 emission rate is expressed in g/s instead of g/m because no distance was travelled during idling.
NA: Zero acceleration mostly happened during idling, where no distance was travelled during idle.
^ A proportion of the maximum CO_2 emissions in its category.
Note: Data from all driving cases was used except for Case No. 13 and 14, where 600 m segment at Intersection 10 was used.

7.9 Applicability of Carbon Savings to Other Vehicles

Field data collected from the instrumented vehicle showed a potentially significant amount of carbon savings, if driving behaviour was to change or interruption in driving was to reduce at signalised intersection. However, carbon emissions and fuel consumption of the instrumented vehicle used in this study may be different from other vehicles, with different drive chains, weight and other characteristics. Thus, whilst it is likely that the amount of carbon savings demonstrated by the instrumented vehicle will be different for other vehicles, the results should be indicative of what may be achieved more generally. Nonetheless, consideration of other vehicle types is important. Therefore, following sections considers the implication for a wider spectrum of petrol, diesel and hybrid vehicles.

Petrol and Diesel Cars

CO_2 emissions were reported to be strongly dependent upon the gross vehicle weight (Jung, Lee et al. 2011). However, the age of the vehicle, maintenance history, etc., could also affect its CO_2 emissions. Therefore, it is important to compare vehicle performance based on independent variables, e.g., comparing CO_2 emissions (g/km) based on the speed, acceleration, engine speed or the vehicle specific power. Considering the variation in driving behaviour of a driver could be observed from changes in vehicle speed, investigations of CO_2 emissions for different vehicles were made based on speed.

Vehicles in the class similar to the instrumented vehicle were used for comparison, i.e., Euro class III and Euro Class IV that have similar emission rates. Two types of vehicles were compared to the instrumented vehicle, i.e., petrol and diesel cars (Table 7-34). These vehicles were assumed to be able to achieve the same amount of CO_2 savings, if the changes in their CO_2 emission rates were similar to the instrumented vehicle.

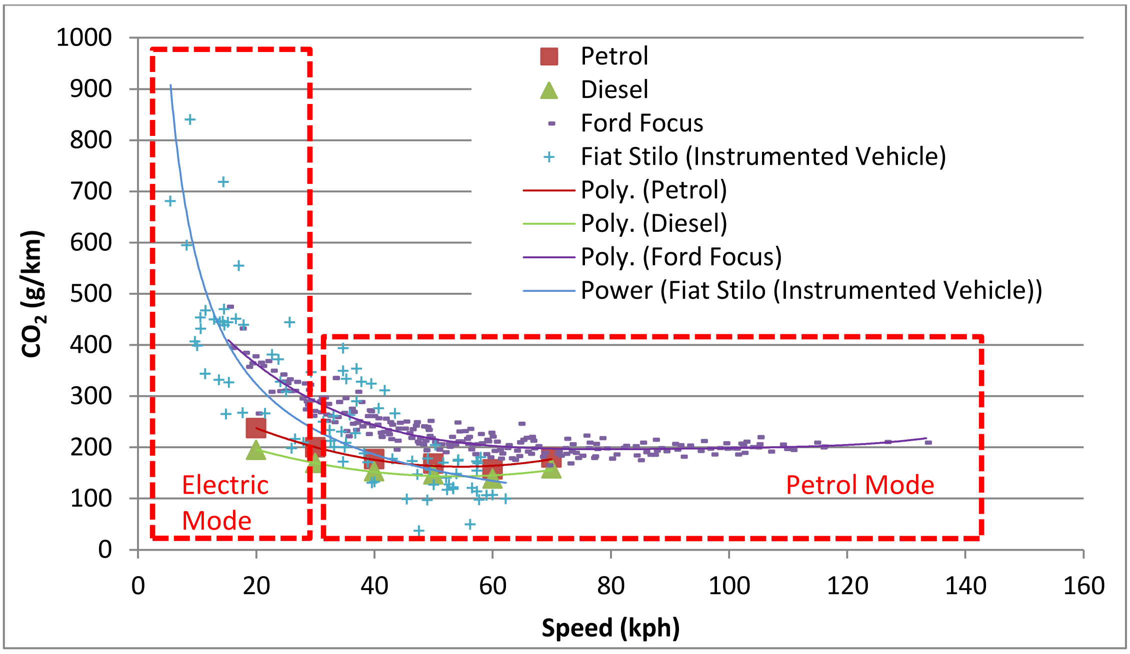
Carbon emission curves were found to be quite similar between the instrumented vehicle and other types of vehicles in the similar classes (Figure 7-41). However, the instrumented vehicle showed higher CO_2 emissions than other types of vehicles at low speed. This might be because data for the instrumented vehicle was collected at signalised urban streets as compared with data of other vehicle types that was collected from large road networks, ranging from local roads to national trunk roads. CO_2 emission curves for the average Petrol and Diesel vehicles were found to be more uniform compared with the Ford Focus and instrumented vehicle (Figure 7-41). This is because the averaging of high and low performance vehicles within one type flattened the curves.

Therefore, it is reasonable to believe that carbon savings demonstrated by the instrumented vehicle through changing driving behaviour can also be achieved by other internal combustion vehicles (ICVs) in the same class. However, the level of savings might vary from one vehicle to another as every vehicle has its unique characteristics.

Table 7-34: Vehicle Characteristics (Carslaw, Goodman et al. 2010)

Fuel	Vehicle Model	Euro Class	Engine Size (cc)	Odometer (km)
Diesel	Audi A3	III	1896	25004
	Audi A4	III	2496	-
	Ford Focus	III	1753	-
	Volvo S60	III	2401	29462
	VW Polo	III	1422	34552
	BMW 320	IV	2000	31717
	Fiat Punto	IV	1300	46628
	Mazda 6	IV	2000	24098
	Mercedes A170	IV	1700	31768
	Toyota Corrola	IV	2000	28666
	VW Golf	IV	2000	36545
Petrol	BMW 525i	III	2494	61646
	Fiat Punto	III	1242	43636
	Ford Galaxy	III	2259	50907
	Kia Magentis	III	2493	34663
	MCC Smart	III	599	50907
	Mercedes C240	III	2597	35594
	Mitsubishi Carisma	III	1834	29771
	Nissan Almera	III	1498	25455
	Peugeot 306	III	1761	31195
	Rover 45	III	1796	22360
	Seat Leon	III	1896	19409
	Toyota Yaris	III	998	44381
	Audi A4	IV	2000	30485
	Ford Fiesta	IV	1600	26970
	Mitsubishi Spacestar	IV	1600	36063
	Skoda Octavia	IV	1984	15662
	Vauxhall Vectra	IV	1800	28877
	Vauxhall Zafira	IV	1600	39347
	Volkswagen Polo	IV	1390	27575

Figure 7-41: CO_2 emissions vs. speed



Note: Data for Petrol, Diesel and Ford Focus were extracted from (Carslaw, Goodman et al. 2010)

HYBRID CAR

Changing driving behaviour on new-generation vehicles, i.e., hybrid electric vehicles (HEVs) at signalised intersections may achieve carbon savings as much as conventional internal combustion vehicles (ICVs), when the vehicle is operating under the petrol mode. According to Lave and MacLean, 2002, carbon savings from changing aggressive driving to economical driving were similar between the HEVs and ICVs (Table 2-3).

Due to limited data available on the hybrid electric vehicle, CO_2 emissions were compared based on Vehicle Specific Power, *VSP* in kW/ton. Similar to the speed variable, VSP could reflect the impact of changes in driving behaviour on CO_2 emission since it was derived from vehicle speed and acceleration. The *VSP* can be calculated using the following equation.

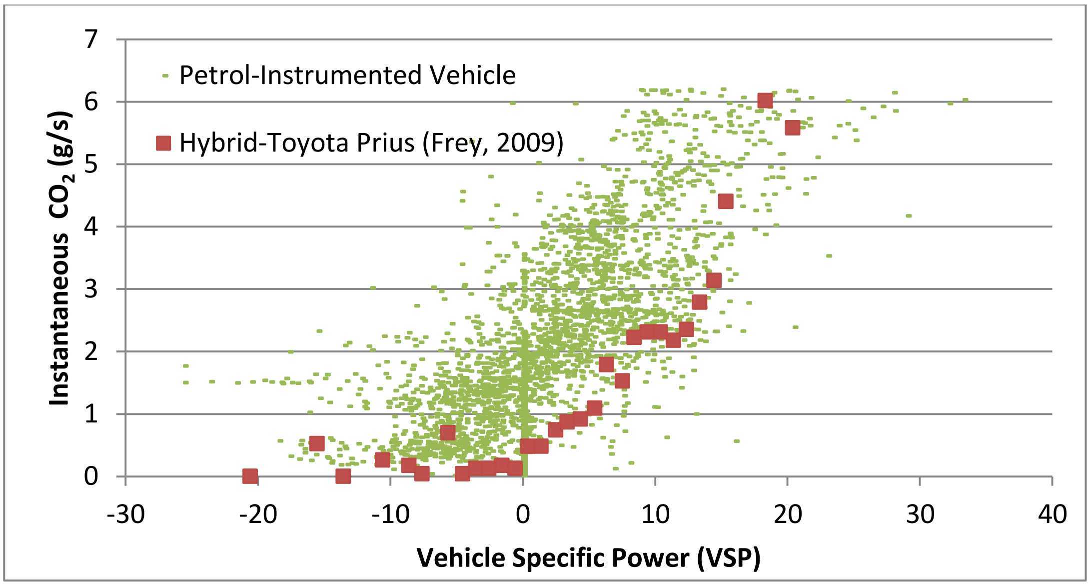
$$VSP = 0.278\left[0.305a + 9.81 * sin\left(atan\left(\frac{r}{100}\right)\right) + 0.132\right] + 0.0000065 * v^3$$

Equation 7-11

- *v* is the vehicle speed in kph.
- *a* represents the acceleration in kph/s.
- *r* is the road grade in %.

Similar CO_2 emission patterns were found between the instrumented vehicle, and the hybrid vehicle under the petrol mode (Figure 7-42). However, hybrid vehicles use electric power and power stored from regenerative braking during low speed, when CO_2 emissions are high. Therefore, CO_2 emissions of the hybrid vehicle, in general, were found to be lower than the instrumented vehicle by approximately 1.5g/s (Figure 7-42).

Figure 7-42: Instantaneous CO_2 emissions vs. vehicle specific power



Note: Instantaneous CO_2 emissions for Hybrid-Toyota Prius was converted from fuel consumption with a factor of 3.14 (refer Equation 4-1)

Source: (Jiménez-Palacios 1998; Frey, Choi et al. 2009)

7.10 Carbon Abatement Measures

Many countermeasures can be adopted to reduce carbon emissions of the vehicle at signalised intersections. This section proposes a few countermeasures based on the results and findings discussed earlier. The countermeasures can be divided into two categories: changing driving behaviour, improvements on traffic control and road management. The impact of the proposed countermeasures was demonstrated through London city as an example.

7.10.1 Change in driving behaviour

There was a significant difference in CO_2 emissions (also fuel consumption) between aggressive and economical driving at signalised intersections. These two types of driving behaviours, referred to as high carbon and low carbon driving in this report were characterised by different speed and acceleration profiles (refer earlier sections in this chapter). Average variations in cumulative carbon emissions between low carbon and high carbon driving were found to be 27% and 30%, for interrupted and uninterrupted driving, respectively (refer Table 6-14). Maximum variations were found to be 128.9g (86%) and 190.6g (73.6%), for uninterrupted and interrupted driving, respectively (Table 7-33). Therefore, it is possible to achieve significant reductions in carbon and fuel through changing driving behaviour to more economical driving at intersections.

At signalised intersections, sustaining stable and uniform speed reduced the need for acceleration and minimised the total CO_2 emissions. Similarly, maintaining low acceleration helped to keep the CO_2 emission level low. For interrupted driving, driving behaviour was distinctly different between three driving modes, i.e., acceleration, idling and deceleration. Each of these modes has its own unique carbon reduction tactics. Therefore, changing driving behaviour designated to particular driving mode would be more effective in tackling the high carbon emission problem as compared to one solution for all. For the acceleration mode, keeping acceleration below $0.6m/s^2$ and reducing leaving speed from 60kph to 45kph might save up to 30.3g and 31g of CO_2 emissions, respectively (refer 7.6.1 Analysis for Acceleration Mode). For the deceleration mode, applying smooth deceleration might potentially save up to 54g of CO_2 (refer 7.6.2 Analysis for Deceleration Mode). For the idling mode, adopting the idle-stop system could potentially reduce an average 32.3g of CO_2 per vehicle at each signalised intersection (refer Table 7-33). If these strategies were to be combined, an optimistic carbon reduction of 144.7g could potentially be achieved from the total CO_2 emissions of 258.92g.

The city of London has 2532 signalised intersections and an average traffic flow of 2216vph per intersection (Table 2.1 and Table 3.3 from (Buchanan C. and Partners 2009)). Applying the carbon reduction strategies discussed earlier to the city of London, assuming 50% of the traffic stop at the signalised intersections and 30% of the drivers change the worst driving to the best driving, significant carbon reductions of 25-39 metric Tonnes CO_2 per hour could be achieved (Table 7-35). However, the real carbon reduction could be varied when the driving environment, traffic condition or driver expectation changed. For instances, a driver may not be able to perform smooth deceleration if traffic is dense, congested or there is changes in traffic signal. Similarly, a decision for soft acceleration could often be affected by the number of cars following behind the car. Drivers may be pressured to accelerate when they are closely tailgated. In general, speed and acceleration of vehicles are governed by the intersection capacity, level of service, and traffic control.

Table 7-35: Potential savings from changing driving behaviour

Mode	Strategy	Average CO_2 Saving By Changing the Worst to the Best Driving		Scale of Effect[a]
		(g)	(%)	(metric Tonnes per hour)
Deceleration	Smooth Deceleration	45.5	54	39
Acceleration	Keep Acceleration Below $0.6 m/s^2$	66.9	26	57
	Reduce Leaving Speed from 60kph to 45kph	35	31	30
Idling	Adopt Idle-Stop System	32.3	25	28

[a] For the city of London with 2532 signalised intersections (exclude pedestrian crossing) and an average intersection flow of 2261vph, assuming 50% of the traffic stop at the signalised intersections and 30% of the drivers change the worst driving to the best driving

7.10.2 Traffic control and road management

If a driver has to stop at a signalised intersection, this interruption could induce twice as much CO_2 of an uninterrupted driving over a 300m long intersection. Therefore, reducing traffic interruptions would be an effective way of cutting CO_2 emissions from road traffic. The average carbon reduction from preventing the interruption was 66.4g CO_2 (51.2%) per vehicle per signalised intersection (refer Table 7-33). However, it is impossible to prevent interruptions at the intersection completely without causing interruptions to traffic on other approaches. Priority systems, for example, Gating, Greenwave, etc., are good strategies that help reduce interruptions at signalised intersections. These systems collect vehicles at minor approaches to maximise traffic flow on major approaches. On the other hand, completely removing an intersection or replacing it with links could potentially reduce CO_2 emissions by 62% (refer Table 7-33). However, this method often involved high cost and resources, which might not be easy to implement.

For the city of London, CO_2 reductions of 28-67 metric Tonnes per hour could be expected if interruptions are prevented at intersections, or intersections are replaced (Table 7-36).

Table 7-36: Potential savings from preventing driving interruption (refer Table 7-33)

Strategy	Average CO_2 Savings Changing the Worst to the Best Driving		Scale of Effects [a]
	(g)	(%)	(metric Tonnes per hour)
Prevent Interruption at Intersection	66.4	51.2	28 [b]
Replace Intersection With Flyover	77.6	62	67

[a] For the city of London with 2532 signalised intersections (exclude pedestrian crossing) and an average intersection flow of 2261vph.
[b] Assuming 50% of the traffic stop at the intersections.

Chapter 8 Conclusion

The definition for the terms used in this chapter is given in GLOSSARY section at the beginning of this thesis.

8.1 Carbon Reduction

Reducing the carbon footprint and increasing fuel efficiency have become the biggest challenge in transportation. Therefore, this study investigated the impacts of driving behaviour on CO_2 emissions, and recommended some driving practices for carbon reduction at signalised intersections. A highly instrumented vehicle was employed in this study to measure 1) instructed driving styles of two drivers on a mixed route, i.e., economical and aggressive driving and 2) natural/normal driving behaviour of a large sample (29 drivers) on a designated urban route.

The average carbon emission rate (g/m) at a signalised intersection was 2.6 times (refer Table 7-33) higher than on a link, for the same driving distance. Also, the maximum carbon variation between runs for the instrumented vehicle at a signalised intersection was as much as 89% (refer Case No.5 in Table 7-33) and average CO_2 savings of 8-35% could be achieved by changing an aggressive driving. This indicated a real opportunity to reduce carbon emissions if drivers were to change their driving behaviour from the worst to the best. The carbon reduction is feasible if drivers were positively motivated to change from high carbon driving to low carbon driving (Van Mierlo, Maggetto et al. 2004). Good motivation could come from the potential fuel/carbon savings, also incentives from transport policies.

Changing the worst driving to the best driving involves carbon abatement strategies in the aspects of driving behaviour, traffic control and vehicle technology. This study found that applying smooth deceleration could reduce CO_2 emissions by 54% during the deceleration mode. Maintaining acceleration below 0.6 m/s^2 or reducing leaving speed could reduce 26-31% of the CO_2 emissions during the acceleration mode. Adopting idle-stop system could potentially reduce total CO_2 emissions at signalised intersection by 25% (Table 7-35). Overall, an optimistic carbon saving amount of 144.7g could potentially be achieved from these strategies, which is equivalent to 56% reduction from the maximum total CO_2 emissions of 258.9g. On the other hand, traffic control strategies that reduce interruption to driving could also be used for reducing

CO_2 emissions from road traffic, where interferences to other traffic shall be taken into consideration to ensure real CO_2 reductions from all traffic.

Carbon emission rates of the instrumented vehicle were found to be similar to other internal combustion vehicles (ICVs) in Euro Class III and Euro Class IV. The hybrid electric vehicle (HEV) also showed an identical CO_2 emission trend to the Instrumented Vehicle. However, instantaneous CO_2 rates of the instrumented vehicle were found to be higher than the HEV. Therefore, it is reasonable to believe that carbon savings through changing driving behaviour demonstrated by the instrumented vehicle could be potentially achieved by other vehicle types in the same class. The savings could also be applied to the hybrid electric vehicle when the vehicle is running under the petrol mode, although the level of saving would be smaller. The TRG instrumented vehicle has some characteristics that are different from other vehicles in terms of engine, transmission, loading, etc. Data obtained in this study was related to these characteristics to some extent. However, the variability in driving behaviour should not be significantly different if other vehicles were used for the field test. The results in this study provided an understanding of the possible levels of changes in driving behaviour. However, the actual level of impacts on CO_2 emissions on other vehicles would require larger scale field tests to be conducted on different instrumented vehicles.

In summary, there is a huge potential of carbon reductions at signalised intersections, which could be achieved via changing driving behaviour, optimising traffic control and applying new vehicle technology. The carbon savings demonstrated in this study can be achieved by the internal combustion vehicles in the similar classes, and attained by the hybrid electric vehicle when the vehicle is running under the petrol mode, although the level of impact on these vehicles might be different. Changing driving behaviour would be the most cost effective strategy of all because it could reduce a substantial amount of CO_2 without resorting to costly infrastructure or new vehicle technology.

8.2 Future Vehicle Technology

Existing vehicle fleets will be replaced by more carbon friendly and better fuel efficient vehicles, for example, hybrid, electric and alternative-fuel vehicles, in the future. Driving behaviour might evolve when these new-generation vehicles are introduced. Potential behavioural changes during driving include applying harder deceleration to maximise idle-stop, travelling at higher speed as vehicles are quieter, etc. In general, more aggressive driving behaviour could be expected if vehicles are equally or more powerful than now. To date, some of the new vehicles have already been equipped with the idle-stop system, a system that automatically turns off the engine when a vehicle is idling. Considering the significant carbon savings an idle-stop system could potentially achieve at signalised intersections (Table 7-36), harder deceleration shall be expected on these vehicles when the drivers attempt to maximise the idling duration.

During the transition period, there could be potential clashes in driving behaviour because of the conflict of behaviour related to different driving styles between the conventional ICVs and new generation vehicles. For instance, drivers of new generation vehicles who attempt to perform harder deceleration to maximise idling time could be hindered by the conventional ICVs that are aiming to decelerate slowly and smoothly.

8.3 Research Contribution

The findings of this research help to identify CO_2 emission reduction strategies for driving at signalised intersections. These findings would be useful in establishing transport policies to promote more economical driving, or to support awareness campaigns in changing driving behaviour towards more economical driving. Furthermore, these findings can be integrated into vehicle designs to produce not only powerful vehicles, but also more efficient and environmentally friendly vehicles. The recommendations in changing driving behaviour could be incorporated into the traffic control and management, planning of the transportation network, driver training and driving test.

No prediction models that are specific to carbon emissions at signalised intersections have been established yet. Therefore, developing such a model in this study, particularly focusing on the individual driving mode would be useful in complementing the general microscopic/macroscopic carbon emission model. This is expected to improve the predictability and accuracy of the existing emission models, as most of the models have not been able to capture CO_2 emissions during the transient mode.

As a summary, this research has:

- Validated the linear relationship between the instantaneous CO_2 emission rate and instantaneous fuel consumption.

- Demonstrated that driving behaviour could be changed, and the change has a significant impact on CO_2 emissions and fuel consumption.
- Demonstrated that speed, acceleration, idling, braking and low-gear are the major factors affecting carbon emissions. Their impacts on carbon emissions have been discussed.
- Demonstrated that there are two clusters of driving behaviour, i.e., high carbon and low carbon driving, with 27-30% difference in average CO_2 emissions between the clusters.
- Quantified impacts of the interruption, average speed, average acceleration, instantaneous speed, instantaneous acceleration, low gear duration, positive acceleration duration, braking duration, etc., on CO_2 emissions.
- Proposed strategies that could reduce carbon emissions from the aspects of changing driving behaviour, managing traffic control and applying new vehicle technology.
- Demonstrated that the CO_2 savings in this study are applicable to other petrol and diesel vehicles in the same class, also the hybrid vehicle but to a lesser extent.
- Established carbon emission models for signalised intersections, in terms of instantaneous emissions and cumulative emissions, under different driving modes.

8.4 Recommendation for Future Research

This research focused on changing driving behaviour for internal combustion vehicles (ICVs) that are still relying on fossil fuels. The recommendations made in this study could be used to reduce vehicle emissions at signalised intersections during the transitional period, before the vehicle decarbonisation technologies are matured. Future research could be extended to investigate the effect of road and traffic conditions on drivers' behaviour and decisions. Furthermore, there could be a shift in driving behaviour when new strategies, i.e., new vehicle technology, new fuels, more efficient traffic management and policy, are implemented. The shift of driving behaviour will be an important research area in the future.

Appendix A: CO_2 Emissions by Sector

(International Energy Agency 2010)

	Total CO2 Emissions From Fuel Combustion	Electricity and Heat Production	Other Energy Industries**	Manufacturing Industries and Construction	Transport	% from Transport	Of Which: Road	% From Road Transport	Other Sectors	Of Which Residential
World***	29381.4	11987.9	1491.9	5943.6	6604.7	22.5	4848.4	16.5	3353.4	1905.1
Latin America	1068.2	215.9	96.4	279.6	361.8	33.9	326.8	30.6	114.5	63
Europe	3222.9	1063.9	164.4	514.3	850.5	26.4	790.6	24.5	629.8	402.8
Pacific	1582	708.7	65.5	303.8	319.9	20.2	283.1	17.9	184.2	66.8
North America	6146.8	2522.7	333.5	730.9	1853.5	30.2	1582.7	25.7	706.2	373.6
European Union - 27	3850	1409	179	610	943	24.5	880	22.9	708	451
Asia	3022.8	1384.5	161.4	737.8	447.7	14.8	418.5	13.8	291.5	140.2
Former Soviet Union	2426.5	1207.3	111.1	413	329.7	13.6	200.6	8.3	365.4	219
Middle East	1492.3	529.9	126.6	332.3	326.6	21.9	324.2	21.7	176.9	127.3
Africa	889.9	384.4	45.6	140.4	211.6	23.8	197.4	22.2	107.9	72.4
China	6550.5	3136.9	268.6	2174.5	456.9	7.0	334.4	5.1	513.5	285.9
United States	5595.9	2403.4	268.3	633.1	1691.6	30.2	1455.9	26.0	599.5	332.7
United Kingdom	511	195	32	59	125	24.5	115	22.5	100	76
Malaysia	180.9	63.9	25.8	43.7	42.1	23.3	41.5	22.9	5.3	2.7

* This table shows CO_2 emissions for the same sectors which are present throughout this publication. In particular, the emissions from electricity and heat production are shown separately and not reallocated as in the table on pages 68-70.

** Includes emissions from own use in petroleum refining, the manufacture of solid fuels, coal mining, oil and gas extraction and other energy-producing industries.

*** World includes international bunkers in the transport sector.

Appendix B: Technical Details of the Instrumented Vehicle

technical details | equipment | features

General

Insurance Group 1	15
Insurance Group 2	D
Manufacturers Paintwork Guarantee - Years	3
Insurance Group 1 - 50 Effective January 07	30D

Fuel Consumption

EC Urban (mpg)	20.8
EC Extra Urban (mpg)	37.2
EC Combined (mpg)	28.8

Performance

0 to 62 mph (secs)	8.5
Top Speed	132
Engine Power - BHP	170
Engine Torque - LBS.FT	N
Engine Torque - NM	221
Engine Torque - RPM	3500
Engine Torque - MKG	22.5

Emissions

CO2 (g/km)	233
Standard Euro Emissions	Euro 3

Engine and Drive Train

CC	2446
Cylinders	5
Fuel Delivery	Multi Point Fuel Injection
Engine Layout	Front Transverse
Transmission	Auto
Gears	5 Speed

Vehicle Dimensions

Length	4253
Width	1756
Wheelbase	2600
Width (including mirrors)	N
Height	1525

Weight and Capacities

Minimum Kerbweight	1320
Gross Vehicle Weight	1830
Fuel Tank Capacity (Litres)	58
Max. Towing Weight - Braked	1300
Max. Loading Weight	510
Luggage Capacity (Seats Up)	370
No. of Seats	5
Max. Roof Load	80
Luggage Capacity (Seats Down)	1120
Turning Circle - Kerb to Kerb	11.1

Appendix C: Specifications for OBS-2200

Measuring components / Input signals	CO	HNDIR (wet)
	CO_2	HNDIR (wet)
	THC	HFID (wet)
	NOx	HCLD (wet)
	Exhaust flow	Pitot flow meter
	Standard input *1	From accessory sensors
	External input *2	Max. 16 channels (optional)
	OBD data *3	Max. 16 items (optional)
System specification	Power supply	20 to 30 V DC
	Power consumption (at stable state)	Approx. 0.5 kW
	Dimension	Approx. 350 (W) x 330 (H) x 500 (D) mm
	Mass *4	Approx. 29 kg
	Recommended battery	Deep cycle battery, 24 V DC, 100 Ah (5 h rate), approx. 64 kg
Application	Diesel vehicles	Ö
	Gasoline, LPG and CNG vehicles	Ö
	CFR 1065 subpart J Conformity	Ö

Appendix D: Questionnaire

Document 2

Pre-Trial Questionnaire

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

This project aims to study the impacts of different driving behaviours on carbon emissions. Driving behaviour between different individuals may not be the same even though the road and traffic conditions are similar. To assess how this difference in driving behaviour may affects the carbon emissions, you have been asked to take part in a driving trial.

This questionnaire is divided into 2 sections. Section A specifies your demographic background and Section B your driving experience.

In this study you will be placed in different categories based on your driving experience and behaviour. However, your answers will not affect whether or not you are selected to take part in this study. Therefore, please answer these questions as accurately and truthfully as you can.

SECTION A DEMOGRAPHIC

For following tick box, double click to open the pop up window and select **checked** under the Default Value option, then click ok.

A1) Gender: (Please tick one box only)

Male ☐ Female ☐

A2) Age: (Please tick one box only)

25-29 ☐	40-44 ☐	55-59 ☐
30-34 ☐	45-49 ☐	60-64 ☐
35-39 ☐	50-54 ☐	65+ ☐

A3) What type of vehicle have you driven most often? (Please fill in the blank)

Type: ______________________________ (e.g. passenger car, heavy vehicle and etc)

Brand: ______________________________ (e.g. Toyota, Ford and etc)

Model: ______________________________ (e.g. Camry, Classic and etc)

Engine capacity (litre): _______________ (e.g. 1.3 litres, 1.5 litres, 2.0 litres and etc)

SECTION B DRIVING EXPERIENCE

B1) Considering your total driving mileage, please estimate the percentages of your driving on the following types of roads. (Please write for each road type)

Motorway	%
City	%
Rural	%

Document 2

Thank you for your time and cooperation

Data Protection Act 1998. The information you provide will only be used for research purposes. As with any data in this trial, any information you give as a volunteer will be treated in the strictest confidence and no information will be published that allows individuals to be identified. Your address will only be processed if you wish to volunteer to take part in further vehicle trials. No organisations outside this project will have access to your personal data.

Appendix E: Information Sheet & Consent Form

Document 1

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

Information for Participant

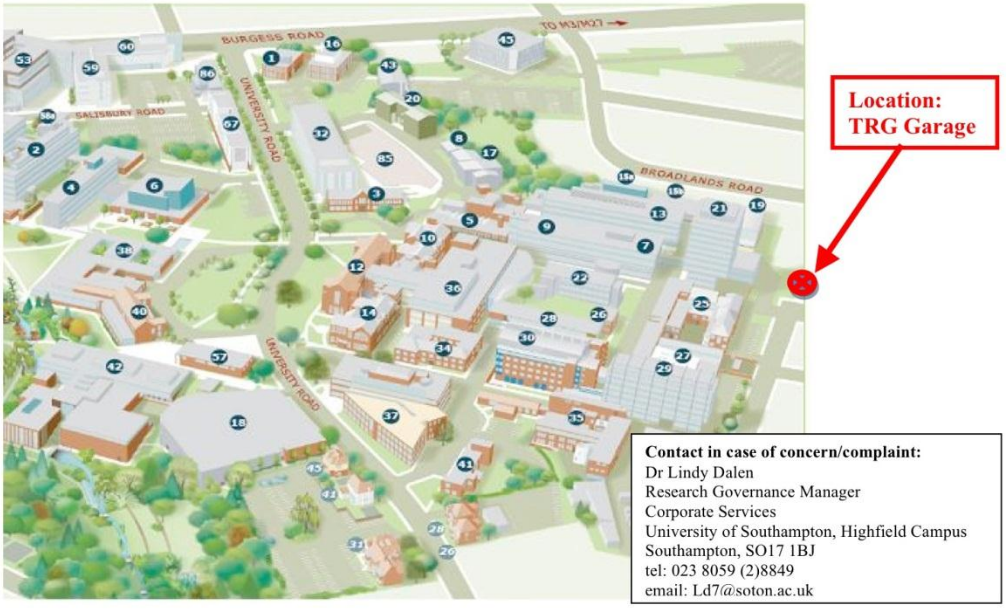
Project Title: Carbon emission abatement at the signalised intersection
RGO ref: 7249
This is a project conducted by PhD student in Transportation Research Group of University of Southampton. This project aims to study the impacts of different driving behaviours on carbon emissions. Driving behaviour between different individuals may not be the same even though the road and traffic conditions are similar. To assess how this difference in driving behaviour may affects the carbon emissions, you have been asked to take part in a driving trial.

Your driving behaviour will be recorded using various in-vehicle devices which provide data to study the effects of driving behaviours on vehicle's carbon emission. Therefore, **you are required to drive in your natural driving style**. The driving task would require you to use the automatic gear transmission on the instrumented vehicle provided by us.

The trial for every individual volunteer will take 2 hours. This includes a brief introduction, signing of consent form, a brief run to get you familiar with the instrumented vehicle, following by an actual test run on the designated test route. You will be paid with £20 if you accomplished the trial as required. However, a maximum pay of £5 is applied if you did not finish the task but complete a minimum of two laps.

You are required to **bring your valid UK driving license (with the paper copy) or any equivalent driving license acceptable by the UK road authority**. The latter should include any supporting documents if required.

Please **arrive on time**. If, for any reason, you are not able to come, please notify Koh Moi Ing (Tel. 07838954270). The task will take place at the TRG garage located behind Building 21 (refer map below).



Contact in case of concern/complaint:
Dr Lindy Dalen
Research Governance Manager
Corporate Services
University of Southampton, Highfield Campus
Southampton, SO17 1BJ
tel: 023 8059 (2)8849
email: Ld7@soton.ac.uk

Document 3

Ref:

Instrumented Vehicle Trial
Consent form

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

This project aims to study the impacts of different driving behaviours on the carbon emission. Driving behaviour between different individuals may not be the same even though the road and traffic conditions are similar. To assess how this difference in driving behaviour may affects the carbon emissions, you have been asked to take part in a driving trial. To show that you agreed to take part in this trial, we require you to complete this consent form.

SECTION A INFORMED CONSENT

I ………………………………………………… have received both verbal and written explanation of the study, and have also been given the opportunity to ask for clarification and/or further details should I wish.

I have freely given my consent to take part in this study. I understand my participation is voluntary and that I have the right to withdraw at any time and also for my data to be removed at a later date should I so wish. Finally I understand that all data will be used in accordance with the Data Protection Act 1998 (see next page).

I understand that it is my responsibility to drive in a manner that does not endanger other road users or myself.

Please tick the appropriate box:

☐ I confirm that:
- I am over the age of 25,
- I have three full years driving experience
- I hold a full valid driving licence for use in the UK,
- I have no current endorsements/penalty points on my driving licence,
- I have no medical condition or disability that precludes me from driving a motor vehicle on the public highway.

OR

☐ I do not fulfil all the above requirements but have been given dispensation to drive the University of Southampton instrumented vehicle *(this will be confirmed to you by the person administrating the test)*

Signed: ……………………………………………. **Date:** ………………….

Print name: ………………………………………

SECTION B PARTICIPATION IN FUTURE TRIALS

B1) This project may be require participants for future driving trials in a similar test. Are you willing to be contacted in future to be asked to take part in further trials? (Please tick one box only)

Yes ☐ No ☐ **End of questionnaire**

Continued overleaf…

B2) Please write in your preferred contact details so we may contact you regarding future trials. (Please write in)

Address: ....

....

Postcode: ....

Tel. Number: ....

Email: ....

Thank you for your time and cooperation

Data Protection Act 1998. The information you provide will only be used for research purposes. As with any data in this trial, any information you give as a volunteer will be treated in the strictest confidence and no information will be published that allows individuals to be identified. Your address will only be processed if you wish to volunteer to take part in further vehicle trials. No organisations outside this project will have access to your personal data. A summarised copy of the project report associated with this work can be provided upon request.

To be completed by person administrating the trial

☐ I confirm I have seen this individual's driving licence and they fulfil the standard requirements to drive the instrumented vehicle

OR

☐ I confirm I have seen this individual's driving licence and they have been given special dispensation to drive the instrumented vehicle because:

....

....

....

Those not meeting the requirements listed in Section A can be given special dispensation to drive the instrumented vehicle if:

- They are under 25 but over 21 and they have been cleared to drive by Head of School
- They have less than 3 years driving experience and have been cleared by Head of School
- They have endorsements up to three penalty points on their licence for minor offence. The following website can be consulted regarding motoring offences that carry penalty points.

http://www.direct.gov.uk/en/Motoring/DriverLicensing/EndorsementsAndDisqualifications/DG_10022425

If in any doubt check with the insurance office (Ruth McFadyen ext. 22417). Insurance office should be informed of all drivers who do NOT meet standard requirements.

Signed: ………………………………………………. **Date:** ………………….

Appendix F: Data Resampling Program Code

* This Matlab program is developed by Dr. PengJun Chen based on linear interpolation

```
% data resample function//
% with time checking
function ddata=jvResamplev3(odata)
% first column time, other column data
% up to 0.1 seconds
dlen=length(odata);
dwid=length(odata(1,:));
% odata(:,1)=odata(:,1)*24*3600; % convert to sec data
% sort the data first
odata=sortrows(odata,1);
% excluding zero time readings
curpos=1;
for i=1:dlen;
    if odata(i,1)<=0; % missing data or invalid data
        curpos=curpos+1;
    else
        break;
    end;
end;
% data excluding invalid time ones
odata=odata(curpos:dlen,:);
dlen=length(odata);
% sorting data with same time stamp,
tt=odata(:,1);
rptcount=1; % repeat count
for i=2:dlen;
    if (odata(i,1)-odata(i-1,1))==0;
        tt(i)=odata(i-1)+0.0001*rptcount;
        rptcount=rptcount+1;
    else
        rptcount=1;
    end;
end;
t0=odata(1,1);
te=odata(dlen,1);
t0=fix(t0*10)/10;
te=round(te*10)/10;
step=0.1; % 10 Hz sampling
t=t0:step:te;
t=t';
tlen=length(t);
ddata=zeros(tlen,dwid);
ddata(:,1)=t;
for j=2:dwid;
    ddata(:,j)=interp1(tt,odata(:,j),t,'linear');
end;
%***********************************
% for debug
% data end position
%for tpos=1:tlen-1;
%    for depos=dspos:dlen;
%        if (odata(depos,1)>=t(tpos) && odata(depos,1)<t(tpos+1))
%            depos=depos+1;
%        else
%            ddata(tpos,:)=mean(odata(dspos:depos,:),1);
%            dspos=depos+1;
%            ddata(tpos,1)=t(tpos);
%            break;
%        end;
%    end;
%end;
%ddata(:,1)=ddata(:,1)/24/3600;
```

Appendix G: Specifications for Datron

Performance Specifications	
Speed range:	0.3 ... 250
Distance resolution	2.08 mm
Uncertainty of measurement*:	< ±0.2%
Speed linearity - desired distance	< ± 0.5 %
Distance linearity	< ± 0.2 %
Working distance and range:	200 +/-70 mm
Outputs	
CAN Bus:	CAN V2.0B - switchable terminating resistor (Intel or Motorola Format)
Analog Output:	0...10V
Digitale Output:	1...1000 pulses/m
USB:	USB 1.1
System Specifications	
Power supply:	10,5 V ... 14.5 V; 28 W (12 VDC)
Temperature range: operation:	-25 ... 50°C
storage:	-40 ... 85°C
rel. humidity:	5 ... 80%, non condensing
System Protection of the sensor:	IP 67
Illumination wavelength:	850 nm, laser class 1M
Dimensions of the sensor head (l x w x h):	100 x 28 x 40 mm (without plug)
Weight sensor head:	180 g
Dimensions of the electronics (L x H x B):	130 x 86 x 33 mm
Weight of the electronics:	approx. 490 g
Schock:	50 g half-sine, 6 ms
Vibration:	10 g, 10 ... 150 Hz

Appendix H: Specifications for Dashdyno SPD™

Processor	32-bit, software upgradeable
Screen	High contrast monochrome, white LED backlit
Keys	Backlit silicon rubber
Expansion Slot	Support for MultiMediaCard, SD and SDIO cards
File Formats	FAT12, FAT16, FAT32
Card Size	1GB max
Power	OBD II cable or AC adapter
Sleep Mode	Auto power-off
Keypad	Backlit, secondary function keys
Aux Port 1	Mini-DIN, four analog inputs, 5V output
Aux Port 2	Mini-DIN, one digital input, one digital output, serial port, 5V output
Aux 5V Output	Current limited 25mA max (combined both ports)
Analog Inputs	Selectable ranges of 0-6V, 0-12V or 0-24V, 10-bit ADC
Analog Input Impedance	95k ohm 6V range, 62k ohm 12V range, 54k ohm 24V range
Oscilloscope Mode	200Hz bandwidth, 1mS sample rate
Digital Input	24V max, 4V high min, 1.6V low min
Digital Output	Open Collector, 15V max, 75ma sink max
External GPS Baud	4800, 9600, 19200, 38400
External GPS Protocol	NMEA 0183
USB Port	Mini USB type B
OBD II Port	Modular
OBD II Cable	6ft, low-profile OBD II connector
Alarm Lights	Three high intensity LEDs
Mounting	Two brass 8-32 rear mounting screw holes
Windshield Mount	Suction cup with quick release
OBD II Protocols	J1850 (VPW, PWM), ISO 9141, ISO 14320 (KWP), and ISO 15765 (CAN bus) protocols

Appendix I: Specifications for VBOX-III

GPS

Velocity

Accuracy	0.1 Km/h (averaged over 4 samples)
Units	Km/h or Mph
Update rate	100 Hz
Maximum velocity	1000 Mph
Minimum velocity	0.1 Km/h
Resolution	0.01 Km/h

Absolute Positioning

Accuracy	3m 95% CEP**
Accuracy with DGPS	1.8m 95% CEP**
Update rate	100 Hz
Resolution	1 cm

Heading

Resolution	0.01°
Accuracy	0.1°

Acceleration

Accuracy	0.5%
Maximum	20 G
Resolution	0.01 G
Update rate	100Hz

Memory

Compact Flash	Type I
Recording time	Dependent on flash card capacity*

** Approximately 29Mb per hour used when logging GPS data at 100Hz*
Approx 182Mb per hour total logging capacity.

Distance

Accuracy	0.05% (<50cm per Km)
Units	Metres / Feet
Update rate	100Hz
Resolution	1cm
Height accuracy	6 Metres 95% CEP**
Height accuracy with DGPS	2 Metres 95% CEP**

Time

Resolution	0.01 s
Accuracy	0.01 s

Power

Input Voltage range	5.3v-30v DC
Power	Max 10.6 watts

Environmental and physical

Weight	Approx 900 grammes
Size	170mm x 121mm x 41mm
Operating temperature	-20°C to +70°C
Storage temperature	-30°C to +80°C

Definitions

** CEP = Circle of Error Probable
95% CEP (Circle Error Probable) means 95% of the time the position readings will fall within a circle of the stated diameter

Appendix J: Speed Smoothing Program Code

* This Matlab program is developed by Dr. PengJun Chen based on moving average smoothing algorithm.

```
% Iv Speed filter
%purpose: smooth a time-series data
%method: 1. exclude outlier according to the thredshold
%        2. find discontinous point
%        3. separate data into several segment accoding to the contiuous
requirement
%        4. apply a low pass butter filter
%        5. recombine smoothed data, discontinous point represented by
function ddata=rdSpeedFilter(odata,order,normpf,cri,tag);
[b,a]=butter(order,normpf);%filter to be applied
%end point checking
% step 1: coarse outlier exluding
dlen=length(odata);
ddata=odata;
% excluding all negative speed point and outlier
for i=1:dlen
    if (abs(odata(i))<cri/30 | odata(i)<0 | isnan(odata(i))==1);
        ddata(i)=0;
    end;
end;
for i=2:dlen-1;
    if ddata(i-1)==0 & ddata(i+1)==0;
        ddata(i)=0;
    else if abs(ddata(i)-ddata(i-1))>cri & abs(ddata(i)-ddata(i+1))>cri &
abs(ddata(i)-ddata(i+1))<=cri;
            ddata(i)=(ddata(i-1)+ddata(i+1))/2;
    end;
end;
end;
i=1;
while i<dlen-5;
    if abs(ddata(i+1)-ddata(i))>3*cri;
        spos=i;
        for epos=spos+1:spos+5;
            if abs(ddata(epos)-ddata(spos))<2*cri;
                break;
            end;
        end;
        if epos<spos+5;
            for k=spos+1:epos-1;
                ddata(k)=(ddata(spos)+ddata(epos))/2;
            end;
            i=epos;
        end;
    end;
    i=i+1;
end;
% processing ddata using moving average
%mvdata=ddata;
%for i=10:dlen-10;
%    mvdata(i)=mean(ddata(i-8:i+8));
%end;
%ddata=mvdata;
%ddata=rdDisFilter(ddata,order,normpf,tag);
fltdata=filtfilt(b,a,ddata);
for i=1:dlen;
    if ddata(i)==0 & fltdata(i)<=cri/10;
        fltdata(i)=0;
    end;
    if (fltdata(i)<0)
        fltdata(i)=0;
    end;
end;
ddata=fltdata;
for i=1:dlen;
    if ddata(i)<cri/10;
        ddata(i)=0;
    end;
end;
```

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