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AN INVESTIGATION OF THE PASSIVE CONTROL OF AIR POLLUTION IN THE URBAN ENVIRONMENT



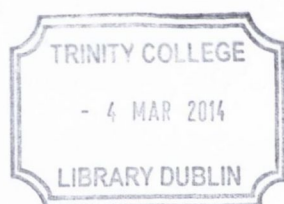
A Thesis submitted for the Degree of Doctor of Philosophy in Engineering to the
University of Dublin, Trinity College

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JULY 2013

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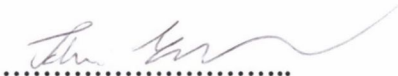


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JOHN GALLAGHER

EXECUTIVE SUMMARY

Poor air quality is a universal problem in built-up environments and presents a continued threat to the health of urban populations. Vehicle emissions have been identified as the predominant source of urban air pollution. This research aims to investigate controls which engineer the natural air flow patterns in urban street canyons. The control of air pollutants between a vehicle source and human receptor is carried out through the introduction of passive controls, such as low boundary walls or parked cars, and reduces personal pollutant exposure by increasing dispersion at street level in an urban canyon.

This thesis describes three investigations; two generic modelling studies and a real world case study, to determine the potential of these passive controls in urban street canyons. The computational fluid dynamic (CFD) software FLUENT was adopted to simulate these street canyons and evaluate the effects of passive controls on pollutant dispersion within an urban environment.

The first of the modelling investigations assessed the potential of parked cars as an effective passive control in street canyons. Four parking configurations were investigated under different meteorological conditions: parallel, perpendicular, diagonal and central parking. Parallel parking provided the most comprehensive parking layout, with improvements in air quality of between 31% and 49% on both footpaths for all varying wind conditions. These parking configurations assumed full parking bays in all model scenarios and therefore the influence of different parking occupancy rates was examined. The results displayed clear incremental improvements in air quality with increased fractions of parallel parked cars in the parking bays, with evidence of deteriorations in air quality on the footpaths for low occupancy rates of up to 45% in parallel wind conditions. The assessment of hybrid parking layouts (based on selecting the best percentage reduction in pollutant concentrations on each separate footpath) did not demonstrate enhanced improvement of air quality on the footpaths, but rather the hybrid parking layouts counteracted one another by altering the air flow patterns in the street. However, reducing the width of the parking bays did improve air quality on the footpaths. The study considered how a common feature of street

canyons i.e. parked cars, can be engineered to optimise air quality conditions on the adjacent footpaths under specific geometric and meteorological conditions.

The asymmetry modelling study examined the effects of street geometry for a previously investigated passive control i.e. low boundary walls (LBWs). The study showed the potential of LBWs as an effective passive control and enhanced the understanding of their influence on air flow and pollutant dispersion in a range of asymmetric street canyons. Asymmetric canyons are more realistic to a typical urban street canyon environment, so the findings of this investigation aimed to enhance the ability to select the most suitable location and type of passive control to improve air quality at street level. The study considered two LBW configurations; two footpath LBWs located on the outer edge of both footpaths and a single central LBW between the traffic lanes. The two sets of models displayed two distinct air flow patterns: the footpath LBWs created a single primary vortex with two small secondary vortices in the footpath regions, with the central LBW creating two primary vortices in the canyon. The results demonstrated potential improvements and deteriorations in air quality at street level in varying geometry and meteorological conditions. The study enhanced the understanding of the interaction of air flow with LBWs acting as passive controls in asymmetric canyons.

The real world application of the findings from the generic modelling investigations was carried out as part of the Pearse Street study. Pearse Street in Dublin city centre represented an ideal location to assess the impact of passive controls for improving air quality on the footpaths in the street. Data were collected from various sources for the construction and calibration of the Pearse Street model to determine the potential of introducing parked cars and/or LBWs in the street. The data collected included street geometry, local and background meteorological conditions, local air quality measurements and traffic data. A CFD model was constructed and calibrated to local wind conditions. The pollutant emissions were simulated in the canyon model and a semi-empirical equation was adopted in addition to the simulation output to take into account several parameters which simplified the conditions in the previous generic modelling studies. These parameters included variable lane distribution, fleet composition and vehicular turbulence. This allowed for the accurate calibration of the Pearse Street model and the subsequent assessment of the parked cars and the LBW as

effective passive control in the street under different traffic conditions. The results of the investigation displayed a good agreement with the findings of the generic investigations. It also demonstrated the potential applicability of the results from the generic studies to real case street canyon scenarios such as Pearse Street.

The studies provided evidence that passive controls influence air flow patterns in street canyons and can improve air quality at street level under different geometrical and meteorological conditions. There is potential for implementing passive controls in urban canyons, in particular as parked cars are a common element in many urban streets, the research can guide design optimisation for a parking layout. The cumulative findings from the three investigations set passive controls in a more favourable context for their implementation in future urban planning strategies.

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(Dr.) John G

1. INTRODUCTION

1.1 THE PROBLEM – URBAN AIR POLLUTION

Rapid economic and industrial expansion over the past century has led to a near exponential rate of increase in demand for energy; to heat and light our homes, provide a high quality transport infrastructure and power our businesses and public services. Moreover, people in developed countries have become dependent on having these amenities at their fingertips. This energy dependency has occurred in conjunction with continued increases in global and urban populations. With energy conversion, whether in the form of power generation for electricity or transport, fossil fuels are being consumed at a faster rate than ever before in history (Geng et al., 2008). The residue of burning fossil fuels in combustion engines has led to increased air pollutants being emitted into the atmosphere.

Transport emissions in particular, have contributed to high concentrations of air pollutants in urban centres and their surrounding regions. In Ireland, and indeed globally, cities have expanded steadily in the past century to become hubs for economic, infrastructural and population growth. Urban expansion is projected to continue, suggesting that air pollution is set to continue to be a negative impact on urban inhabitants. Thus, it will remain as an inherent problem due to its association with detrimental health and environmental effects. Future urban development strategies need to prioritise green technology and improved public transport as well as investigate potential solutions to the long term problem that is air pollution.

1.2 THOSE AT RISK - URBAN INHABITANTS

Urban inhabitants are at continuous risk of exposure to pollutants in the urban environment. As part of their daily routine, urban inhabitants are exposed to high concentrations of air pollutants compared to their rural counterparts. Traffic volumes in urban areas create volumes of air pollutants and high concentrations in street canyons can coincide with high pedestrian numbers on adjacent footpaths. Studies have shown that pollution concentrations at street level may be at least two times higher than concentrations at roof level (Johansson et al., 2009b). In some street canyons, which Solazzo et al. (2009) defined as a street flanked on both sides by buildings, a human receptor can be as little as one or two metres from a vehicular

emissions source. This close proximity to pollutant sources for urban inhabitants further emphasises the risk to human health associated with any duration of personal pollutant exposure. Therefore, the objective of this investigation is to investigate methods of protecting human health and improving air quality on the footpaths by introducing alternative air pollution control methods.

1.3 A POTENTIAL SOLUTION - PASSIVE CONTROLS

Passive controls are a relatively new concept in terms of addressing personal pollutant exposure on footpaths (McNabola, 2010). The passive control of air pollution in urban street canyons aims to engineer natural air flow patterns, thus increasing local dispersion and reducing pollutant concentrations on the footpaths. Previous investigations have identified low boundary walls (LBWs) and avenue trees as passive controls in urban street canyons (Gromke & Ruck, 2007; McNabola et al., 2009; McNabola, 2010; Buccolieri et al., 2011). This study aims to further investigate the potential of passive controls by (i) investigating a new passive control in the form of parked cars, (ii) extending the current knowledge on the efficiency of LBWs and (iii) carrying out a detailed real world assessment of passive controls at a city centre location in Dublin, to evaluate previous and current research. The results from the studies could be beneficial to urban planners for the future direction of urban planning strategies and street canyon design.

1.4 PROJECT AIM & OBJECTIVES

The overall aim of this research study was to investigate novel methods of passively controlling air pollution in urban street canyons, with a specific focus on engineering air flow patterns to reduce pollutant concentrations and improve air quality at street level. To meet this project aim, a number of objectives were considered which could the depth of knowledge in the area of air pollution controls. These objectives included (i) investigating a new and novel form of passive controls i.e. parked cars, and their influence of air flow and pollutant dispersion in the urban environment, (ii) gain a better understanding of the relationship between canyon geometry and passive controls to allow for their broader application of passive controls in urban street canyons, (iii) use CFD modelling as a technique to investigate passive controls in generic and real world conditions, and consider innovative methods of mesh

discretization to optimise model running times and (iv) develop a calibrated model of a real world urban street canyon to determine the potential of passive controls in a more complex environment and relate these findings to the other generic modelling studies.

1.5 THESIS LAYOUT

CHAPTER 2 – LITERATURE REVIEW

The literature review in Chapter 2 aims to establish a background to the research question, identifying the problem, research to date in this area, identify the tools required to investigate this problem and pinpoint areas where further research is required on the topic of passive controls. These topics include; the history of air pollution with a discussion of pollutant sources and their effects on human health: methods of controlling pollution by reducing the intensity and quantity of emissions and controlling pollutant pathways; different forms of passive controls as an engineered method of increasing pollutant dispersion, addressing areas which have been investigated; an introduction to Computational Fluid Dynamics (CFD) as a numerical method of simulating urban canyon environments to investigate passive controls; identify the limitations in the field of passive control research and propose a scope for further studies to fill in the gaps in knowledge to assess the true potential of these passive controls.

CHAPTER 3 – METHODOLOGY

Chapter 3 discusses the steps associated with the CFD modelling procedure. The modelling processes are best described under three distinct stages: pre-processing, solving and post-processing of each modelling investigation. The pre-processing section takes into account the model construction and meshing in *GAMBIT*, and defining model properties and simulation criteria in *FLUENT*; the solving section discusses the optimisation of model running times through model initialisation and parallel processing; and the post-processing stage includes a discussion of the effective methods of data extraction from the modelling studies, assessment of convergence criteria results, data analysis and the visualisation of results.

CHAPTERS 4-6 – PASSIVE CONTROL MODELLING INVESTIGATIONS

These chapters assess the effects of passive controls in street canyons, extending the current knowledge in the area of passive controls. The study in Chapter 4 investigates the influence of a new form of passive control i.e. parked cars and assesses the effects of these on air flow and pollutant dispersion on the footpaths. Chapter 5 extends the current modelling knowledge of LBWs as effective passive controls by simulating the implementation of the boundary walls in asymmetric canyons. Chapter 6 investigates the results from a calibrated case study model of a street canyon in Dublin city centre (Pearse Street) to assess the introduction of passive controls in a real canyon environment. The Pearse Street model includes both parked cars and LBWs as passive controls and suggests their potential in a real world street canyon.

CHAPTERS 7-8 – DISCUSSIONS & CONCLUSIONS

Finally, Chapters 7 and 8 discuss the research findings from the three investigative chapters to summarise the overall potential of passive controls in urban street canyons. The chapters examine the practical implications of this research for urban planners and identify its potential as a passive solution to improve air quality on the footpaths, and outlines areas for further research.

2. LITERATURE REVIEW

2.1 AIR POLLUTION

2.1.1 HISTORY OF AIR POLLUTION

Air pollution has existed since before historical records began, and from the first forest fire, to the decay of the first animal or piece of vegetation, this has shaped an ever-changing environment through the evolution of the planet. Throughout history, air pollution has been considered as more of an inconvenience than a problem. In ancient Athens and Rome, citizens complained about the negative effects of air pollution on human health (Mosley, 2012). Over the centuries (Figure 2.1), coal became a cheaper substitute for wood and this combined with significant population growth caused a substantial increase in demand and pollutant emissions.



FIGURE 2.1. IMAGES DEMONSTRATING THE HISTORY OF AIR POLLUTION.

As time passed, air quality became a visible problem and increased the number of complaints about smoke emissions. The view that these emissions were harmful led to the introduction of a coal ban in London and other cities in the 20th century, yet previous short-lived bans have dated back to as far as the 14th century. The introduction of this ban was rather due to the taste, odour and visual staining of buildings in the city and any link to poor health was not yet evident (Vallero, 2008).

The first health acts were instigated in the 19th century (Vallero, 2008). Despite the attempted bans on coal, coal was still burned up until the early to mid-20th century. However, the 18th century industrial revolution instigated the inherent dependency on fossil fuels through steam energy and this magnified air pollution emissions. Once again in London, in 1952, the '*Great Smog*' trapped fog and pollutants and led to the deaths of approximately 4000 people (Ministry of Health, 1954). This finally led to the Clean Air Act in 1956, which aimed to control the growing problem of urban pollution and protect human health. Protecting human health became a priority and regulations now became a control mechanism of air pollution.

A rapid evolution of our energy resources and exponential increases in our energy demands has occurred over the latter half of the 20th century (De Nevers, 2000). In addition, air pollution has come to the forefront of world affairs as industrialised nations have committed to reduce their contribution to greenhouse gas emissions by means of the Kyoto Protocol (UN, 1998). The introduction of new greener technologies has therefore aimed at improving air quality by providing cleaner and more efficient methods of extracting energy from fossil fuels. The underlying aim of reducing air pollution is to reverse the global warming effect and improve quality of life. Meanwhile, further research is required for implementing alternative methods of controlling air pollution, which can reduce personal pollutant exposure and lead to individuals living longer and healthier lives.

2.1.2 AIR POLLUTION

The wide range of airborne emissions created from the incomplete combustion of burning solid fuels is a direct source of air pollution (Smith, 1993; Morawska et al., 2008). As air pollution is linked to the release of organic inorganic materials and chemicals into the atmosphere, they can therefore threaten the welfare of both humans and the environment (Hicks, 2003). The current dependence on fossil fuels indicates that air pollution cannot be prevented, due to the backbone of most economies depending on their fossil fuel driven infrastructure (Geng et al., 2008). Therefore, air pollution poses a risk to human health and reducing personal exposure is the best solution as there is no associated safe level of air pollution (Barry, 2010). Subsequent sections of this literature review will discuss methods of reducing pollutant concentrations with a specific focus on their effects on urban air quality.

2.1.2.1 URBAN AIR POLLUTION

A number of studies have identified the health risks associated with pollutant exposure on urban inhabitants (Jennings et al., 2006; Johansson et al., 2009b; Zamboni et al., 2009). Urban centres have concentrated populations and this has associated high energy requirements. The negative impact of using fossil fuels to supply this high demand is the increased pollution of urban air (Smith, 1993; Fenger, 1999; Jennings et al., 2006). As urban morphology plays such a key role in the dispersion of air pollutants, air quality in the urban environment can be significantly higher than in a rural area (Xie et al., 2005; Zhou & Levy, 2008). This is due to reduced ventilation in street canyons with tall buildings flanking the street, preventing air exchange between road and roof level (Chan et al., 2001; Vardoulakis et al., 2003).

The projected expansion of global populations and urban cities indicates a continuation of current patterns of urban population growth (Fenger, 1999; United Nations, 2009). The UN's (2009) *World Urbanisation Prospects – The 2009 Revision* predicts an increase of the world urban population to 6.3 billion by 2050, almost doubling the number of urban dwellers from 2009 figures of 3.4 billion people. This rate of population growth highlights a likely increase in energy demands and associated pollution in these urban areas, which will cause increased health risks for urban dwellers (Geng et al., 2008). Therefore, an assessment of the sources of urban pollution is required to understand where passive controls can be implemented in the urban environment.

2.1.3 VEHICLE EMISSIONS SOURCES

Transport emissions are one of the largest sources of air pollution in Ireland (O'Mahony et al., 2000) and it is globally considered as the biggest contributor to poor air quality in urban cities (Wehner et al., 2002; Vardoulakis et al., 2003; McNabola, 2010). Vehicular emissions comprise a combination of air pollutants including: particulate matter (PM_{2.5} & PM₁₀), sulphur oxide (SO₂), carbon compounds (CO and CO₂), combined nitrogen oxides (NO_x) and other pollutants highlighted in the subsequent sections (EPA, 2012a). Background air quality monitoring in Ireland has shown that ambient air pollution concentrations have reduced over the past several years (EPA, 2013). The EPA (2013) annual report entitled *Ireland Greenhouse Gas*

Emissions for 2009 presents the total emissions across all sectors in 2009, which showed a reduction in the emissions concentrations in individual sectors and a reduction in total cumulative emissions from 2008. Unlike other urban centres across the globe, Irish cities have a low urban population density with few high-rise buildings, which is considered as a primary cause of the reduction of urban air exchange and quality (So et al., 2005; Kumar et al., 2008).

The development and introduction of new efficient technologies in engine design has led to cleaner vehicles, thus reducing air pollution (Zamboni et al., 2009). The latest EPA (2012a) report concurs with these findings, as technological improvements (e.g. catalytic converter and hybrid engine) are offset by increased vehicle numbers on Irish roads. In the US, a study by Baldauf et al. (2009) noted that significant reductions of pollutant concentrations were recorded since 1970, yet an increase in vehicle use has counteracted the positive effect of emissions reduction on urban dwellers. McNabola (2010) states that numerous pollution regulatory approaches in recent years have led to initiatives such as carbon based vehicle tax to promote cleaner vehicles in Ireland. The ranges of values are related to the level of development of individual infrastructures, as less developed countries utilise increased quantities of raw fossil fuels for heating and cooking (Smith, 1993). Table 2.1 displays the progression of percentage pollutants associated with vehicle emissions since the introduction of the 1990 National Emission Ceiling (NEC) limits to more recent figures associated with transport sector emissions.

TABLE 2.1. PERCENTAGE OF AIR POLLUTANTS GENERATED FROM VEHICLE EMISSIONS.

Pollutant	Greenpeace ^a	EPA ^b	EP ^c	UK AQ ^d
(%)	1992	1999	2000	2001
PM	77	10	28	24
NO _x	75	34	36	50
CO	97	51		73
VOCs	53		15	24

^a The Environmental Impact of the Car: A Greenpeace Report (Greenpeace, 1992)

^b Online E-zine Article [Accessed January 2011] (Karsemeyer, 2008)

^c European Parliament Fact Sheets (EP, 2001)

^d Air Pollution Emissions in the UK (www.air-quality.org.uk)

This has been driven by the European emission standards for vehicles (Defra, 2001a; EP, 2007), which aims to reduce emissions and this downward trend is identifiable from Figure 2.2.

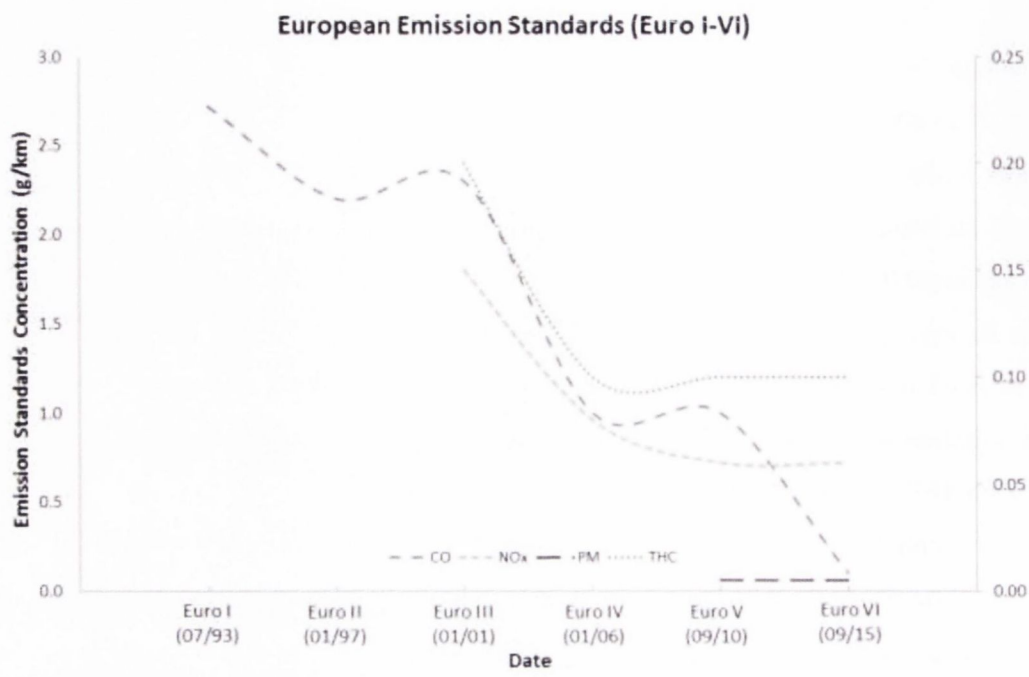


FIGURE 2.2. TRENDS FOR EUROPEAN EMISSION STANDARDS (EURO I-VI).

Measures to reduce air pollution from vehicle emissions have been implemented, but it remains a challenge for government bodies as there is no level of personal pollutant exposure that is deemed to have no detrimental effects on human health (Pope et al., 2009). In Ireland, achieving the Kyoto agreement targets poses the same issues as other developed countries, with emissions from the transport sector currently being 156% higher than 1990 baseline concentrations (EPA, 2013). This equates to 21.1% of the contribution for total emissions. The EPA (2013) report shows pollutant concentrations have reduced since 2007 due to the economic downturn in conjunction with improvements in public transport and more efficient vehicles. Numerous studies have shown that any level of air pollution is inevitably linked to a decline in human health (Palmgren et al., 1999; Pope et al., 2009), suggesting a zero tolerance of air pollutants is the only ideal solution to protecting the urban dweller. Therefore, a need for the implementation of additional controls to improve urban air quality would be beneficial within future urban planning strategies. This would further reduce pollutant concentrations on urban footpaths and minimise the risks to human health.

2.1.4 AIR POLLUTANTS

Air pollutants are primarily generated from a variety of practices that involve the combustion of fossil fuel to supply energy to support the residential, transport,

industry and commerce sectors. The latest EPA, (2013) report on greenhouse gas emissions in Ireland categorises these sectors in addition to agriculture and waste as the combined sources of carbon emissions for the country. The air pollutants generated from energy conversion can have different effects on human health, depending on the exposure rate and duration (Moller et al., 2008; Giuliano et al., 2009). Studies have indicated that meteorological conditions can also influence the formation of different types of primary and secondary pollutants, thus each country requires an independent analysis for air pollutant composition (Jennings et al., 2006; Morawska et al., 2008). This section aims to highlight individual air pollutants which can cause health problems, particularly in urban environments. Vehicular pollutants contribute part of the total emissions for most pollutants investigated within this section, with the focus of source pollution with respect to an urban context. Table 2.2 summarises the health effects of some of the most common anthropogenic pollutants.

TABLE 2.2. EFFECTS OF POLLUTANTS ON HUMAN AND ENVIRONMENTAL HEALTH.

Pollutant	Effects on Immune System and the Environment ^{a,b}	
PM	Respiratory	• PM irritates the lungs and air pathways
	Cardiovascular	• Penetrates tissue and absorbed into bloodstream • Linked to acute myocardial infarctions
CO/CO₂	Cardiovascular	• CO + haemoglobin = <i>Carbon Monoxide Poisoning</i> • Increase of CO₂ emissions = greenhouse effect
PAHs	Carcinogenic	• Benzo(a)pyrene and others are known carcinogens • Prenatal exposure linked to adverse birth outcomes
NO_x	Respiratory	• Cellular damage of the lungs • Vehicle combustion common source => acid rain
Ozone	Respiratory	• Respiratory illness, asthmas, bronchitis
	Cardiopulmonary	• Heart attacks
SO₂	Respiratory	• Susceptible to infections by penetrating the lungs • Acid Rain
VOCs	Respiratory	• Benzene exposure associated with tumours and cancer • Methane contributes to greenhouse emissions
	Cardiovascular	
	Carcinogenic	
Heavy Metals	Respiratory	• Acts similarly to PM by penetrating lungs
	Carcinogenic	• Generated from wear of vehicle parts

^a (EPA, 2012a)

^b (Barry, 2010)

2.1.5 HEALTH EFFECTS TO URBAN POPULATIONS

Annually, it is estimated that two million premature deaths worldwide can be connected to air pollutant exposure (WHO, 2006). The health effects of vehicular pollutant exposure can differ for each individual depending on such factors as age (Sichletidis et al., 2005), current health (McMichael, 2000; Mishra, 2002; Moller et al., 2008) and occupation (Palli et al., 2008; Karakatsani et al., 2010), which is typically related to their social and economic status (Smith, 2002; Pope et al., 2009). Personal pollutant exposure is also affected by the pollutant concentration and the duration of exposure, as they both significantly influence the health impact on an individual (Mishra, 2002; Moller et al., 2008; Giuliano et al., 2009). The presence of multiple pollutants from vehicular sources magnifies the detrimental effects on the human respiratory and cardiovascular systems. The health effects of personal exposure is further enhanced by the occurrence of traffic jams at peak travel times which increases emissions and personal exposure for urban inhabitants (Buczynska et al., 2009). From the perspective of vehicle pollutant exposure, Wehner et al. (2002) states that the distribution of particulates is related to the distance from the road, but varies based on local meteorological conditions and aerosol dynamic processes. This highlights the benefits of increasing the distance between the vehicle emissions source and human receptor on the footpath or within adjacent buildings to reducing personal exposure (Zhao et al., 2004). Another study justified the context of the previous findings, as higher pollutant concentrations were measured adjacent to a congested traffic lane as opposed to a free moving lane of traffic (O'Donoghue et al., 2007).

On urban footpaths, pedestrians are exposed to high concentrations of vehicular emissions, due to the close proximity to the pollutant source. Those working or living in urban buildings are also exposed to similar concentrations of vehicular pollution, which penetrates their residences and places of work through openings and ventilation systems. Urban inhabitants and commuters have limited control over the extent of their personal pollutant exposure from vehicular pollution as it widely varies based on changing meteorological conditions. In Dublin, pedestrians account for approximately 22% of all daily commuters (DTO, 2010), in addition to other urban commuters and residents who are exposed to pollution on a daily basis. In London, a smaller figure of 8.2% of the daily commuters are pedestrians, yet this figure omits the large number of

people that also live in the city and walk to work or school on a daily basis (Kaur et al., 2005). Further afield, a study by Zhao et al. (2004) comments that pedestrians in Ghangzhou, China account for up to 42% of the commuter population. The human immune and respiratory systems are sensitive to all common vehicular sourced pollutants, which can cause acute or chronic health problems (Jennings et al., 2006; Pope et al., 2009). Numerous studies have been carried out to monitor and analyse the exposure concentrations of air pollutants by pedestrians in urban areas (O'Donoghue et al., 2007; Buzzard et al., 2009; Westerdahl et al., 2009). The monitoring investigation carried out by O'Donoghue (2007) in Dublin, Ireland showed that pedestrian commuters and cyclists were exposed to lower pollutant concentrations compared to bus passengers, yet the increased breathing rate of cyclists meant they inhaled a larger fraction of pollutants. The exposure of bus passengers to higher hydrocarbon concentrations than cyclists was due to slow moving traffic and congestion in comparison to the further displacement of the cyclist in the street. The study highlighted the fact that traffic congestion common to peak pedestrian commuter times, led to higher pollutant concentrations across the canyon flow than at times of free flowing traffic (Kaur et al., 2007; O'Donoghue et al., 2007).

2.1.6 CONTROLLING AIR POLLUTION

To protect urban populations from air pollution, there are three clear options available: (i) controlling the quantity of pollution (g), (ii) controlling the emission intensity (g/km) and (iii) controlling source-receptor pathways (g/m³). Each control mechanism provides its own benefits with respect to improving air quality in the urban environment. Implementing new government policy and legislation is fundamental to the continued success of current and proposed air pollution control strategies (Roumboutsos & Kapros, 2008). The following subsections outline some of the solutions that have been implemented as methods of improving air quality in the urban environment.

2.1.6.1 CONTROLLING POLLUTION QUANTITY

The most effective method of reducing pollution is to control the quantity (g) of air pollutants created. As discussed in the introduction section of the literature review, the ban on coal burning has been a significant influence in improving urban air quality

(Vallero, 2008; Barry, 2010). In more recent years, the introduction of the smoking ban has led to improvements in air quality by reducing the quantity of pollution (McNabola et al., 2006; McNabola et al., 2012). Government legislation has led to the control of pollution quantities with the introduction of these bans, yet the further control of pollution has been encouraged through the introduction of the European IPPC (Integrated Pollution Prevention and Control) directive (EPA, 2012b). This directive aims to control emissions by encouraging a reduction in wasted energy resources.

From a transport perspective, the introduction of congestion charges has been a recent development in some countries to promote this change from private to public transport (Atkinson et al., 2009; Johansson et al., 2009a; Liu et al., 2009). In Sweden, the introduction of the congestion tax caused a reduction of 10% pollution concentrations and a 15% reduction of vehicles numbers (Johansson et al., 2009a). However, in the UK the improvements in air quality were negligible at the roadside monitoring stations, yet some reductions were noted at background sites (Atkinson et al., 2009; Kelly et al., 2011).

A reduction of vehicle numbers on our roads is the simplest solution to improving air quality (Brady & O'Mahony, 2011; De Nazelle et al., 2011). The reduction of private vehicles requires improved public transport services and a simultaneous shift of use by private vehicle owners to use these services or green transport alternatives such as cycling (Unwin, 1995; Briggs et al., 2008; Thøgersen, 2009; De Nazelle et al., 2011). However, a study by Thøgersen (2009) noted that private vehicle owners are habitual and changing their travel mode habits is the biggest challenge of promoting public transport. Therefore, public transport policy requires to focus on finding innovative ways of promoting public transport (Parkhurst, 2004; Sohail et al., 2006), while simultaneously creating a sustainable public transport network (Sohail et al., 2006; Roumboutsos & Kapros, 2008; Walker, 2008; National Transport Authority, 2010).

The promotion of public and green transport as sustainable forms of travel can impact the quantity of pollutants emitted and reduce emissions (Unwin, 1995; Thøgersen, 2009). Improved public transport has been carried out through continuous improvements to services, discounted travel and easy pay methods across different

public service providers. In addition, new policies have also targeted methods of reducing emissions rates through encouraging the use of greener transport (Muradov & Veziroglu, 2008; Brady & O'Mahony, 2011). Therefore, ensuring public and private transport vehicles have better fuel efficiency rates can reduce emissions (Hu et al., 2012), which has been accelerated in recent years compared to historical trends (Sivak & Tsimhoni, 2009).

2.1.6.2 CONTROLLING EMISSIONS INTENSITY

Controlling the intensity of pollutant emissions (g/km) is another useful method of improving air quality. As vehicular emissions will remain an on-going air pollution problem for the foreseeable future, constructing more efficient, green vehicles (Parkhurst, 2004; Sivak & Tsimhoni, 2009; Brady & O'Mahony, 2011) and better mechanisms to capture emissions (Fenger, 1999; Maricq et al., 2002) has become common practice in recent years.

The introduction of carbon taxes has targeted controlling emissions intensities as they are based on engine size, which is relative to emissions intensity (Giblin & McNabola, 2009; Attard & Ison, 2010; Galinato & Yoder, 2010; Fu & Kelly, 2012). Galinato & Yoder (2010) determined that carbon taxes are an effective method of mitigating greenhouse gas emissions. Investigations by Giblin & McNabola (2009) and Fu & Kelly (2012) considered adjusting costs of vehicle registration tax (VRT) and both studies found reductions in CO₂ emissions intensity of up to 3.8%. The tax would promote users to purchase more efficient vehicles with smaller engines. In addition to the associated emissions reductions, Giblin & McNabola (2009) monetised the introduction of the carbon tax as a reduction of €191 million in tax revenue. Attard & Ison (2010) reviewed an alternative fixed annual charge, such as VAT, with a time-based road user charge and concluded that more research is needed for both systems.

Vehicle technology is a direct method of reducing emissions intensity (De Nevers, 2000; Santos & Costa, 2008; Zhang et al., 2011a). The development of catalytic converters has provided one such method of reducing pollutant emissions from vehicles since the 1970's (Farrauto & Heck, 1999; Kašpar et al., 2003). Catalytic converter technology in vehicles controls emissions by converting some fuel

combustion by-products (CO, NO₂ and Hydrocarbons) to a less harmful state (CO₂, N₂ and water) (MECA, 2012). Zhang et al. (2011a) highlighted how improvements in vehicle specifications, regular maintenance and driver behaviour can control the intensity of vehicle emissions. A study by Retting et al. (2003) further suggested that vehicle speed and driver behaviour is a significant influence on the fraction of pollutant emissions created by vehicles. Also, with regards to the improvements in vehicle technology, the promotion of public transport to reduce the quantity of pollutant emissions can also be enhanced with the implementation of new technology in public transport (Parkhurst, 2004).

2.1.6.3 CONTROLLING POLLUTANT PATHWAYS

In the case of vehicle emissions and pedestrians, the pathways between the pollutant source and human receptor can be relatively direct. It can typically be related to the distance between the source and receptor in addition to the processes and reactions that take place as the pollutants are transported through the air. Therefore, a reduction in the pollutant concentration (g/m³) that an individual is exposed to can be controlled from gaining an understanding of the transport pathways between the source and receptor.

Each pollutant behaves in a different manner in the atmosphere and therefore distinct processes exist for each pollutant (De Nevers, 2000). For vehicle emissions, an understanding of the processes which take place in a street canyon environment between the source and receptor can be of benefit in the development of pathway controls. These processes can include one or a combination of dispersion, deposition and photochemical reactions and can depend on local atmospheric conditions (Vallero, 2008).

Increasing the distance between the source and receptor is directly proportional to a reduction in personal exposure (Zhao et al., 2004; Kaur et al., 2005; King et al., 2009). Retting et al. (2003) found that the separation of pedestrian and vehicles reduces accidents, yet this can also reduce personal pollutant exposure, benefitting their quality of life. More effort is needed to segregate vehicles and pedestrians and promote walking through the development of green routes e.g. pedestrianised streets

(Briggs et al., 2008). However, as personal exposure is a function of exposure time and the pollutant concentration, increasing pedestrian's journey times by walking along pedestrianised routes may not be a practical solution. Therefore, it can require extensive planning and consideration as a shift of vehicular traffic may occur to another area, which may in itself create more problems. Therefore, the segregation of pedestrians and traffic is not always a feasible option to reduce personal pollutant exposure in the urban environment.

Methods of controlling air pollution can enhance air quality in the urban environment, yet these controls are a secondary solution to directly reducing emissions from the pollutant source. De Nevers (2000) stated that traditionally, improving dispersion to lower pollutant concentrations was the most used process to improve air quality by government authorities. This concept in conjunction with reducing the quantity and intensity of pollutant emissions can further enhance the range of methods to improve air quality in the urban environment. The passive control of air pollution can provide such a solution to improve air quality conditions for urban populations and these solutions are discussed in the following section.

2.2 PASSIVE CONTROLS

In the continually expanding urban environment, reducing urban pollution and protecting urban inhabitants is an important aspect of sustainable development. Reducing vehicular emissions (Muradov & Veziroglu, 2008; Zamboni et al., 2009), congestion charging (Atkinson et al., 2009; Johansson et al., 2009a) and the segregation of human and vehicular traffic (Barry, 2010) provide control measures to improving conditions or protecting pedestrians from vehicular pollution. Significant urban planning is required to investigate and introduce these strategies. The introduction of passive controls provides an alternative method to improve urban air quality. The use of these controls in an urban environment aims to reduce the pollutant concentration in an urban canyon by reducing the local pollutant concentration by increasing natural dispersion. A passive control provides a method of reducing personal exposure to high pollutant concentrations by increasing local dispersion and the recirculation of air through the canyon to protect the pedestrian (McNabola et al., 2009; McNabola, 2010).

2.2.1 PASSIVE CONTROL APPLICATIONS

Several passive controls methods have been investigated by researchers across the globe, with the common interest of increasing local dispersion within the urban environment and minimising personal pollutant exposure (McNabola, 2010). These controls range from low boundary walls (McNabola et al., 2009), avenues trees or vegetation (Heath et al., 1999; Gromke et al., 2008), noise barriers (Baldauf et al., 2008; Finn et al., 2010) and pedestrian ventilation systems (Mirzaei & Haghighat, 2010b). The research to date for each passive control will be evaluated in this section, and areas will be identified for further studies to be carried out as part of this research thesis. Passive control studies were carried out by numerical modelling (McNabola et al., 2009), wind tunnel experimentation (Gromke et al., 2008; Buccolieri et al., 2009) and/or real time air quality monitoring (Finn et al., 2010).

2.2.1.1 LOW BOUNDARY WALL

A low boundary wall (LBW) can influence the air flow within an urban street canyon thus altering the amount of dilution of local pollutants (McNabola, 2010). McNabola et al. (2008b) describe the effect of a LBW at street level as that of a baffle plate, as it re-circulates the air flow in a canyon, by diverting pollutants in the road away from the pedestrian on the footpath. Previous LBW investigations have combined air quality sampling with numerical modelling to determine the difference in pollutant concentration upon the introduction of a boundary wall between an urban canyon and a newly constructed river boardwalk in Dublin (McNabola et al., 2008a; King et al., 2009), as shown in Figure 2.3.



FIGURE 2.3. RIVER LIFFEY BOARDWALK IN DUBLIN, IRELAND (KING ET AL., 2009).

The road adjacent to the boardwalk consisted of three lanes of one-directional traffic (McNabola et al., 2008a) with an average 2000 vehicles per hour (King et al., 2009). The boardwalk extends along and overhangs a stretch of the River Liffey and acts as an additional footpath and seating area along the Dublin quays. King et al. (2009) found that a reduction in the pollutant concentration occurred for pedestrians walking on the boardwalk instead of the footpath, as the boundary wall acted as a baffle to increase dispersion. The study also identified the benefit of segregating human and vehicular traffic on either side of the LBW, thus increasing the distance between the pollutant source and the human receptor (King et al., 2009).

A study by McNabola et al. (2008a) carried out an air sampling investigation to determine the reductions in pollutant concentrations by comparing the pollutants inhaled by an individual on the roadway footpath against an individual on the boardwalk. The results indicated a reduction of between 43% and 65% for pollutant exposure between the footpath and boardwalk (McNabola et al., 2008a). The study further examined the boardwalk using numerical modelling to determine the relationship between vehicular emissions and personal pollutant exposure for different wind speeds and directions. McNabola et al. (2008a) found that emissions travelled away from the boardwalk in wind conditions perpendicular to the street and moving traffic (Figure 2.4).

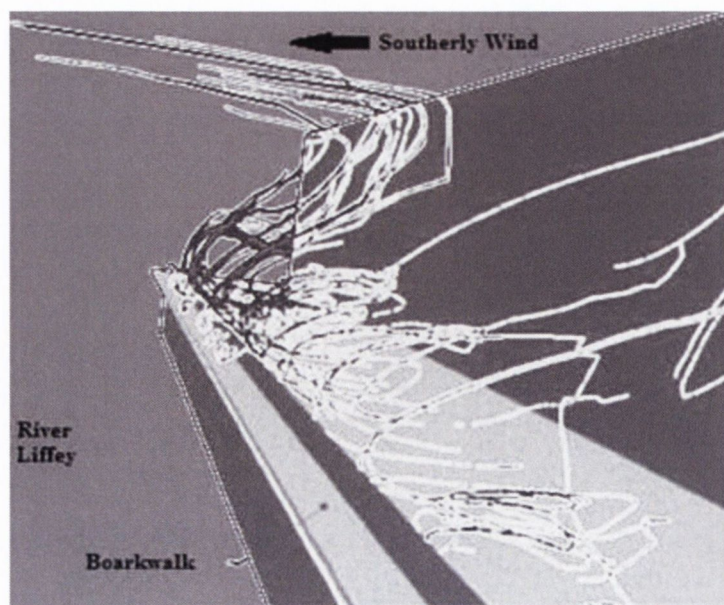


FIGURE 2.4. TRAFFIC EMISSIONS TRANSPORT AWAY FROM BOARDWALK IN PERPENDICULAR WIND CONDITIONS (MCNABOLA ET AL., 2008A).

The dispersion of pollutant concentrations were channelled along the street in wind conditions parallel to the street and moving traffic. The results identified that pollutant concentrations are reduced along the boardwalk in both perpendicular and parallel wind conditions due to the presence of the LBW.

A further investigation by McNabola et al. (2009), found that reductions in personal pollutant exposure of 70% and 40% for parallel and perpendicular wind conditions, respectively, were found from the numerical modelling of a generic urban canyon. The study analysed two LBW configurations: a configuration of two walls on the outer edge of both footpaths (Figure 2.5(a)) and one configuration of one central wall along the middle of the canyon (Figure 2.5(b)) in a canyon with a Height to Width (H/W) ratio of 1.

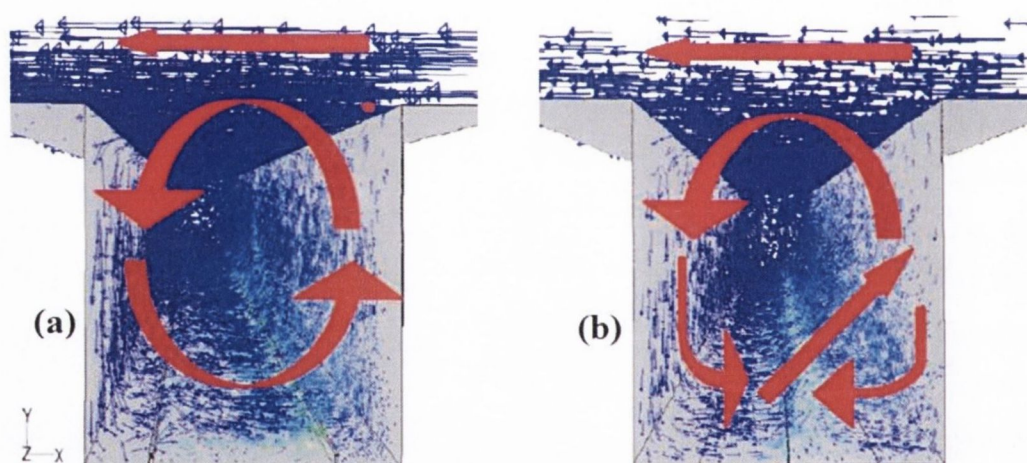


FIGURE 2.5. AIR FLOW PATTERNS IN STREET CANYON WITH (A) 2 FOOTPATH LBWS AND (B) 1 CENTRAL LBW CONFIGURATION IN PERPENDICULAR WIND CONDITIONS.

The two adjacent walls provided the best results for protection of the urban populations in parallel wind conditions, with reductions ranging from 41 to 65%. This was due to the baffle effect of the LBWs, as they channel the pollutants along the street, reducing the penetration of pollutants onto the footpaths (McNabola et al., 2009). A decrease in pollutant concentration occurred on the leeward footpath for perpendicular wind conditions, as the LBW traps pollutants between the buildings and wall. The central boundary wall provided the largest reduction during perpendicular wind conditions as the resulting vortices generated in the canyon altered the air flow to transport pollutants away from both footpaths. Pollutant reductions ranged from 6% to 31% for the central boundary wall on both footpaths (McNabola et al., 2009).

Further numerical analysis was carried out to evaluate the effect of a 0.75 H/W ratio as most urban canyons do not tend to be symmetrical in design. The observations showed that the H/W ratio and wind conditions primarily influence the air flow and dispersion patterns in a canyon with or without LBWs (McNabola et al., 2009). LBWs are one plausible form of a passive control that have the potential of increasing local dispersion in a canyon (McNabola, 2010). However, further extensive research is required to determine the effects of varying canyon geometry, wind conditions and mechanical dispersion from moving vehicles with the use of LBWs as a potential passive control in future urban planning strategies. The series of research investigations described within this thesis aims to extend the current findings with regards to the effects of these factors.

2.2.1.2 TREES AND VEGETATION

The introduction of urban green infrastructure can be beneficial to air quality in street canyons (Pugh et al., 2012), as footpath design is considered to be a contributing factor to localised turbulence and pollutant dispersion (Jicha et al., 2000). The investigation of the aerodynamic effects of trees and vegetation in urban canyons (Gromke & Ruck, 2007; Buccolieri et al., 2009; Ottel   et al., 2010) is a relatively new concept as a passive control. Previous research had determined that the rate of passive cooling in urban canyons is effected by planted trees, as trees provide shade and thus affecting the rate of solar radiation reaching the canyon floor (Shashua-Bar & Hoffman, 2003). The study found that more than 25% of urban areas are defined as streets and that the street layout influences the air temperature, wind flow and humidity in an urban environment.

The abilities of wooded areas (Heath et al., 1999), climber vegetation (Ottel   et al., 2010) and roof greening (Fehon & Peters, 2010) have been assessed to determine the potential for vegetation to increase pollutant deposition and reduce pollutant concentrations in the urban environment. Wooded shelterbelts influence the rate of deposition of heavy metals in roadside environments (Heath et al., 1999) and these benefits can be adapted to urban areas to reduce the predominant influence of wind direction on atmospheric pollutant deposition. As building features create a roughness factor along building surfaces and these roughness parameters affect air flow

properties (Blocken et al., 2007), climber vegetation also alters air flow in the region of building surfaces. The climber vegetation study found that the vegetation influences deposition of finer particles more than coarse particles and Ottelé et al. (2010) also identified that the deposition rate is dependent on the variety of vegetation and local meteorological conditions. Climber vegetation provided increased PM deposition of fine and ultrafine particles on the leaves of the vegetation. In addition, the vegetation was considered to be aesthetically pleasing (Figure 2.6) as vertical greening on building facades (Ottelé et al., 2010; Pugh et al., 2012).



FIGURE 2.6. VARIETY OF CLIMBER VEGETATION IN URBAN ENVIRONMENTS.

Urban greening in the context of placing vegetation on roofs has also come to the forefront of recent research into improving urban air quality (McNabola et al.; Fehon & Peters, 2010). Fehon & Peters (2010) found that roof greening improved the urban thermal environment, which led to improved air quality near the road and a reduction in measured pollutant concentrations. However, the degree of improvement was noted to be dependent on the wind direction. A study by compared the influence of roof greening on an urban site and rural background site and noted additional reductions in particulate concentrations for both sites.

Planted avenue trees have been the focus of a series of research papers in the past few years as they can act as a passive control to manipulate air flow on both footpaths in a canyon (Gromke & Ruck, 2007; Gromke et al., 2008; Buccolieri et al., 2009). Gromke & Ruck (2007) assessed the effects of avenue trees on pollutant dispersion and established that broad tree spacing was crucial to ensure adequate ventilation within a canyon. The study identified the effects of tree height, crown volume and distances between tree crown and buildings in urban canyon locations to allow the flow of clean air through the canyon. Further investigations found that varying tree crown porosities did not affect the air flow or concentration, as the tree crowns acted as impermeable volumes (Gromke et al., 2008; Buccolieri et al., 2009). This information is useful in terms of the selection of the tree variety as the changing rate of porosity for different trees can occur throughout the seasons. The avenue trees research combined wind tunnel experimentation (Figure 2.7(a)) with numerical modelling (Figure 2.7(b)) to determine the distribution of pollutant concentrations across the canyon floor (Gromke et al., 2008; Buccolieri et al., 2009).

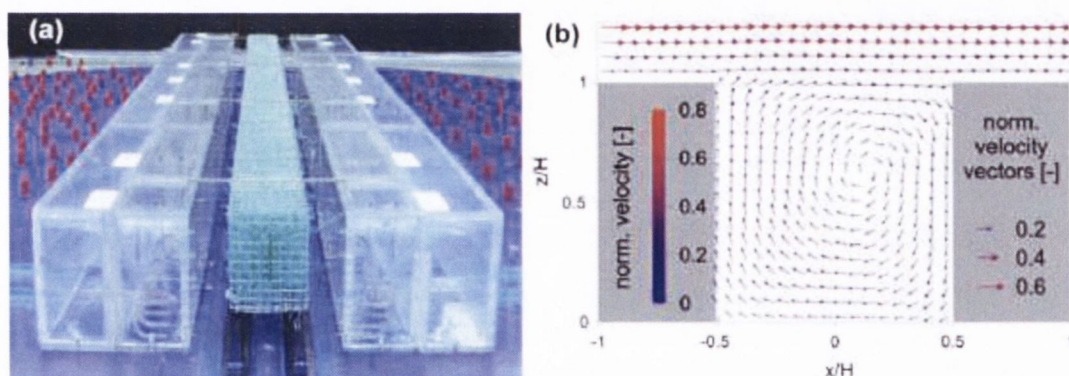


FIGURE 2.7. (A) WIND TUNNEL MODEL AND (B) CFD CANYON MODEL (GROMKE ET AL., 2008).

Buccolieri et al. (2009) observed that tree planting in symmetrical urban canyons (Figure 2.8) affected pollutant concentrations at street levels in canyons of differing H/W ratios. A reduction in pollutant concentrations was attained at street level for a wide canyon with a 0.5 H/W ratio, as the planted trees increased dispersion. Conflicting results were found for a canyon with a 1.0 H/W ratio, which identified an increase in pollutant concentration at street level as ventilation and dispersion rates were significantly reduced due to the loss of interaction of air flow and ventilation across the top of the canyon (Buccolieri et al., 2009). The results of the study found that the H/W ratio has a significant influence on air pollutant dispersion as it affects

the air flow in street canyons with avenue trees. It also identified the suitability of planted trees in wide canyons to improve local dispersion and reduce pollutant concentrations at ground level.



FIGURE 2.8. A SELECTION OF IMAGES OF AVENUE STYLE TREES IN URBAN CANYONS.

Gromke (2011b) furthered the investigation of planted trees in urban canyons by analysing the aerodynamic effects of urban vegetation in street canyons. The findings revealed that the vegetation is a highly complex and flexible porous medium which makes it susceptible to adjusting its shape based on the constantly varying local wind conditions. This analysis was taken into account in further research of the aerodynamic effect of trees at street junctions by Buccolieri et al. (2011) in which a more complex study was carried out of PM_{10} in preference to previous studies using SF_6 as a tracer gas. It assessed the effects of particulate deposition and re-suspension, and allowed for chemical reactions to occur with other pollutants. The study identified the importance of including vegetation in urban canyon models, as their exclusion can lead to prediction errors of modelling results.

The results of the studies on avenue trees have combined wind tunnel experimentation with the modern method of assessment in numerical modelling, which has become a useful tool in urban passive control assessment for avenue trees. A study by Salim et al. (2011a) has assessed the accuracy of numerical modelling to determine the capabilities of the k-epsilon Reynolds-averaged Navier-Stokes (RANS) and the Large Eddy Simulation (LES) models compared to wind tunnel experiments. The study found that the LES model more accurately imitates the wind tunnel air flow compared to the RANS model.

An investigation by Pugh et al. (2012) suggested that the introduction of urban greening requires case-by-case analysis as it is greatly influenced by canyon geometry and local meteorological conditions. This analysis ensures that urban greening initiatives has a positive impact and does not negatively impact urban air quality.

2.2.1.3 NOISE BARRIERS

Noise barriers are commonly placed on major carriageways to reduce noise pollution from vehicles reaching housing estates in urban commuter belt regions. Several studies have reviewed the effect of roadside noise barriers to determine their effect on local pollutant dispersion (Bowker et al., 2007; Baldauf et al., 2008; Finn et al., 2010; Ning et al., 2010). Finn et al. (2010) carried out a tracer study on a temporary noise barrier, shown in Figure 2.9, to measure the dispersion of the tracer pollutant around the barrier.



FIGURE 2.9. STRAW STACK CONSTRUCTED AS A ROADSIDE NOISE BARRIER (FINN ET AL., 2010).

The results identified that the barrier acted similarly to a LBW in some wind conditions, as the barrier trapped pollutants near the roadway in low wind conditions. This improved air quality by in excess of 50% in the deficit zone of the noise barrier.

Hagler et al. (2011) assessed the effect of barrier height on the pollutant concentration on both sides of the road in perpendicular wind conditions. The results found that increasing the barrier height from $0.5H$ to $3.0H$ led to a reduction in pollutant concentration of 15-61% at a location 20m from the road (Hagler et al., 2011). Another recent investigation of the impacts of noise barriers on PM distribution near urban carriageways, determined that these walls act as a pollutant dispersion mechanism (Ning et al., 2010). The study showed that PM concentrations are proportional to the distance from the source and that the introduction of a barrier generates a recirculation of air on the roadside of the wall. The results show a reduction in pollutant concentration of 45-50% in the deficit zone (Figure 2.10), similar to that found by Finn et al. (2010).

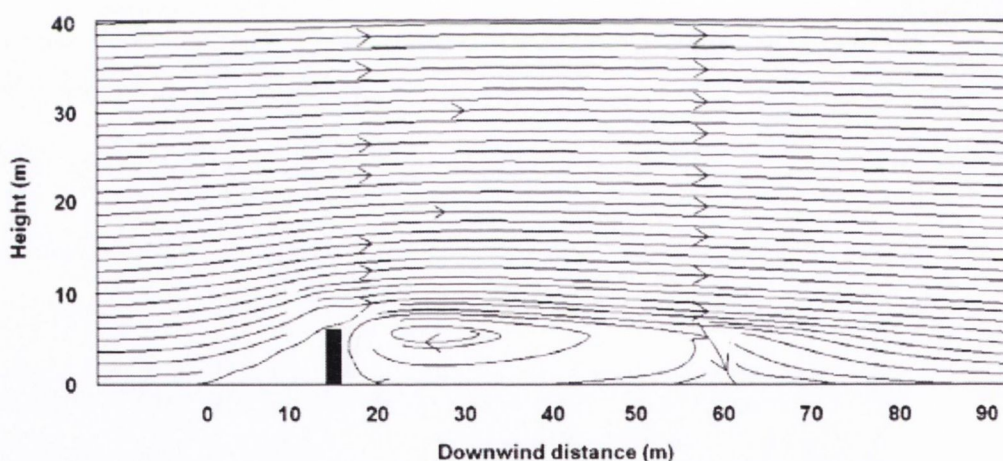


FIGURE 2.10. ELEVATION VIEW OF AIR FLOW AROUND A NOISE BARRIER (BOWKER ET AL., 2007).

Other studies have assessed the combined effect of roadside effects and trees along carriageways (Bowker et al., 2007; Baldauf et al., 2008). This combination of passive controls further improves the capabilities of reducing pollutant concentrations. Baldauf et al. (2008) found that the noise barrier blocked initial dispersion and increased local turbulence and trees provided additional mixing and increased dispersion. Overall, increased vertical mixing was observed by the noise barrier studies to reduce pollutant concentrations at ground level. A noise barrier provides a

similar function to an LBW in an urban street canyon. However, along a carriageway, there is adequate scope to combine the benefits of the roadside barrier and vegetation to further improve local dispersion and promote the settlement of pollutants. Noise barriers have been shown to trap pollutants on the roadside of the wall, increasing the pollutant concentration for vehicle drivers and passengers (Finn et al., 2010; Hagler et al., 2011). Further investigations are therefore required to assess the effects on vehicle passengers, in addition to the effect of vehicular turbulence and omitted obstacles to air flow on the potential of noise barriers as a passive control.

2.2.1.4 PEDESTRIAN VENTILATION SYSTEMS

The Pedestrian Ventilation System (PVS) is another concept that has been devised to provide cleaner air at street level within high-rise urban canyons (Mirzaei & Haghighat, 2010b; 2011). The PVS can be adapted for current high-rise canyons and retrofitted to multi-storey buildings to improve air quality in polluted urban environments. The purpose of the PVS is to counteract the phenomenon that is known as the Urban Heat Island (UHI), which increases the temperature at street level from re-radiated solar heat in a street canyon (Kolokotroni et al., 2006; Rizwan et al., 2008). The canyon H/W ratio influences the effect of the UHI on the air exchange rate between roof and ground level, as increasing the H/W ratio inversely reduces the air exchange rate on the canyon floor (Mirzaei & Haghighat, 2010b). Tong et al. (2005) also stated that the geometric layout of an urban canyon influences the rate of the UHI effect in the street. Several studies have shown that high energy costs are associated with controlling indoor temperatures in urban canyon buildings, where the UHI exists on the canyon floor (Konopacki & Akbari, 2002; Akbari & Konopacki, 2005). Researchers have identified that planting vegetation within the canyon and reflective surfaces on the roofs of buildings reduce the UHI effect (Konopacki & Akbari, 2002; Rizwan et al., 2008).

The limitation of increasing dispersion within high-rise urban canyons requires additional processes to improve canyon floor air quality. Therefore, several studies by show the potential of the PVS to reduce the pollutant concentration at street level by inducing increased air flow to diminish the UHI effect (Mirzaei & Haghighat, 2010a; b; 2011). The PVS (Figure 2.11) consists of ventilation ducts which exchange clean

air from building roof level to the canyon floor. The ducts provide ventilation to the building canopy zones and urban footpaths with clean air from roof level to improve air quality conditions.

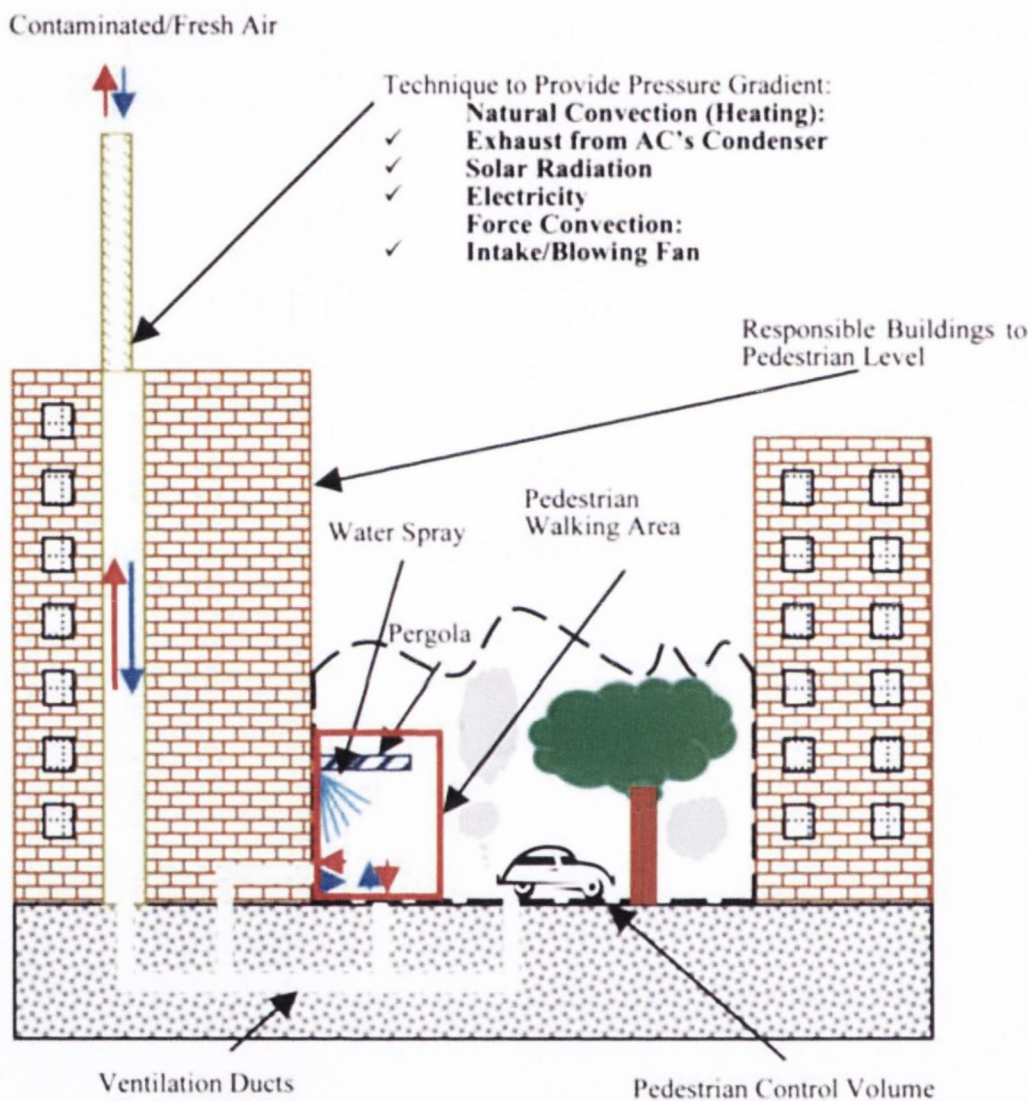


FIGURE 2.11. PEDESTRIAN VENTILATION SYSTEM LAYOUT (MIRZAEI & HAGHIGHAT, 2010B).

The PVS has the potential to be retrofitted in existing high-rise street canyons, yet detailed urban design is crucial for future urban planning of canyons and junctions to prevent the need for technologies such as PVS's (Soulhac et al., 2009). As the UHI is dependent on local seasonal temperatures and the urban city location and research has shown that the UHI is more predominant in summer (Kolokotroni et al., 2006), it is not known if the PVS would provide effective relief to personal pollutant exposure during winter months with cooler ground temperatures.

2.2.1.5 ROAD CUT AND FILL

Road design can have a significant effect on air flow and pollutant dispersion (Baldauf et al., 2009; Heist et al., 2009). Heist et al. (2009) states that road configurations play a significant role in influencing air flow, therefore pollutant dispersion is manipulated by a given road design. Baldauf et al. (2009) found that roadway cut and fill sections can alter air flow and affect pollutant dispersion. The study carried out a series of wind tunnel experiments of different shaped section of roads. The findings suggested that both elevated fill sections and cut sections increase turbulence and thus increase dispersion. The study also identified that roadside structures provided additional dispersion near the roads. Based on the findings of this investigation and other studies outlined in the previous passive control sections, a number of factors influence the potential of passive controls. Therefore, the following sections aim to discuss, in detail, the influencing factors of the effectiveness of passive controls on pollutant dispersion in an urban street canyon.

2.2.2 FACTORS INFLUENCING PASSIVE CONTROLS

The introduction of a passive control in an urban canyon requires detailed examination by means of numerical modelling and experimentation prior to implementation (Buccolieri et al., 2009; McNabola et al., 2009; Ning et al., 2010). A typical canyon can have poor air quality due to the restricted natural ventilation of the narrow street channel. The wind flow through the canyon provides a primary form of dispersion and the rate of dilution varies with direction and speed (Ghenu et al., 2008). Pollutant dispersion in an urban street is greatly influenced by the canyon geometry (Qin & Kot, 1993; Xie et al., 2005; Di Sabatino et al., 2008), vehicular mixing (Jicha et al., 2000; Solazzo et al., 2008) and changing meteorological conditions (Gualiteri & Tartaglia, 1997).

2.2.2.1 CANYON GEOMETRY

The geometry and orientation of an individual urban street canyon (Santiago & Martin, 2005), a series of urban canyons (Chang & Meroney, 2003; Xie et al., 2005) or a street junction (Wang & McNamara, 2007; Yassin et al., 2009) can significantly influence the dispersion pattern of pollutants at ground level (Crowther & Hassan, 2002). Therefore, the introduction of passive controls within a canyon should provide

additional dispersion in a street canyon environment. The dimensions of a canyon are specified in terms of the geometrical ratios, the arrangement of street junctions and the layout of nearby canyons and roof shapes (Jicha et al., 2000; Santiago & Martin, 2005; Di Sabatino et al., 2008; Yassin et al., 2009). The pollutant concentration in an urban canyon is proportional to the vertical dispersion of air in the canyon (Tsai & Chen, 2004; Prajapati et al., 2009), indicating that high-rise buildings can cause a deterioration of air quality within an urban canyon (So et al., 2005; Li et al., 2007).

CANYON H/W RATIO

The geometrical ratios of a street canyon significantly influence the flow patterns and dispersion of pollutant concentrations in an urban canyon (Oke, 1988; Qin & Kot, 1993; Jicha et al., 2000; Chan et al., 2001; Santiago & Martin, 2005). The asymmetrical geometry of the canyon, in terms of the H/W ratio plays a more significant role on dispersion and air flow patterns than any meteorological parameter (Hoydysh & Dabberdt, 1988; Di Sabatino et al., 2007). High pollutant concentrations commonly occur at street level in narrow canyons and are of concern to the health of pedestrian and vehicle passengers (Li et al., 2007; Tang & Wang, 2007; Salim et al., 2011a). Several studies found that the air flow and dispersion patterns in canyons with an increasing H/W ratio led to a higher pollutant concentration on the leeward (LW) side of the canyon compared to along the windward (WW) buildings in the canyon (Baker et al., 2004; Li et al., 2007). An investigation by Crowther & Hassan (2002) showed that the LW concentration increased for an increasing H/W ratio of up to 1.25, but a H/W ratio more than 1.25 led to a steady concentration along the LW side of the canyon at heights of 0.82 m and 2.64 m.

Oke (1988) identified three distinctive flow patterns in canyons of different H/W ratios: isolated roughness flow (IRF), wake interference flow (WIF) and skimming flow (SF) as shown in Figure 2.12. The IRF pattern occurs in canyons with a small H/W ratio (Figure 2.12(a)), as air enters the canyon over the LW buildings, sweeps downward on to the canyon floor and exits over the WW buildings. This pattern carries a fraction of pollutants out of the canyon. The remaining quantity of the pollutants is circulated within the secondary vortices at the corners of the canyon, with little interaction between the vortices (Oke, 1988; Chan et al., 2001).

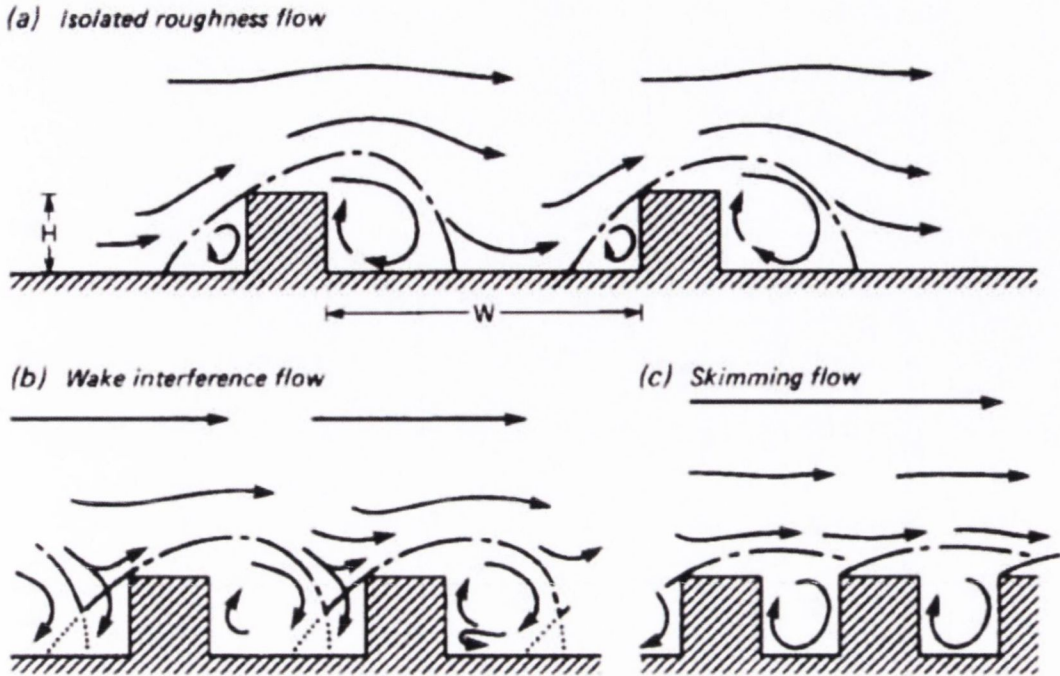


FIGURE 2.12. FLOW PATTERNS FOR CANYONS OF VARYING H/W RATIOS (A) ISOLATED ROUGHNESS FLOW, (B) WAKE INTERFERENCE FLOW AND (C) SKIMMING FLOW (OKE, 1988).

This flow pattern develops into a WIF (Figure 2.12(b)) as the H/W ratio increases and the transition of the secondary vortices shifts towards the centre of the canyon. This increases the level of turbulence and mixing, improving air quality and reducing the pollutant concentration within a street canyon. The combination of the separate vortices into a singular primary vortex in a deeper canyon with a higher H/W ratio, leads to the development of the SF pattern (Figure 2.12(c)). The fraction of clean air that is entrained within this canyon is significantly less than the previous building arrays, as pollutant concentrations require interaction between the air flow over the buildings and the eddy within the canyon, which circulates the pollutants in the canyon from the ground to roof level (Oke, 1988; Chan et al., 2001). The H/W ratio of a canyon plays an important role in terms of influencing buoyancy and inertia, which greatly influences the rate of dispersion of pollutants within a canyon. Therefore, the effectiveness of passive controls in a canyon is controlled by the given H/W ratio of a given street canyon.

The effect of the H/W ratio on the maximum pollutant concentration in the different flow patterns is identified by the plot in Figure 2.13 (Chan et al., 2001). The study established that the maximum pollutant concentrations varied for different H_1/H_2

canyon ratios. A study by Liu et al. (2005) found that optimum ventilation occurs in canyons with a lower H/W ratio, as the air exchange rate increases with a decreasing H/W ratio (Crowther & Hassan, 2002).

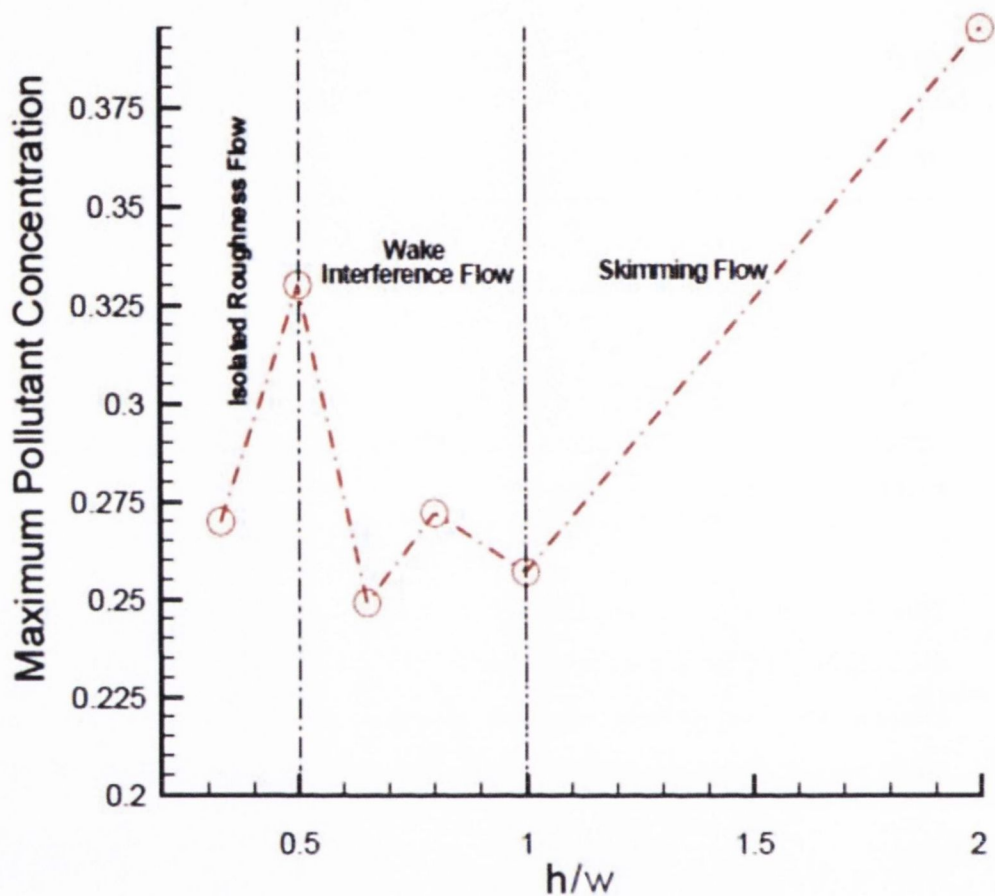


FIGURE 2.13. EFFECT OF FLOW PATTERNS ON POLLUTANT CONCENTRATIONS IN CANYONS OF VARYING H/W RATIOS (CHAN ET AL., 2001).

A modelling investigation by Santiago & Martin (2005) identified the formation of multiple vortices in canyons with larger H/W ratios, as a H/W ratios of 1.0, 2.0 and 4.0, led to the formation of a single, two and four anti-clockwise rotational vortices, respectively, in the asymmetrical street canyons. Another study similarly found the formation of a single vortex in a canyon with a 1.0 H/W ratio (Baker et al., 2004). The majority of past canyon geometry investigations have focused on symmetrical canyon cases. However, the focus of more recent investigations has been on asymmetrical street canyons, which represent more typical and realistic canyons in an urban environment (Prajapati et al., 2009).

CANYON ASYMMETRY

Canyon asymmetry is another geometrical parameter which influences the air flow and dispersion patterns within urban canyons. Canyon asymmetry is classified as the ratio between the leeward building (H_1) and windward building (H_2) heights i.e. H_1/H_2 ratio (So et al., 2005). Figure 2.14 shows plots of the pollutant concentrations within two canyons of different H_1/H_2 ratios.

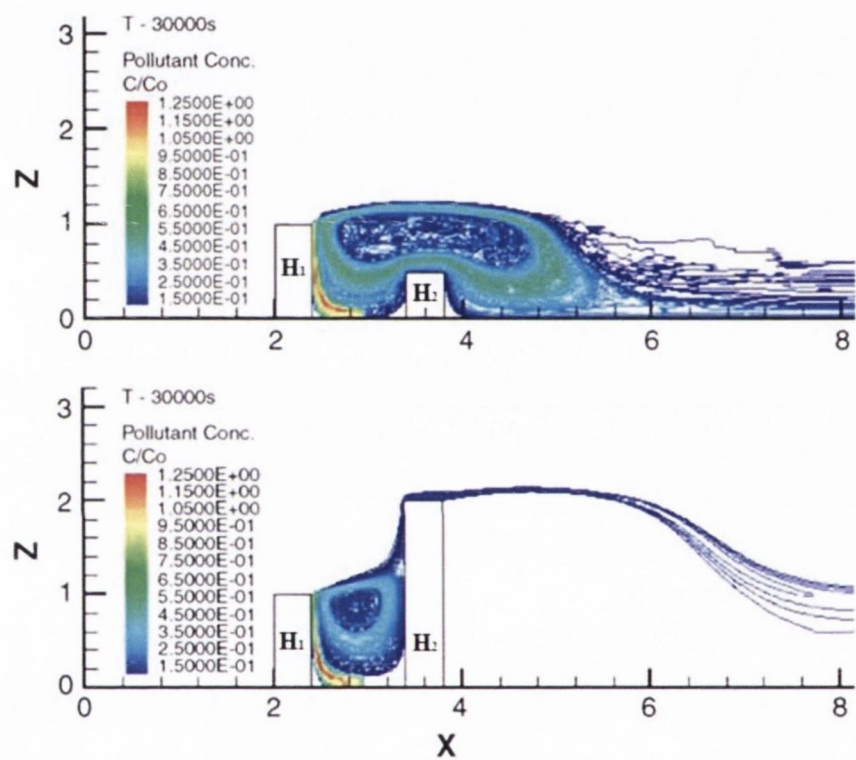


FIGURE 2.14. ASYMMETRIC MODELS WITH 0.5 & 1.5 H_1/H_2 RATIOS (SO ET AL., 2005).

Other literature refers to a difference in heights as a step-up ($H_1 < H_2$) or a step-down ($H_1 > H_2$) configuration, as a step-up layout categorises a canyon where H_2 is greater than H_1 and the opposite occurs for a step-down configuration (Hoydysh & Dabberdt, 1988). The study found that a step-up canyon configuration led to high pollutant concentrations in the centre of the canyon with the concentration along the LW buildings to be twice that along the WW buildings. In the step-down layout, the concentration along the WW buildings was greater than along the LW buildings. The study also identified that an increase of the H_1/H_2 ratio led to a higher overall pollutant concentration within the canyon, as the step-up ($H_1 < H_2$) configuration forces additional air from roof level into the canyon, which increases dispersion of

pollutants. Chan et al. (2001) identified a critical H_2/H_1 ratio of between 1.00 and 1.25 whereby pollutant concentrations reached a maximum in an urban canyon. The study concluded that building geometry influences pollutant dispersion characteristics due to the dependence on pollutant transport and air exchange between clean air at roof level and polluted air within the canyon.

CANYON JUNCTION GEOMETRY

Previous investigations identified that street junction configurations influence air dispersion in the canyon (Qin & Kot, 1993; Crowther & Hassan, 2002; Garbero et al., 2007; Wang & McNamara, 2007). Garbero et al. (2007) highlighted the effects of street intersections and squares on pollutant dispersion. Increased dispersion occurs around street junctions, as Crowther & Hassan (2002) identified lower pollutant concentrations at the ends of the street, depending on the layout of the intersection and the H/W ratio of the canyon. Other studies have identified that the highest pollutant concentrations occur around street junctions along the upwind face of the street and in the crosswind streets (Wang & McNamara, 2007; Yassin et al., 2009). Yassin et al. (2009) compared three canyon types; regular, T-shape and skew junction (Figure 2.15) with respect to the pollutant dispersion patterns in the canyons.

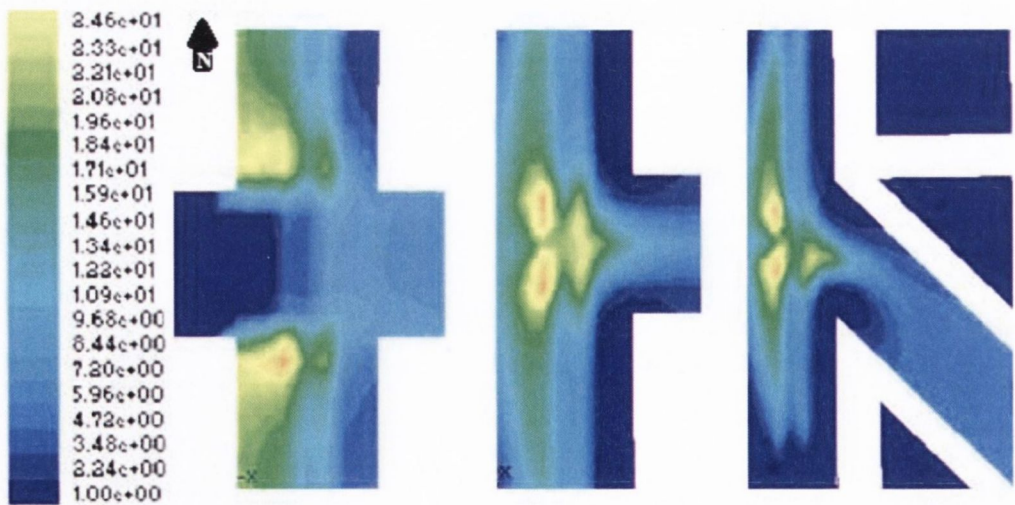


FIGURE 2.15. DISPERSION PATTERNS OF DIMENSIONLESS POLLUTANT CONCENTRATIONS IN DIFFERENT STREET CANYON LAYOUTS WITH NORTHERN WIND DIRECTION (YASSIN ET AL., 2009).

The results found that the regular shaped canyon had the highest pollutant concentrations compared to the other junction layouts (Yassin et al., 2009). Similarly, Wang and McNamara (2007) identified high concentrations in the regular junction

compared to the skewed junction, with the highest concentrations observed at ground level.

CANYON ROOF SHAPES

Several investigations have identified the influence of different roof shapes and geometry on air flow and pollutant dispersion in street canyons (Leitl & Meroney, 1997; Jicha et al., 2000; Chan et al., 2001; Xie et al., 2005; Yassin, 2011). Figure 2.16 illustrates the different air flow patterns observed within canyons with different roof shapes.

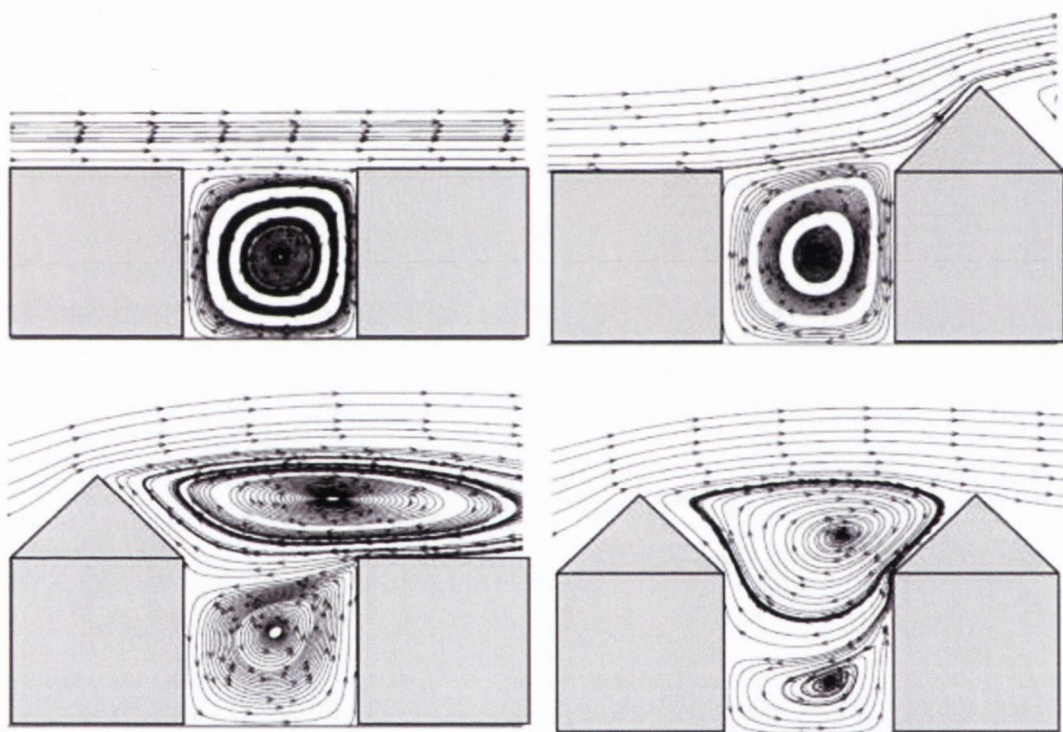


FIGURE 2.16. INFLUENCE OF DIFFERENT ROOF SHAPES ON STREAMLINES IN STREET CANYONS (XIE ET AL., 2005).

Studies investigating the air flow patterns with respect to different roof geometry shapes found that the roof shape alters the location of the primary vortex within the canyon (Leitl & Meroney, 1997; Xie et al., 2005). Leitl & Meroney (1997) carried out a modelling investigation of air flow patterns for different roof geometries with two and three-dimensional layouts. Both models identified the effect of roof geometry on air flow, yet the two-dimensional model omitted lateral velocity and reduced the overall accuracy of the model. Xie et al. (2005) determined that the roof shape can

affect the dynamics of the vortices created within the canyon and the pollutant concentration at street level. Non-uniform roof heights were noted to improve ventilation within a street canyon (Chan et al., 2001).

CANYON FACADES

Numerical modelling studies have simplified models to optimise computational requirements with accuracy of results. Franke et al. (2007) identified the modelling errors that occur in numerical models due to the simplification of surface complexities in urban canyons, such as balconies, eaves details, doorsteps and window and door cavities or outcrops. Another study highlighted the effect of building fronts and footpath design on air flow and pollutant dispersion in urban canyons (Jicha et al., 2000).

2.2.2.2 METEOROLOGY

Varying wind speed (Ghenu et al., 2008; Hu et al., 2009; Hu et al., 2011) and direction (Hoydysh & Dabberdt, 1988; Crowther & Hassan, 2002) are the predominant factors influencing dispersion and mixing of clean air at roof level and polluted air at canyon floor level. The introduction of passive control in street canyon models would alter the natural air flow patterns in a street canyon and thus has an effect of meteorological conditions. The rooftop wind speed is considered to be correlated to the rate of dispersion and pollutant concentration in the canyon (Hahn et al., 2009; Parra et al., 2010). The thermal properties of air in an urban canyon can also affect the dispersion pattern of pollutants (Santese et al., 2007; Huang et al., 2008). Modelling reactive pollutants shows that additional influences of solar radiation and thermal stratification play a role in pollutant dispersion in urban canyons (Gualiteri & Tartaglia, 1997; Mirzaei & Haghighat, 2010b).

WIND SPEED

The wind speed in an urban canyon influences the rate of dispersion and formation of vortices in a street canyon (Karim & Matsui, 1998; Karim et al., 1998; Moryń-Kucharczyk & Gnatowska, 2007; Ghenu et al., 2008; Hu et al., 2009). Hu et al. (2009) identified that the entrainment of CO between air at ground level and roof level is related to the wind speed. Several other studies found that the rate of dispersion is

dependent on wind speed (Karim & Matsui, 1998; Karim et al., 1998; Moryń-Kucharczyk & Gnatowska, 2007). The results of the investigation by Karim et al. (1998) indicated that the wind velocity is lower in a street canyon compared to roof level. The reduction in wind speed is considered to cause an increase in pollutant concentrations in the canyon. De Paul & Sheih (1986) found that the primary vortex in an urban canyon during perpendicular wind conditions faded in lower wind conditions (1.5 – 2.0 m/s), signifying the reduction of the vertical air flow on the leeward side of the building which carried polluted air out of the canyon. A study by So et al. (2005) determined that air flow in a canyon was dependent on the Reynolds (Re) number, as a turbulent flow was related to a large Re number of between 800 and 1600 and depended on the specific asymmetric canyon layout. Correlations between the Re number and wind speed were also evident in the urban canyon models.

WIND DIRECTION

Numerous investigations have identified the influence of the approaching wind direction on air flow and pollutant dispersion in urban canyons (Hoydysh & Dabberdt, 1988; Crowther & Hassan, 2002; Chang & Meroney, 2003; Ghenu et al., 2008; Hahn et al., 2009). Chang & Meroney (2003) carried out a combined numerical and wind tunnel investigation to assess the distribution of pollutant concentration in urban canyons. The study found that the canyon orientation and wind direction primarily effects pollutant dispersion in an urban environment. A measurement study by Hahn et al. (2009) of PM recorded the distribution and fluctuation patterns of the pollutant in an urban canyon. The findings from the investigation identified wind direction as an influential factor on pollutant dilution near the urban canyon(Hahn et al., 2009)(Hahn et al., 2009)(Hahn et al., 2009)(Hahn et al., 2009)(Hahn et al., 2009)(Hahn et al., 2009)(Hahn et al., 2009)(Hahn et al., 2009)(Hahn et al., 2009). In addition, the conclusions of a case study by Ghenu et al. (2008) showed that pollutant dispersion patterns change in canyons with varying wind directions.

Two more comprehensive investigations solely focused on the effects of wind direction on pollutant dispersion (Hoydysh & Dabberdt, 1988; Crowther & Hassan, 2002). Both investigations analysed the effects of wind direction by modelling an urban canyon with a range of different wind directions; from a parallel wind to the canyon to a perpendicular wind in 10° increments. Hoydysh & Dabberdt (1988) found

that wind direction is secondary to canyon asymmetry with respect to pollutant dispersion. Crowther & Hassan (2002) focused their investigation on the effect of modifying the wind direction on pollutant concentrations on the LW and WW sides of the canyon. Figure 2.17 displays the concentration profiles at different heights in the leeward and windward zones through a 90° rotation in wind conditions in 10 degree increments.

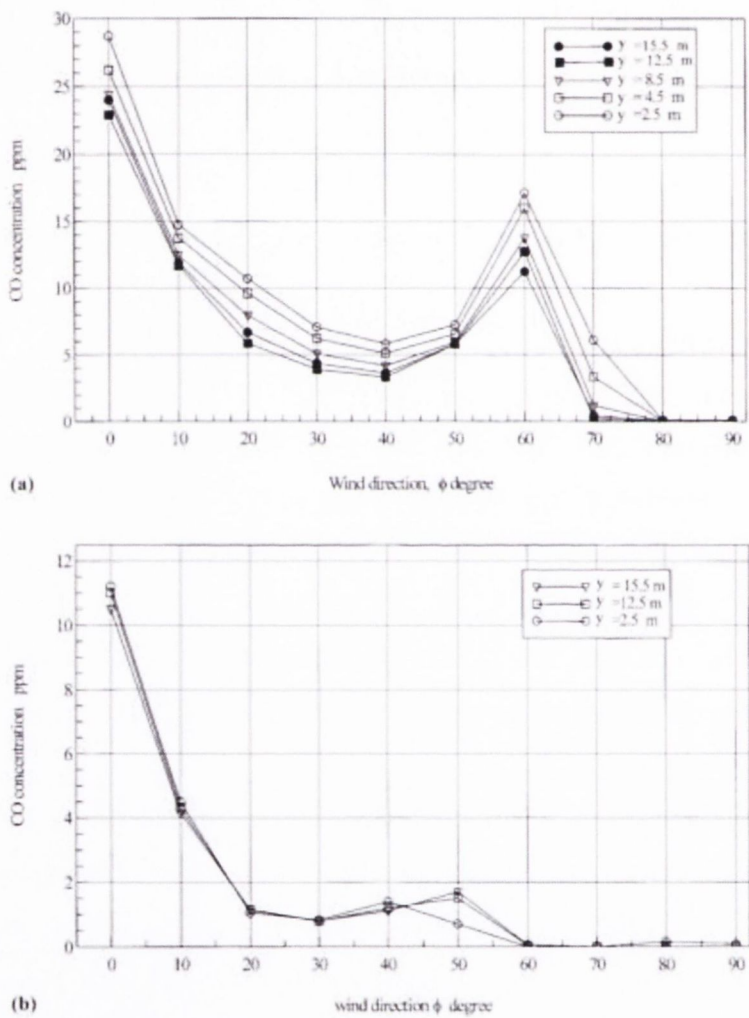


FIGURE 2.17. CO CONCENTRATION AT MID-BLOCK OF CANYON ALONG (A) LEEWARD FACE AND (B) WINDWARD FACE WITH RESPECT TO WIND DIRECTION (CROWTHER & HASSAN, 2002).

The study found that wind direction has a strong influence on the dispersion of pollutants in an urban canyon (Crowther & Hassan, 2002). Concentrations in the LW zone were higher than in the WW zone for most wind conditions. As the oncoming wind direction rotated, the wind became channelled by the canyon itself and the difference in pollutant concentrations were considerably reduced and was most

notable in parallel (90°) wind conditions. The unusual concentration in the leeward zone at 60° (Figure 2.17(a)) was due to the wind direction directing additional pollutants across the canyon and the deterioration of the primary vortex which existed in perpendicular conditions.

TEMPERATURE

A difference in temperature across an urban canyon is also considered to affect pollutant dispersion in addition to wind conditions (Oke, 1988; Jicha et al., 2000; Santese et al., 2007; Huang et al., 2008). Oke (1988) stated that in terms of urban planning, warmth and solar access can affect dispersion. The results of the study identified a difference in the angle of penetration of solar radiation throughout the year (Figure 2.18), which affects the thermal stability of air in the urban canyon. Thermal stratification is considered to either enhance or suppress ventilation, thus it can contribute to the rate of dispersion in an urban canyon (Jicha et al., 2000).

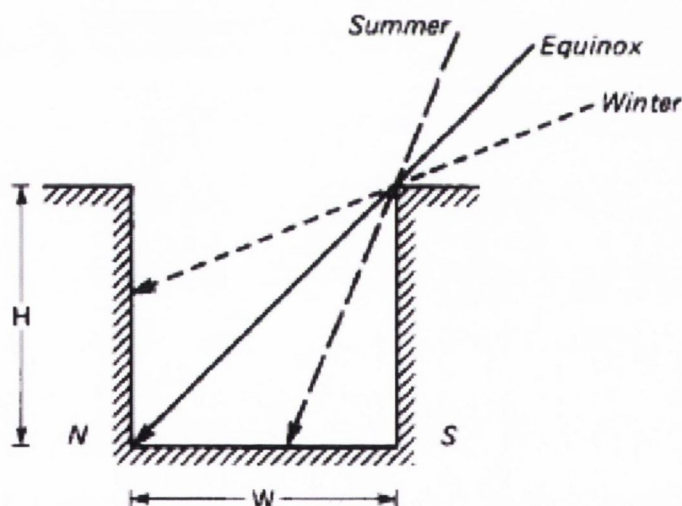


FIGURE 2.18. ANGLES OF INCIDENCE FOR SOLAR RADIATION IN DIFFERENT SEASONS (OKE, 1988).

A detailed study by Huang et al. (2008) found that the stable atmospheric conditions in winter led to higher pollutant concentrations at road level and reduced dispersion. The study compared pollutant concentrations in canyons with isothermal and non-isothermal conditions and found that concentrations were a fraction lower in non-isothermal conditions. It concluded that the difference in pollutant concentration was due to an increase in the buoyancy effect due to increased surface temperature in summer time. Another investigation assessed the effects of solar radiation on pollutant

dispersion in canyons of different H/W ratios (Santese et al., 2007). It found that solar radiation on the WW face was more significant than on the LW face or canyon floor. An increasing H/W ratio altered the buoyancy effect in the canyon as H/W ratios of 0.5 and 1.0 caused a decrease in pollutant concentration on the LW face from the canyon floor to the roof, with a constant value on the windward face. An increase of the H/W ratio to 2.0 showed the opposite effect on the canyon faces.

2.2.2.3 VEHICULAR TURBULENCE

The mechanical mixing of vehicles travelling through a canyon increases the amount of dispersion of pollutants (Jicha et al., 2000; Solazzo et al., 2008). Jicha et al. (2000) carried out a modelling study of different traffic conditions and found that each configuration of traffic flow independently affects pollutant dispersion. In another study, vehicular turbulence was shown to affect pollutant dispersion in low wind speeds, during high volumes of traffic and is dependent on the direction of traffic (Solazzo et al., 2008). Vehicular turbulence is most influential at ground level within the canyon (Qin & Kot, 1993; Karim & Matsui, 1998; Karim et al., 1998).

TRAFFIC CONGESTION

The free flowing or congested nature of traffic can influence the amount of vehicle induced turbulence in urban canyons (Qin & Kot, 1993; Tsai & Chen, 2004; Ning et al., 2005). Qin & Kot (1993) carried out a measurement study of different urban canyons in China and identified that vehicular movement dominates air flow at ground level and the pollutant concentration is correlated to the traffic flow. It found that an increase in the speed of moving vehicles leads to increased dispersion (Qin & Kot, 1993). A more recent measurement study by Tsai & Chen (2004) stated that the pollutant concentrations follow the rate of traffic flow in an urban canyon. A numerical study determined that slow moving and idle vehicles suppress vehicular mixing, reducing dispersion and increasing local pollutant concentration at street level in urban canyons (Ning et al., 2005). The study measured an exponential decrease of the pollutant concentration from the exhaust plume. Other research investigations have also shown that vehicular turbulence occurs in the wake of the vehicle (Pospisil et al., 2004), as a stream of vehicles suppresses the wake of an individual vehicle (Jicha et al., 2000).

TRAFFIC DIRECTIONAL FLOW

A series of numerical modelling investigations have been carried out to assess the role of vehicular traffic flow, in terms of its effect on pollutant dispersion in urban canyons (Jicha et al., 2000; Solazzo et al., 2008; Hu et al., 2009). Studies of traffic directional flow have stated that vehicular turbulence is most evident in calm wind conditions (Jicha et al., 2000; Solazzo et al., 2008). A study by Jicha et al. (2000) compared 1-way and 2-way directional traffic flows with respect to its effect on pollutant dispersion. The results identified that 1-way traffic has better ventilation across the canyon floor, which enhances the circulation of air in the canyon. Hu et al. (2007) determined that two crossing vehicles interfere with the natural air flow in an urban canyon, and Solazzo et al. (2008) found that 1-way traffic in urban canyons led to increased pollutant dispersion (Figure 2.19).

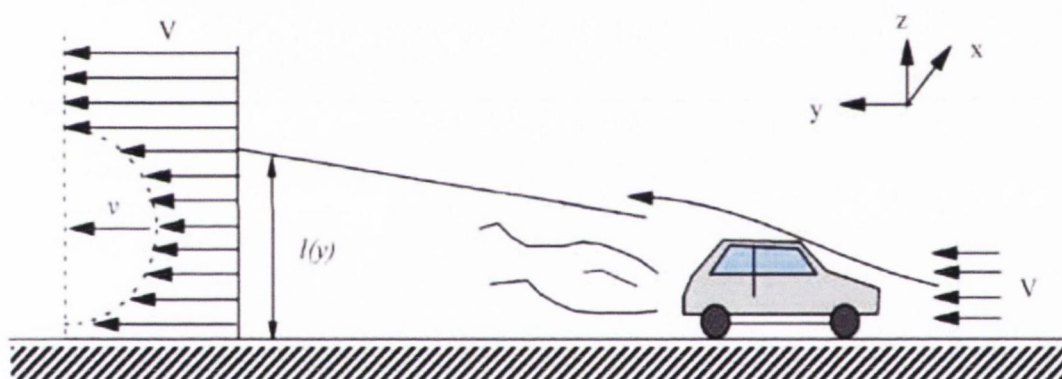


FIGURE 2.19. VELOCITY DEFICIT IN WAKE OF A MOVING VEHICLE (SOLAZZO ET AL., 2008).

VEHICULAR TURBULENCE EFFECTS

Numerous studies have closely investigated the effects of vehicular turbulence at ground level in urban canyons (Qin & Kot, 1993; Karim & Matsui, 1998; Karim et al., 1998). Several investigations have linked the vehicular turbulence to additional turbulent kinetic energy (tke) in the canyon (Pospisil et al., 2004; Solazzo et al., 2008; Liu, 2010; Fu et al., 2013). Solazzo et al. (2008) noted an increase in the tke value along the canyon floor for a model including moving vehicles. A linear relationship was recently identified between vehicle speed and tke (Fu et al., 2013). Another numerical modelling study examined vehicular exhaust dispersion in different moving traffic scenarios to determine differences in turbulent energy values (Liu, 2010). Pospisil et al. (2004) found that improved accuracy in the models occurred by including an additional source of tke to represent vehicular turbulence, which occurs

specifically in the wake of the vehicle. These modelling investigations are essential to investigate mechanical turbulence, which Qin & Kot (1993) identified as a dominating factor of ground level air flow in low wind speeds. Other studies found that the vehicular turbulence at ground level in street canyons increases the wind velocity along the canyon floor (Karim & Matsui, 1998; Karim et al., 1998).

2.2.3 IMPLEMENTING PASSIVE CONTROLS

The development of a passive control implementation strategy would be useful for urban planners to summarise comprehensive guidelines regarding passive control options and their suitability for different conditions. However, further analysis of passive controls are required to better understand the effects of passive controls in urban street canyons and a numerical modelling approach is to be adopted for this series of research investigation. A numerical modelling approach was considered to assess passive controls, therefore the methodology chapter deals with the selected modelling approach carried out in this thesis and its use to simulate air flow and pollutant dispersion in a street canyon environment.

2.3 CONCLUSIONS OF LITERATURE REVIEW

The literature examined and summarised in this review has determined that air quality is of major concern to both environmental and personal health. In particular, personal health in urban environments is the focus of this research thesis. To identify plausible solutions to poor urban air quality, firstly the predominant source of pollution in urban street canyons was identified i.e. vehicular emissions. Most pollutants emitted from vehicles are associated with various health problems and their exposure to this source of pollution puts the health of urban populations at risk. Therefore, reducing pollutant emissions and controlling personal exposure are two methods of reducing the direct risk to personal health. Air quality legislation and guidelines have been developed and introduced which has led to better public transport, more fuel efficient vehicles and green energy sources. The control of pollution between the source and receptor can enhance air quality. Passive controls fall under the control category of controlling urban air pollution and they aim to reduce pollutant concentrations by increasing dispersion. These passive controls can have many forms including barriers, urban

vegetation and ventilation systems, all of which require further research to assess their potential to improve air quality at street level of urban canyons.

2.3.1 FINDINGS OF LITERATURE REVIEW

The literature review examined the background of air pollution, specifically urban air pollution, and the mitigation procedures that have been already developed and initiated as part of pollution control measures. The review has identified further plausible solutions to the dilemma of air pollution and the associated detrimental risks to personal health. The findings of this review is summarised as follows:

- Urban dwellers are at-risk to air pollution, as poor ventilation combined with high concentrations of vehicle emissions leads to poor urban air quality at ground level in street canyons. The effects of vehicular pollutant emissions have negative impacts on the human body, specifically the respiratory and cardiovascular systems.
- A variety of mitigation strategies have been introduced to improve urban air quality, involving controlling the emissions quantity (g) and/or the emissions intensity (g/km). Some examples of these methods to reduce urban air pollution include introducing congestion charging, carbon emissions taxes, promoting public transport and greener transport solutions. In addition, the control of pollutant pathways (g/m^3) can provide another solution to improve air quality and reduce personal pollutant exposure. Increasing natural dispersion of pollutants or increasing the distance between the pollutant source and receptor e.g. pedestrianisation of streets can improve air quality for urban populations. Using methods of passively controlling air pollution can provide alternative methods of improving air quality, which can be initiated with minimal modifications to current urban street layouts.
- Passive controls can reduce pollutant concentrations in an urban environment to improve personal health and quality of life. Unlike previously stated mitigation controls of air pollution, a passive control requires only minor modifications to the current layout of urban canyons. A passive control requires the construction of a boundary wall within the street to modify the natural air flow and increase local dispersion to reduce pollution concentrations at street floor level.

- A range of passive control methods were reviewed in this chapter to determine their potential and identify the controlling parameters for pollutant reduction in the urban environment. The review identified a passive control of different forms: low boundary walls, trees and vegetation, noise barriers, pedestrian ventilation systems and road design criteria. Each passive control modified the natural air flow within urban canyons, which was found to be primarily influenced by canyon geometry and local metrological conditions. The review identified several shortcomings in passive controls due to the lack of research in the field, which have become a significant aspect within this research study.

3. METHODOLOGY

3.1 RESEARCH OVERVIEW

A numerical modelling approach has been selected as the primary tool to be used in the investigation of passive controls. This chapter will introduce computational fluid dynamics and address modelling techniques, the stages of the modelling process and methods to optimise model output and running times. From the findings of this chapter, a method of approach will be established for investigating passive controls.

3.1.1 RESEARCH STRATEGY

Prior to investigating the potential of passive controls, a series of complementary investigations were considered to further develop the depth of knowledge in this area. A selection of numerical modelling studies has been carried for passive controls over the past number of years. These studies have been evaluated through comparative investigations to wind tunnel models and real time measurement studies. The following studies were considered for this research thesis to (i) investigate a new form of passive control, (ii) extend the knowledge for the potential of an existing passive control and (iii) carry out a real world case study for passive controls in an urban street canyon. This was to be achieved with the following studies:

- On-street parked cars are a common element of street canyons and they influence the natural air flow in urban street canyons. A detailed assessment on the effects of parked cars in different parking configurations will determine the baffle wall effect of the cars on pollutant dispersion between the road and footpath. The study will examine the effects of parked cars on local dispersion in different wind speed and directions. In reality, however, full parking occupancy is not consistent within a street canyon, therefore an assessment of varying occupancy rates should be carried out to calculate the change of pollutant concentration on both footpaths in different parking occupancy rates. In addition, a selection of optimised parking scenarios will be investigated that could be also considered to improve current parking regimes.
- A detailed numerical modelling investigation of low boundary walls in different street canyon environments of varying geometrical design and wind conditions will expand the depth of knowledge on this form of a passive control. Previous studies have limited their research to symmetrical urban

canyons and therefore, canyon asymmetry should be examined, as this will take into account the effect of low boundary walls in a wider range of real case canyons. A comparison of two methods for simulating vehicular emissions would also determine the preferred emissions source model, comparing a surface source and line source model, and with or without a form of vehicular turbulence in each canyon model.

- A real case study is proposed for Pearse Street in Dublin, to combine the knowledge of the other proposed passive control investigations for parked cars and boundary walls in asymmetrical canyons. This combined monitoring and modelling study will merge the findings of the individual research studies in the thesis and adapt them to a real scenario. The study will also use monitoring data collected in the street to calibrate the model to real world conditions. The findings will determine the potential of passive controls in an urban canyon, to protect urban populations, by reducing pollutant concentrations on the footpath by increasing local dispersion.

From the findings of these three suggested studies in combination with the existing knowledge of passive control, a passive control implementation strategy can be developed. This could direct future urban planning strategies for the implementation of alternative passive controls to improve air quality in urban street canyons. Therefore, the results from these investigations should be developed upon to create a comprehensive set of passive control guidelines to provide urban planners with a clear strategy of implementing passive controls in street canyons.

To examine the potential of passive controls for these studies, computational fluid dynamic (CFD) modelling was considered as a method of simulating the interactions of air flow and pollutant dispersion in the urban environment. The following section introduces the fundamental background of

3.2 COMPUTATIONAL FLUID DYNAMICS

To analyse air pollutant dispersion combined with pollutant reactions that take place in urban street canyons, computational fluid dynamics (CFD) numerical software offers a tool which can accurately predict air flow and pollutant dispersion (Vallero,

2008; ANSYS, 2012). CFD is defined as a method of predicting changes in a particular environment by solving mathematical equations which govern the processes which take place within the controlled environment (Vallero, 2008; Bakker, 2012). The software can model a range of applications from fluid flow to heat transfer, chemical reactions to atmospheric turbulence (Figure 3.1Figure 3.) in different controlled environments (ANSYS, 2012).

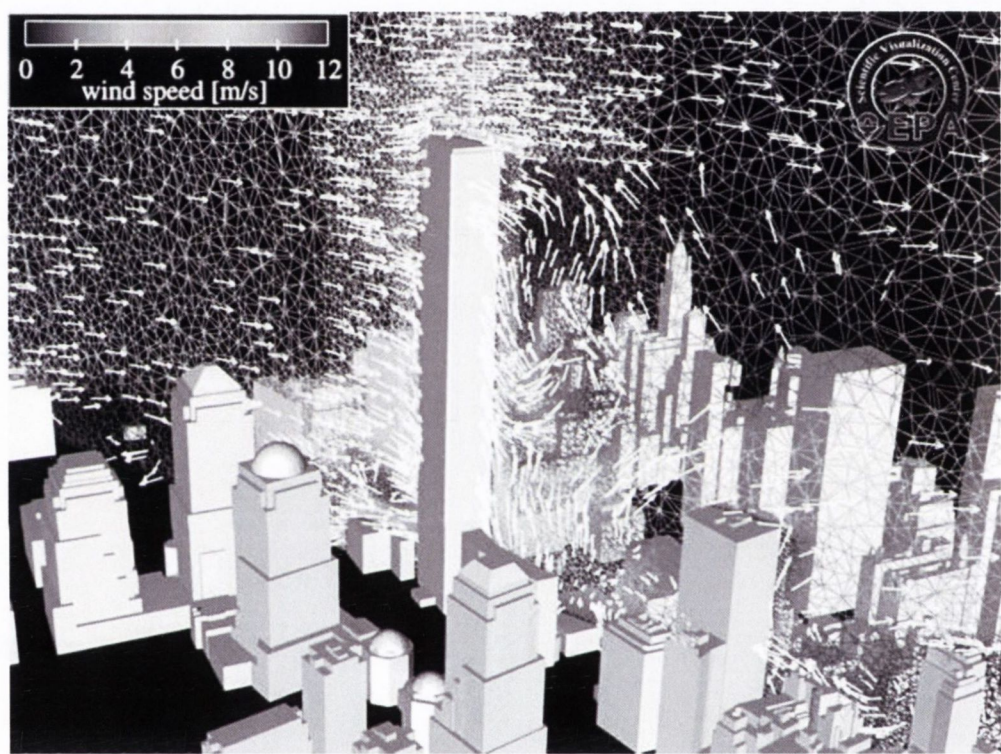


FIGURE 3.1. CFD MODEL OF AIR FLOW IN NEW YORK CITY (VALLERO, 2008).

CFD theory has been incorporated into computer based software packages with the purpose of replicating and simulating dynamic systems in a real-time environment (Versteeg & Malalasekera, 2007). As technological advancements have progressed at a significant rate across all industrial sectors during the 20th century, CFD offers a low cost alternative to the physical experimentation of new products. Modelling tools allow researchers to optimise systems during product development, by changing the design to increase efficiency and reduce product costs.

The development of user-friendly CFD software, such as ANSYS Fluent, COMSOL Multiphysics and OpenFOAM, and the accessibility to high performance computing for simulating complex designs has allowed CFD software to become a viable method

in the system design process (Versteeg & Malalasekera, 2007; Anderson et al., 2009; Zhirkov, 2010). Another benefit of CFD software and high performance computers is the ability to provide significant data output to allow researchers to carry detailed analysis of a complex simulation (Zhirkov, 2010). This is highlighted by Leidl & Meroney (1997) who identified the advantages of the CFD software Fluent for planning and optimising wind tunnel experiments. CFD models are now commonly used for local forecasting and weather pattern simulation (Tripathi, 2004).

CFD bases its methods for calculating simulation on the fundamental principles of the conservation laws of physics which governs fluid flow and combines the following equations: (i) the conservation of mass, (ii) the conservation of energy and (iii) Newton's second law (Tripathi, 2004; Versteeg & Malalasekera, 2007; Anderson et al., 2009). Anderson et al. (2009) state that each of these three principles can be expressed as mathematical equations, and therefore can be solved to calculate the properties and behaviour of a system.

3.2.1 HISTORY OF CFD

The science of fluid dynamics is something that has been developed over the centuries, with one of the first breakthroughs made by Newton with his three laws of motion. This led to further work deriving the motion of fluids: Bernoulli's equation, Euler equations and the Navier-Stokes equation (Bakker, 2012). These findings defined the basis of mathematically describing fluid flow and became the fundamental principles of CFD.

As fluid dynamics could now be derived with numerical equations, a further understanding of these principles led to accurately defining flow properties, including the Reynolds number and the Prandtl number. The first numerical system was developed by Lewis Fry Richardson in 1922, introducing the finite difference method of approximation to a weather prediction problem (Bakker, 2012). From this, Thom (1933) and Kawaguti (1953) calculated numerical solutions for flow around a cylinder. It was noted that these solutions were labour intensive with the work taking 18 months (Bakker, 2012).

The dawn of new numerical methods and access to computers occurred in the latter half of the 20th century which allowed for the calculation of fluid flow problems by writing a program code (Anderson, 1995; Date, 2005; Bakker, 2012). This led to the development of commercial CFD codes, which has expanded the outreach of CFD beyond research to the industry sector. There are many CFD software packages on the market and these packages have become a key element in product or process design, research and development across a broad range of industries (Versteeg & Malalasekera, 2007).

Modern CFD software has also become more accessible as affordable high-performance computing systems have been established and the development of user-friendly software to allow the wider community to use CFD as a method of model analysis and design optimisation (Versteeg & Malalasekera, 2007). The popularity of CFD, in conjunction with faster CFD software and computers, has reduced the cost of the software and further extended its use in research and design as a feasible alternative to intense experimentation and design optimisation. CFD is also considered to provide more accurate results than regulatory air quality models (Huber et al., 2006). It can also complement theoretical and experimental data and provide large quantities of data from each product simulation (Anderson, 1995).

3.2.2 GOVERNING CONSERVATION LAWS OF FLUID DYNAMICS

The principles behind the conservation laws of physics are best described separately. These equations can be generally expressed as mathematical equations, with their most common form as partial differential equations. CFD integrates these governing equations to create a conceptual model for a given fluid flow problem. To provide a visual conceptualisation of a unit volume, we consider a three-dimensional element of such a fluid (Figure 3.2) as the basis for our conservation equations.

The small volumetric element as shown in Figure 3.2 can be used to describe the behaviour of mass, momentum and energy of a fluid, which is made up of a large number of these finite sized elements. The length of the sides of the element is defined as δx , δy and δz . The fluid flow through this element is a function of space (x , y , z) and time (t) (Versteeg & Malalasekera, 2007). The behaviour of the fluid can be

evaluated within CFD from the following properties: velocity (u), pressure (p), density (ρ) and temperature (T) (Bakker, 2012).

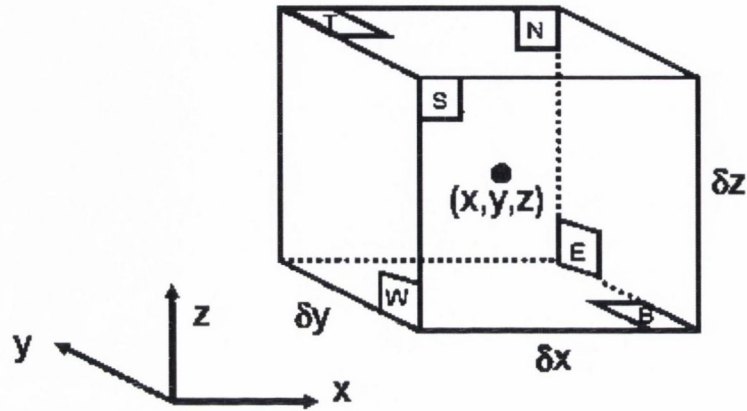


FIGURE 3.2. VOLUME OF FLUID FOR CONSERVATION LAWS (VERSTEEG & MALALASEKERA, 2007).

3.2.2.1 NAVIER-STOKES EQUATIONS

The Navier-Stokes equations govern the properties within a fluid. These equations include the conservation of mass, momentum and energy and are discussed in the subsequent sections. The equations provide the basis for calculating fluid flow in a given fluid using the finite volume method (Versteeg & Malalasekera, 2007).

CONSERVATION OF MASS

This law states that the mass of a given volume remains constant over time i.e. the mass is conserved within the fluid, assuming there are no losses within the domain of the fluid. A mass balance equation is therefore the basis of this equation, whereby the rate of increase of mass inside a fluid element equals the flow rate of mass into the fluid element from its faces. The inflows and outflows are indicated as positive and negative notation, respectively, as shown in Figure 3.3. This law is also known as the continuity equation and is defined by Eqn. 3.1 and shown in a simple compact format in Eqn. 3.2 (or alternatively Eqn. 3.3 for an incompressible fluid).

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad \text{EQN. 3.1}$$

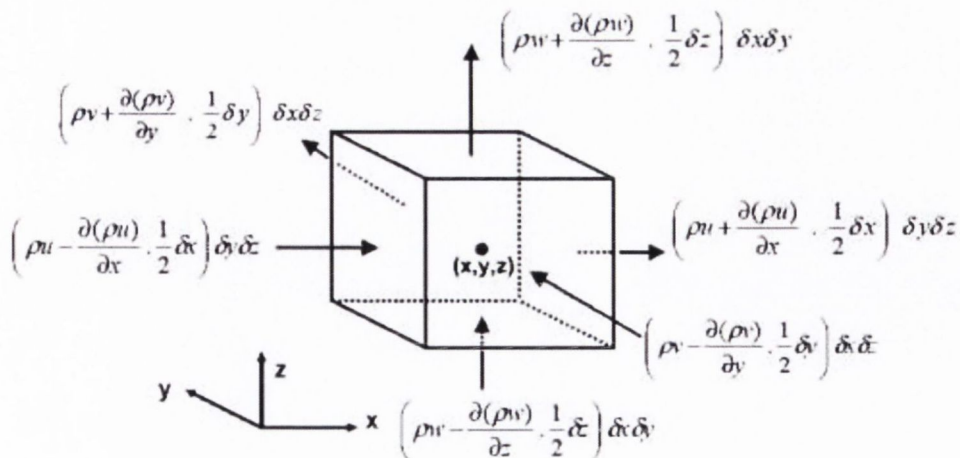


FIGURE 3.3. VOLUME OF FLUID DISPLAYING CONSERVATION OF MASS (VERSTEEG & MALALASEKERA, 2007).

$$\frac{\partial \rho}{\partial t} + \text{DIV}(\rho u) = 0 \tag{EQN. 3.2}$$

Where;

- $\partial \rho / \partial t$ Change in density of fluid (equals zero for incompressible fluids)
- $\text{div}(\rho u)$ Net flow of mass across all boundaries (denoted by Figure 3.3)

$$\text{DIV } U = 0 \tag{EQN. 3.3}$$

The most common notation of the formula which is used to define the continuity equation is shown in Eqn. 3.4:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{EQN. 3.4}$$

CONSERVATION OF MOMENTUM

The conservation of momentum equation is otherwise known as Newton’s second law and states that the rate of change in momentum of a given fluid particle equals the cumulative sum of forces on the particle (Versteeg & Malalasekera, 2007; ANSYS, 2012). Newton’s second law states that “the change of momentum with respect to time equals the sum of all forces acting on the mass” (Ansorge, 2003). This law essentially defines that Force (F) equals mass (m) times acceleration (a) i.e. $F = ma$. The rate of change of momentum combines the sum of surface forces (e.g. viscosity) and body forces (e.g. centrifugal) on the fluid particle (Bakker, 2012). Figure 3.4 illustrates the surface forces upon the fluid particle as viscous stresses (τ).

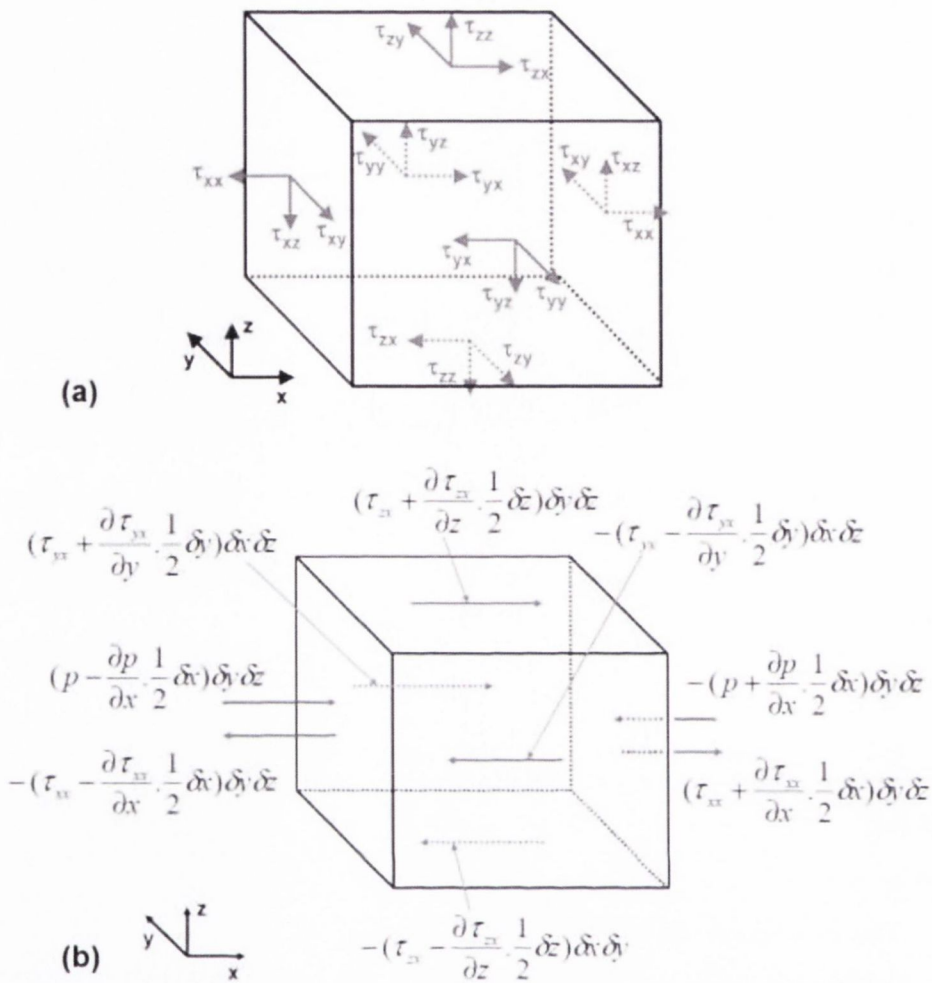


FIGURE 3.4. PLOTS OF (A) TOTAL VISCOUS STRESSES AND (B) VISCOUS COMPONENT STRESSES IN X-DIRECTION FOR CONSERVATION OF MOMENTUM (VERSTEEG & MALALASEKERA, 2007).

The momentum equation sums the net forces in the x-direction on all six faces of the particle and is divided by the volume ($\delta x.\delta y.\delta z$) to get the first part of the momentum equation. This is combined with a source term for the body forces, S_{Mx} to define the X-momentum equation Eqn. 3.5. Similarly, the Y- and Z-momentum equations are defined in the same manner (Versteeg & Malalasekera, 2007; Bakker, 2012).

$$\rho \frac{Du}{Dt} = \frac{\partial(-\rho + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx}$$

EQN. 3.5

Where;

- $\rho(Du/Dt)$
 τ_{xx}
 τ_{xy}
 S_{Mx}

Rate of increase of x-momentum
Normal stress in x-direction on a x-plane
Shear stress in y-direction on a x-plane
Sum of body forces

The combination of these two laws governs fluid motion (Date, 2005; Fluent, 2008). However, in flows which require heat transfer or compressibility, a further energy equation is required to account for these additional forces (Fluent, 2008).

CONSERVATION OF ENERGY

This equation is applied in flows that include heat transfer or fluid compressibility. The equation defines that the total sum of energy in an isolated system remains constant over time (Versteeg & Malalasekera, 2007; Fluent, 2008; Bakker, 2012). The energy equation is derived from the first law of thermodynamics and states that the rate of increase of energy of a fluid particle equals the rate of heat added to the fluid plus the rate of work done on the particle (Versteeg & Malalasekera, 2007). Eqn. 3.6 defines the energy equation combining the source terms for thermal, kinetic and potential energy (Bakker, 2012).

$$\rho \frac{DE}{Dt} = -div(p\mathbf{U}) + \left[\frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} \right] + div(k \text{ grad } T) + S_E \quad \text{EQN. 3.6}$$

Where;

$\rho(DE/Dt)$	Rate of increase of energy
E	Energy = $i + \frac{1}{2}(u^2 + v^2 + w^2)$
i	Internal (thermal) energy
$\frac{1}{2}(u^2 + v^2 + w^2)$	Kinetic energy
S_E	Potential energy, sources due to heat production from chemical reactions, etc.

The equation combines different forms of energy as detailed in the subsequent paragraph. The work done was derived from Figure 3.5 in a similar manner to the momentum equation, by adding all the terms together and dividing by the volume of the particle. The total rate of work on the fluid particle is summarised by Eqn. 3.7 and represents the first part of the energy equation.

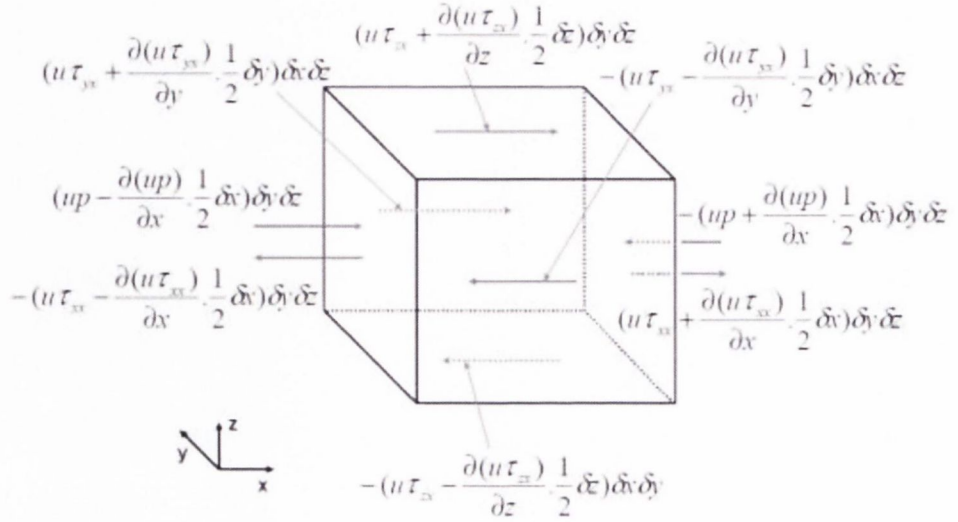


FIGURE 3.5. PLOT OF SURFACE STRESSES IN X-DIRECTION FOR CONSERVATION OF ENERGY (VERSTEEG & MALALASEKERA, 2007).

$$\begin{aligned}
 -\text{div}(pU) + \left[\frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} \right. \\
 \left. + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{xx})}{\partial x} \right. \\
 \left. + \frac{\partial(u\tau_{xx})}{\partial x} \right]
 \end{aligned}
 \quad \text{EQN. 3.7}$$

The vector form representing the energy due to heat conduction is derived from this and is shown in Eqn. 3.8. This part of the energy equation is based on the sum of all terms shown in Figure 3.6 and is divided by the particle volume.

$$-\text{div}(q) = \text{div}(k \text{ grad } T) \quad \text{EQN. 3.8}$$

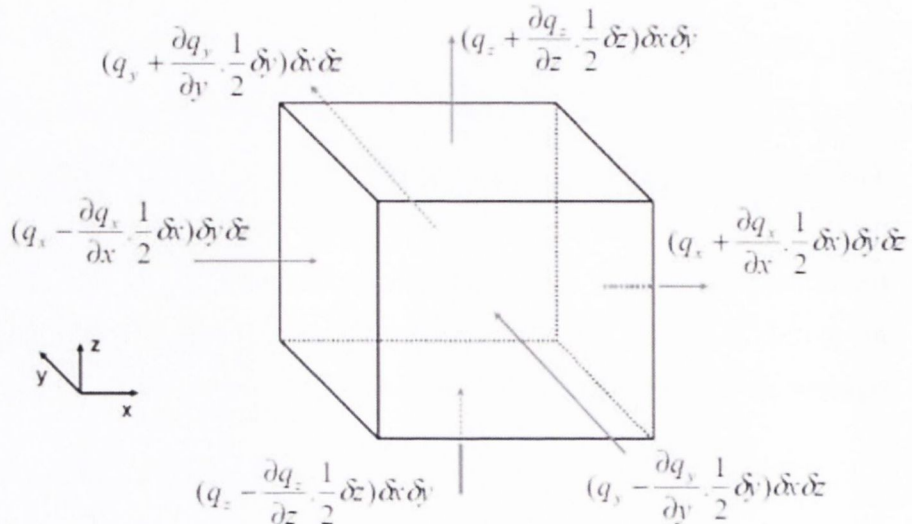


FIGURE 3.6. PLOT OF HEAT FLUX VECTORS (VERSTEEG & MALALASEKERA, 2007).

3.2.3 TURBULENCE MODELLING

The simulation of three-dimensional turbulent air flow is a complex problem as it presents continuously changing fluid flow and behaviour with unstable properties of velocity and pressure with respect to time (Versteeg & Malalasekera, 2007). Turbulence is generated in a fluid as eddies develop and this adds a level of complexity in comparison to laminar flow systems (ANSYS, 2012). These eddies vary in size and scale and the separate turbulence modelling techniques adopt different elements of theory to numerically defining the problem of turbulence.

In laminar flows, the Navier-Stokes equations could be solved analytically, but the development of numerical CFD solutions was required for turbulent flows (Versteeg & Malalasekera, 2007). As turbulent conditions are common in urban canyon models, turbulence models have been adopted as the most realistic method of predicting air flow in a street canyon environment (Chan et al., 2001; Chang, 2006; Kondo et al., 2009; Solazzo et al., 2009; Salim et al., 2011a).

A number of different turbulence models have been developed in the past several decades, yet no single turbulence model has been accepted as the most superior in simulating fluid flow in a range of environments (Fluent, 2008). Each turbulence model provides distinct methods of calculating fluid flow and model selection can depend on the resources available, accuracies required and the physical properties of the fluid. The following is an extensive list of available turbulence models in most CFD software packages (Fluent, 2008).

- Spalart-Allmars Models
- $k-\epsilon$ Models
- $k-\omega$ Models
- Reynolds Stress Model
- Detached Eddy Simulation (DES) Model
- Large Eddy Simulation (LES) Model

The two main turbulence models in CFD applications used for air flow and pollutant dispersion in street canyon models are the $k-\epsilon$ (Santiago & Martin, 2005; Huang et al., 2008) and LES (Liu et al., 2011; Salim et al., 2011a; Zhang et al., 2011b) turbulence models. The following sections will discuss the numerical calculations behind these

turbulence models, which includes a brief comparison of the two aforementioned methods and the application of these turbulence equations in street canyon models.

3.2.3.1 K-ε TURBULENCE MODEL

The k-epsilon or k-ε turbulence model is directly derived from the Navier-Stokes equations with the inclusion of time-averaged properties for a turbulent flow (Harlow & Nakayana, 1968; Launder & Spalding, 1974). The k-ε model has been the most established, validated and widely used turbulence model over the years (Xie et al., 2005; Versteeg & Malalasekera, 2007; Fluent, 2008; Solazzo et al., 2008). It has provided researchers with a low cost method of simulating fluid flow problems as Parra et al. (2010) stated that the k-ε model gives the best compromise between accuracy and computational requirements.

The model adopts the Reynolds-Averaged Navier-Stokes or RANS equations, which are time-averaged equations of fluid flow. The k-ε model is solved using two transport equations; the turbulence kinetic energy or tke (k) equation and the turbulent dissipation rate (ε) equation (Harlow & Nakayana, 1968; Launder & Spalding, 1974; Fluent, 2008). Eqn. 3.9 and Eqn. 3.10 show the transport equations for the tke, k and the rate of dissipation, ε, respectively. The tke equation solves for the rate of change of turbulent kinetic energy and the transport due to convection of k (Versteeg & Malalasekera, 2007).

$$\frac{\partial k}{\partial t} + U_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{v_t}{\sigma_K} \frac{\partial k}{\partial x_i} \right) + v_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} - \varepsilon \quad \text{EQN. 3.9}$$

The mean flow equation for tke shown in Eqn. 3.9 translates as the transport due to diffusion, rate of production and rate of destruction of k. The same form can be applied to Eqn. 3.10, as it solves for the rate of change and the transport due to convection of ε (Versteeg & Malalasekera, 2007).

$$\begin{aligned} \frac{\partial \varepsilon}{\partial t} + U_i \frac{\partial \varepsilon}{\partial x_i} = & \frac{\partial}{\partial x_i} \left(\frac{v_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} v_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} \\ & - C_{2\varepsilon} \frac{\varepsilon^2}{k} \omega \end{aligned} \quad \text{EQN. 3.10}$$

Where;

$$C_u = 0.09, C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, \sigma_K = 1.00, \sigma_\varepsilon = 1.32$$

Each of these dimensionless constants are used in Eqn. 3.10 as follows: C_u is used in the calculation of the eddy viscosity; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are used to calculate the rate of production or destruction of dissipation; σ_K and σ_ε are Prandtl numbers to connect k and ε diffusivities to the eddy viscosity (Versteeg & Malalasekera, 2007).

OTHER K-EPSILON MODELS

Several modified versions have been adapted from the standard k - ε model. The renormalized group (RNG) (Murena et al., 2009) and realizable (Huber et al., 2006) k - ε models are the two most common variations of the standard k - ε model. The main differences between the models are the method of calculating turbulent viscosity, the turbulent Prandtl number and the generation/destruction terms in the dissipation equation (Fluent, 2008).

Several investigations have compared the different k - ε models to identify which model is the most accurate (Leitl & Meroney, 1997; Santiago & Martin, 2005; Xie et al., 2005). Leitl & Meroney (1997) carried out a combined experimental and modelling investigation of pollutant dispersion in a street canyon model. The results displayed no major differences between the flow patterns in the standard and RNG k - ε models. However, Xie et al. (2005) showed that the standard k - ε model performed better than the other models in a comparison of the models to wind tunnel data for pollutant dispersion in canyons with different geometrical features. Each k - ε model offers different qualities for distinct model scenarios. The standard k - ε model provides the most conclusive evidence for accurately replicating air flow and pollutant dispersion in street canyons.

K-E APPLICATIONS IN URBAN ENVIRONMENT MODELS

The k - ε model can simulate turbulent conditions and pollutant dispersion in street canyon environments (Kondo et al., 2009) and has been widely used for this purpose (Chan et al., 2001; Tsai & Chen, 2004; Ning et al., 2005; Huang et al., 2008). In CFD applications, the k - ε model has been used and successfully calibrated for a number of studies including;

- Simulating vehicle emissions in different shaped streets (Xie et al., 2005)
- Simulating emissions in a series of street intersections (Yassin et al., 2009)
- Air flow in symmetric and asymmetric canyons (Santiago & Martin, 2005)
- Assessment of air quality in a street canyon (Chan et al., 2001)
- Simulate pollutant dispersion in different urban geometries and compared to ADMS-Urban model (Di Sabatino et al., 2007)
- Model effects of turbulence in street canyon (Tripathi, 2004)
- Effects of vehicular turbulence in street canyons (Solazzo et al., 2008)

3.2.3.2 LES MODEL

Although being a more computationally demanding turbulence model, the LES model has become more popular in recent years as it has been shown to produce more accurate results than the $k-\epsilon$ models (Chang, 2006; Hu et al., 2007; Hu et al., 2009; Salim et al., 2011a). It provides an alternative approach to the RANS models, as eddies are separated due to behavioural differences between the small and large eddies. It is considered as an effective model that captures the principles underlying both the RANS and direct numerical simulation (DNS) models (COST, 2005). This difference between the computation of the model is due to the *isotropic* behaviour of the small eddies and the *anisotropic* behaviour of the larger eddies. In other words, the small eddies behave with a level of uniformity in all directions (isotropic), while the behaviour of the larger eddies is controlled by the geometry of the domain and is dependent on direction of air flow (Versteeg & Malalasekera, 2007).

In effect, the model is defined as two sets of problems which are computed using two different solving systems. This is carried out with the removal of the small eddies using a spatial filtering function, as the large eddies are calculated as a time-dependent problem using filtered Navier-Stokes equations (COST, 2005; Versteeg & Malalasekera, 2007). The filtering function defines the size difference between the large and small eddies. The LES turbulence model resolves turbulent behaviour rather than modelling the turbulence, thus reducing the likely error in the calculation process (Fluent, 2008). The remaining small scale eddies are considered to have ‘universal’ properties in terms of their turbulence properties and are therefore modelled together.

The LES model has an additional solving system to represent the interaction between the two scales of eddies. This is defined as the subgrid-scale (SGS) stresses model and

is a resultant of the filtering function separating the large and small eddies. The finite volume method is commonly used in the models to solve the equations associated with the large eddies and model the small eddies. As the model is relatively complex due to the separation of the eddies in the simulation process, the use of parallel-computing is advantageous due to the complexity of some models (Fluent, 2008). ANSYS (2012) defines the equations that govern the LES turbulence model as the following from Eqn. 3.11 to Eqn. 3.14.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \bar{u}_i) = 0 \quad \text{EQN. 3.11}$$

$$\frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_i} [\rho \bar{u}_i \bar{u}_j] = \frac{\partial}{\partial x_i} \left(\mu \frac{\partial \sigma_{ij}}{\partial x_j} \right) - \frac{\partial \bar{P}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_i} \quad \text{EQN. 3.12}$$

Where;

μ	viscosity of the fluid
σ_{ij}	stress tensor due to molecular viscosity (Eqn. 3.13)
τ_i	SGS stress (Eqn. 3.14)

$$\sigma_{ij} = \left[\mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right] - \frac{2}{3} \mu \frac{\partial \bar{u}_l}{\partial x_l} \delta_{ij} \quad \text{EQN. 3.13}$$

$$\tau_{ij} = \rho \overline{u_i u_j} - \rho \bar{u}_i \bar{u}_j \quad \text{EQN. 3.14}$$

LES APPLICATIONS IN URBAN ENVIRONMENT MODELS

Numerous studies have used the LES turbulence model for urban street canyon simulations as it provides an accurate solution for air flow and pollutant dispersion in complex urban geometries (Baker et al., 2004; COST, 2005; Chang, 2006; Li et al., 2007; Liu et al., 2011; Salim et al., 2011a). The LES model has been used and successfully calibrated for a number of applications in CFD including;

- Air flow and pollutant dispersion in street canyon model (Zhang et al., 2011b)
- Simulation of unsteady flow in street canyon (Li et al., 2007)
- Transport of reactive pollutants in canyon models (Baker et al., 2004)
- Predict pollutant dispersion in complex street layout (Liu et al., 2011)
- Plume dispersion in street canyon model (Hu et al., 2009; Hu et al., 2011)
- Pollutant dispersion in canyons with avenue trees (Salim et al., 2011b)
- Wind flow and pollutant dispersion in a street canyon (So et al., 2005)

3.2.4 CFD MODELS OF STREET CANYON ENVIRONMENT

The k - ϵ turbulence model has had extensive use and levels of success in assessing air flow and pollutant dispersion in street canyon environments. However, Versteeg & Malalasekera (2007) have stated that the standard k - ϵ models provides only moderate agreement for some flows and the kinetic energy and dissipation rates can be over/under predicted in some cases, as highlighted in a study by Tominaga et al. (2008).

The LES models have shown to provide good agreement with theoretical analysis (Hu et al., 2007). The primary disadvantage associated with the LES turbulence model is the increased demand of computational resources (Li et al., 2007; Murena et al., 2009; Parra et al., 2010).

Both turbulence models offer different qualities and strengths in terms of output and accuracy (COST, 2005; Franke et al., 2007; Tominaga et al., 2008; Salim et al., 2011a). Therefore, the selection of the most suitable turbulence model in CFD is dependent on the user requirements. The model selection process will be subsequently carried out in the following sections as a detailed methodology is to be developed, to identify the importance during model preparation and achieving accurate results. In addition, each of the modelling studies in this thesis will have its own individual methodology regarding its own distinct design selection process.

3.2.5 CFD MODELLING PROCESS

There are many CFD applications and a significant part of this investigation required the development of a good understanding of numerical modelling. CFD modelling requires a lot of testing at different stages of the modelling process to ensure optimised performance of the investigations (COST, 2005). The literature review outlined the numerical equations that are central to the operations of CFD numerical modelling. This chapter aims to define the steps involved in the different stages of the modelling process such as those defined in Figure 3.7Figure 3.. This endeavour was to make a best compromise between accuracy and computational requirements for all the street canyon modelling studies.

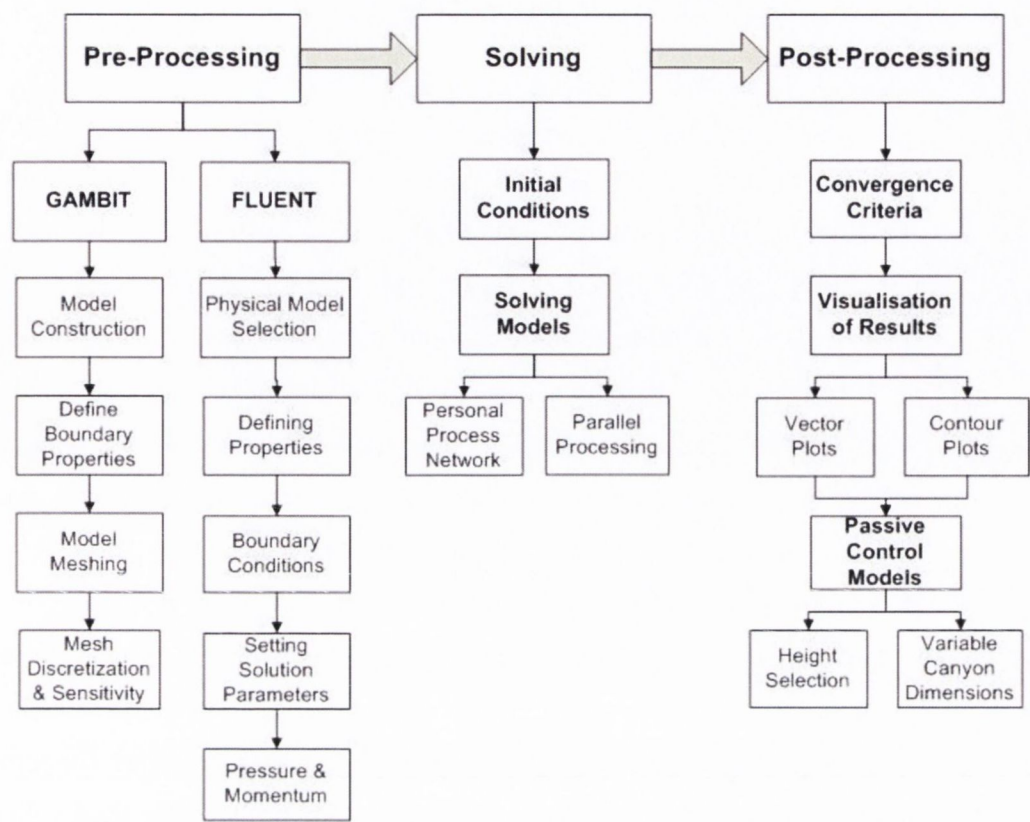


FIGURE 3.7. STAGES AND STEPS OF CFD MODELLING PROCESS FROM INITIAL GEOMETRIC DESIGN TO FINAL ASSESSMENT RESULTS.

The CFD modelling process is considered to have three stages (i) pre-processing, (ii) solving and (iii) post-processing. The steps noted in Figure 3.7 each fall in to one of these three stages of the modelling process. The following sections of this chapter will deal with each of these steps separately and the methods defined to try and optimise accuracy with performance.

3.3 PRE-PROCESSING

This initial stage is the most important phase of the modelling process as it is vitally important to ensure that the model is prepared in line with any relevant guidelines or preceding studies. This methodology refers specifically to the construction and development of street canyon models. This section has been divided into two subsections dealing with the steps taken using *GAMBIT* and *FLUENT*. Both subsections deal with the steps within the pre-processing stage; from model construction and meshing to preparing model conditions and model initialisation.

3.3.1 GAMBIT

3.3.1.1 MODEL CONSTRUCTION

Every canyon model was constructed using GAMBIT v2.3, a CFD model development and meshing tool (Huber et al., 2006; Cheng et al., 2008; Gambit, 2008; Murena et al., 2009; van Hooff & Blocken, 2010; Yassin, 2011). The studies carried out as part of this investigation of passive controls adopted 3D models for each of the cases as they were considered more accurate in assessing street canyons compared to 2D configurations. Three-dimensional models include turbulent conditions are included in the simulations as 2D models omit either lateral or longitudinal flow, which can lead to under/over estimations of turbulence properties in the models (Tsai & Chen, 2004; Letzel et al., 2008; Ryu & Baik, 2009).

The initial phase of the construction process for each model was to define the dimensions of each street canyon. The construction of the canyon models was then carried out using a coordinate system. The point coordinates were connected to one another to create lines, surfaces and volumetric domains, with the final volume shown in the model in Figure 3.8.

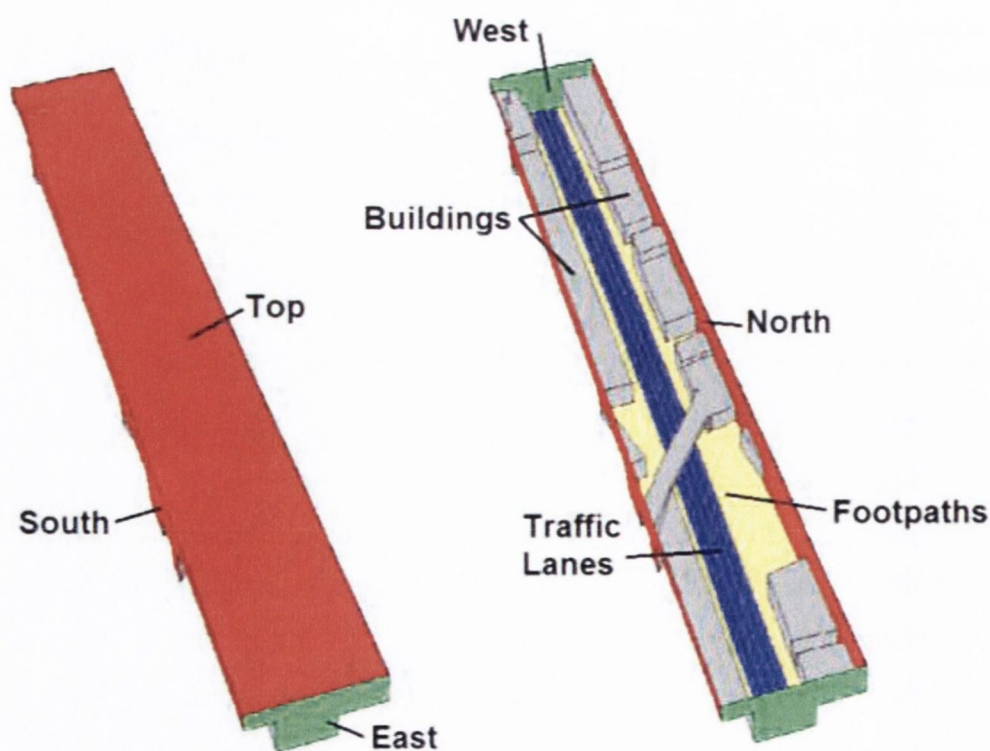


FIGURE 3.8. TYPICAL LAYOUT OF VOLUMETRIC MODEL IN GAMBIT (PEARSE STREET MODEL).

Each of the street canyon models constructed were termed as the reference models. From this, passive controls were introduced to engineer additional turbulence and pollutant dispersion in the canyon models.

3.3.1.2 DEFINING BOUNDARY PROPERTIES

The surfaces of the canyon floor (blue and yellow), buildings and passive control (grey) were constructed as wall boundaries to resemble the impermeable nature of their characteristic materials (Fluent, 2008). Additional faces of the model domain were constructed as atmospheric boundaries (red or green) where air either entered or escaped from the canyon model. The property of a pressure outlet was attached to all atmospheric surfaces where air escaped the canyon and a velocity inlet was attached to any face where air entered the canyon. Some of the models had symmetrical properties, and symmetry faces was introduced to half the size of the volumetric domain and reduce the computational requirements to simulate each street canyon model.

The dimensions of each modelling investigation are outlined in the various chapters. However, the following points were noted to be relevant in the preparation of each of the models. Firstly, the road lane and footpath widths remained constant in all model configurations for each study, to maintain a level of continuity between each model. The width of the roadway remained constant in each model configuration to maintain a similar emissions rate in each study. A constant footpath width was also maintained to allow a clear comparison of the measured pollutant concentration on the footpath in all of the models.

3.3.1.3 MODEL MESHING

The meshing of the volumetric model is considered one of the most important steps of the modelling process as the mesh size defines the likely accuracy of each model. Versteeg & Malalasekera (2007) stated that 50% of the modelling investigative process is required to focus on the mesh analysis, to ensure the best possible mesh scheme was selected. Tripathi (2004) also noted that accuracy depends on the mesh sizing and emphasized that the level of accuracy required depends on the resources available. A detailed mesh discretization analysis was therefore carried out to

determine suitable mesh parameters for each modelling investigation (COST, 2005). Previous investigations have stated that a grid sensitivity study is crucial for independent cases, as conditions vary depending on canyon geometry (Franke et al., 2007; Tominaga et al., 2008).

A typical computational domain is meshed with a series of grid density schemes combining a surface mesh at canyon floor level with a proportionate volume mesh. This aims to compromise the computational running time by inserting a finer mesh in the zone of interest and a coarser mesh throughout the rest of the model domain and is common practice.

There are a number of meshing options available to mesh the surfaces and volumes of the street canyon models. An unstructured mesh was proposed for these investigations (Huang et al., 2005), in addition to using the finite volume method, which is commonly used for fluid flow simulations (Fluent, 2008). For the surface mesh, two specifications are required to be selected; scheme elements and scheme type. The *Tri-Pave* option was selected as the most suitable for the street canyon models as the triangular elements had a good fit along the surface of the canyon and the mesh elements were created in a pave grid pattern. This triangular layout allowed for the best fit of the surface mesh in complex geometries which can occur in street canyon models. The *TGrid* scheme chosen for this modelling study for the volumetric meshing as it similarly used a triangular based mesh in the form of tetrahedral elements, with the inclusion of other shapes where considered suitable (Gambit, 2008). This combination has been successfully used in a series of passive control investigations in urban street canyons (McNabola et al., 2009; Gallagher et al., 2011; 2012; 2013).

3.3.1.4 MESH DISCRETIZATION & SENSITIVITY

Canyon geometry varies for each modelling study and as it plays a significant role in influencing air flow and pollutant dispersion, an investigation of the regime used to mesh the model is necessary (Crowther & Hassan, 2002; Santiago & Martin, 2005; Yassin et al., 2009). A typical street canyon environment requires a fine mesh to account for the dispersion of pollutants at street level (Liu et al., 2005). Therefore,

guidelines exist to define a level of uniformity in mesh selection criteria (COST, 2005; Tominaga et al., 2008). The following factors were noted as some of the guidelines identified in previous literature to ensure that a level of consistency and quality is maintained across all modelling investigations in this area;

- Mesh sensitivity for each independent study (COST, 2005)
- Street width with minimum of 10 grids (COST, 2005)
- Height of first grid cell above ground (or next to wall) at least 20 times roughness length (COST, 2005)
- A minimum of two grid nodes between any solid surface and monitoring point (Franke et al., 2007)
- Fine grid to resolve flow near corners (Tominaga et al., 2008)
- Unstructured grid is most suitable for complex urban area (Huang et al., 2005)

As Gambit was used for the model construction and meshing processes, the meshing was carried out manually. More recent developments have seen advanced meshing technology through *ANSYS Meshing* (ANSYS, 2012). This provides the user with an automated meshing tool which endeavours to provide a balance between accurate results and minimum computational running time for a specific fluid dynamic problem.

MESH OPTIMISATION

Based on the aforementioned mesh guidelines, a series of models were created with different mesh dimensions for each study. This was to determine the most suitable grid mesh for each specific passive control modelling study. Figure 3.9 illustrates an example of a mesh discretization study carried out as part of the canyon asymmetry investigation.

The plot shows the results collected from five sets of models for pollutant concentration measurements along the centre of each footpath (as defined later in Section 0). Each model used different mesh sizes (legend in Figure 3.9) on the floor of the canyon, with the objective being to identify the optimal mesh size, whereby the accuracy of results were not compromised. Similar concentrations were measured on the windward footpath for all surface mesh schemes less than 0.5 m. A finer mesh schemes were deemed necessary on the leeward footpath to provide the best possible accuracy, as the 0.5 m mesh displayed substantial differences to the finer (0.4 m and

smaller) mesh schemes. This case specific investigation identified the importance of carrying out a mesh discretization study for each street canyon scenario to provide optimal accuracy from each model.

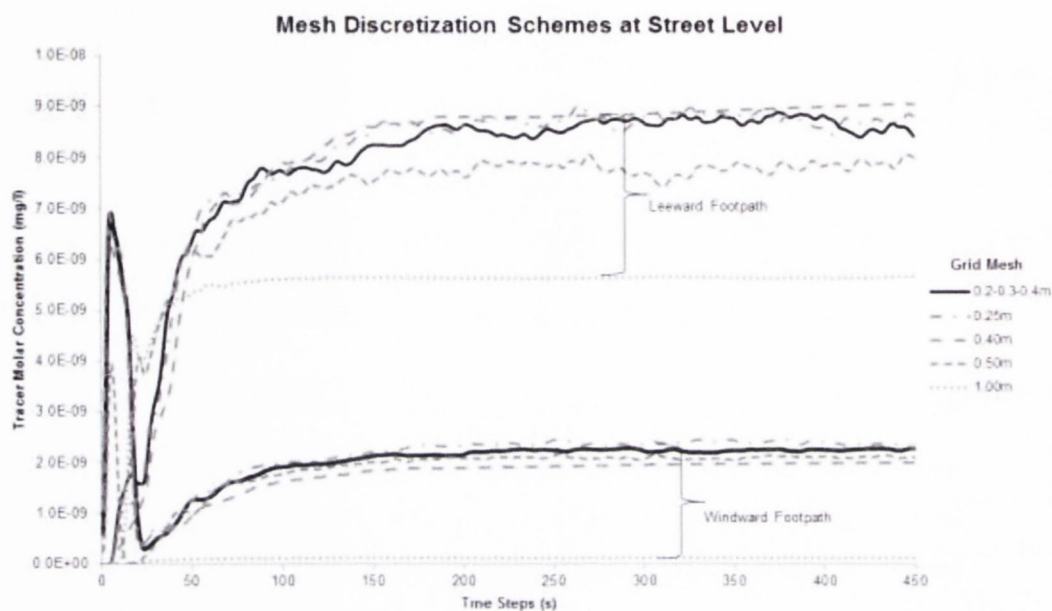


FIGURE 3.9. MESH SENSITIVITY DATA ILLUSTRATING TRACER CONCENTRATIONS ON LEEWARD AND WINDWARD FOOTPATHS.

3.3.2 FLUENT

Each *GAMBIT* model was then exported into the model processor i.e. *FLUENT* for the preparation of the model for preparation and solving. Initially, the grid of each model was checked for any errors and the mesh was smoothed using the skewness-based smoothing technique, which repositions some mesh nodes to improve skewness of cells (ANSYS, 2012). The default values for the minimum skewness (0.8) and number of iterations (4) were used as advised by Fluent documentation (Fluent, 2008).

3.3.2.1 PHYSICAL MODEL SELECTION

TURBULENCE MODEL

As defined in the literature review, the $k-\epsilon$ (Huang et al., 2008; Murena et al., 2009; Parra et al., 2010) and LES (Chang, 2006; Letzel et al., 2008; Hu et al., 2009; Salim et al., 2011a) turbulence models are the two most common methods of simulating air flow and pollutant dispersion in an urban canyon environment. Therefore, this section aims to compare the two methods and justify which method was considered the most

suitable for the purposes of investigating passive controls in street canyons. In addition, both turbulence models were used in Chapter 5 to simulate air flow and investigate the potential of passive controls in the asymmetry study.

Countless studies have adopted both turbulence models for urban environment modelling investigations and have been validated against real-time data or wind tunnel experimentation (Chang, 2006; Murena et al., 2009). Air flow in a street canyon can create complex air flow patterns as primary and secondary vortices can develop in different areas of the canyon. The complex air flow patterns which influence pollutant dispersion can be observed in Figure 3.10.

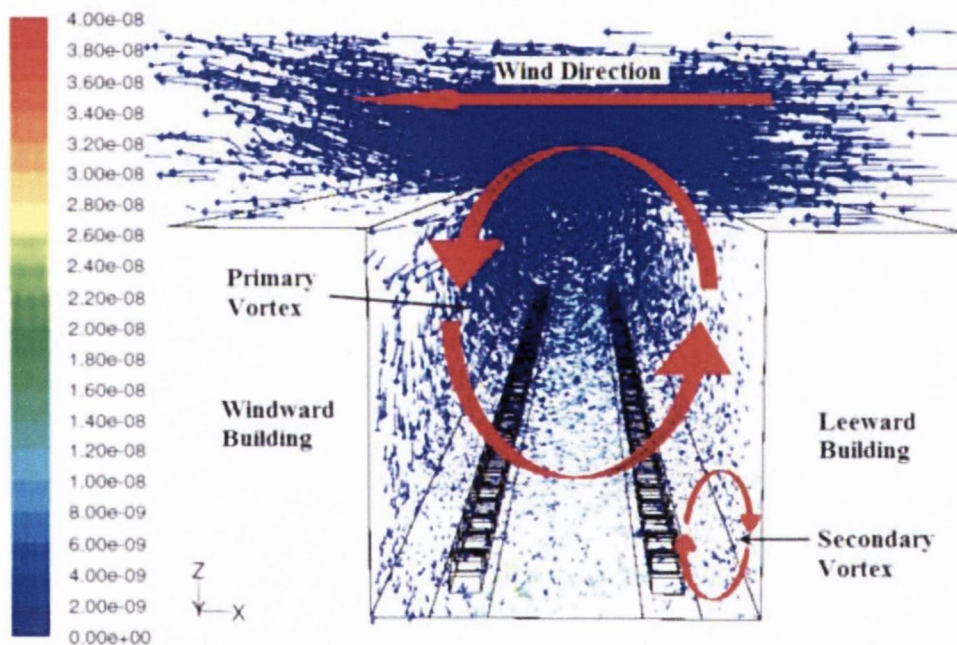


FIGURE 3.10. RESULTANT VELOCITY VECTORS PLOT FOR THE TRACER EMISSION CONCENTRATION IN STREET CANYON FOR PERPENDICULAR WIND CONDITIONS (GALLAGHER ET AL., 2011).

The introduction of passive controls increases local dispersion and alters the natural air flow characteristics in a street canyon. Therefore, the model selection requires a turbulence model which is more suited to accurately simulating turbulent air flow in a complex geometrical environment. Past studies have found that the LES model solution converges with the Navier-Stokes equations and captures unsteady flows, which the RANS $k-\epsilon$ does not (Baker et al., 2004; COST, 2005). This suggests that the LES turbulence model is the most suitable for the purpose of investigating passive controls.

The major disadvantage of the LES model compared to the k- ϵ model is the increased computational requirements to simulate the CFD models (Cheng et al., 2008; Parra et al., 2010; Salim et al., 2011a; Salim et al., 2011b). Despite Franke et al. (2007) stating that the k- ϵ model adequately represents wind tunnel data, this study wants to ensure that the turbulent behaviour at street level around the passive controls is accurately modelled and k- ϵ cannot guarantee accurate turbulent behaviour (Salim et al., 2011b).

In comparison to the k- ϵ model, the LES turbulence model has been shown to perform best against wind tunnel experiments for air flow and pollutant dispersion in an urban environment (Chang, 2006; Hu et al., 2007). The LES model only adopts unsteady state conditions unlike the k- ϵ model, as steady state conditions have been shown to over-predict magnitudes along the vertical canyon surfaces (Chang, 2006). The unsteady solver option is used to simulate dynamic models which are being integrated with respect to time. The model also predicts unsteadiness and intermittency in turbulent flows, common to passive control models at street floor level (Hu et al., 2009; Salim et al., 2011a).

Based on these reasons, each of the passive control investigations used the large eddy simulation (LES) turbulence model in the simulation process. The LES model was considered as the most suitable turbulence model to simulate the complex geometry around the passive controls compared to the k- ϵ model (Baker et al., 2004; Liu et al., 2005; So et al., 2005). Turbulent behaviour is expected at street level, in particular on the footpaths and between the parked cars. Therefore, a suitable turbulence model is required to simulate these conditions along the canyon floor as this is considered the zone of interest, in terms of personal pollutant exposure along the footpaths.

SPECIES TRANSPORT MODEL

The species transport model was selected to calculate the dispersion of gaseous pollutant emissions in the street canyon models. Literature defines the species transport and reactions equations as two factors which are commonly used together (Fluent, 2008). However, in these studies, non-reacting gases were used in the modelling process and the default parameters were used for the diffusion characteristics of the specific tracer pollutant under the mixture properties tab.

ANSYS (2012) defines the mass diffusion equation in Eqn. 3.15 and the diffusion equation for turbulence conditions in Eqn. 3.16.

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i \tag{EQN. 3.15}$$

Where;

- R_i Net rate of production of species i by chemical reaction
- S_i Rate of creation by addition from the dispersed phase

$$\vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right) \nabla Y_i \tag{EQN. 3.16}$$

Where;

- J_i Diffusion flux of species i
- $D_{i,m}$ Mass diffusion coefficient for species i in the mixture
- μ_t Turbulent viscosity
- Sc_t Turbulent Schmidt number (0.7)

The turbulence form of the transport equation is necessary for the turbulent flows which exist in street canyon models.

3.3.2.2 DEFINING PROPERTIES

Several model properties which were selected and defined for the use in simulating air flow and pollutant dispersion in FLUENT are discussed in this section.

MATERIALS

The properties of the gaseous tracer pollutants were edited for each modelling investigation. The fluid properties were edited for density (kg/m^3), constant pressure C_p (J/kg-k) and molecular weight (kg/mol) based on the known properties of the specific tracer gas.

OPERATING CONDITIONS

The inclusion of the effects of gravity was input in the operating conditions window. A value for gravity was inserted as -9.81 m/s^2 (typically in downward Z-direction) in each model to include the effect of gravity on air flow and pollutant dispersion. It was noted that this investigation only simulated gaseous pollutants and showed little deviation between results with the gravity parameters included or excluded. A

comparison of a series of test results from passive control models, both with and without the gravity parameter demonstrated a difference of between 3 and 5%. Therefore, the gravity parameters were included in all models. The default *operating pressure* (101325 Pascals) and *operating temperature* values ($\sim 15^{\circ}$) were selected as typical conditions likely in Irish conditions. In a similar manner of assessment to the effects of gravity on measurements, deviations in pressure and temperature showed differences on less than 1% for lower and higher values.

3.3.2.3 BOUNDARY CONDITIONS

VELOCITY INLET

The inlet velocity boundary conditions were used to introduce wind conditions to the models. Two velocity specification methods were used in the various passive control investigations, depending on the required input values: (i) *magnitude, normal to direction* and (ii) *components* methods (Fluent, 2008). The *components* method is more useful as it allows for defining inflow velocities for wind conditions that flow at any given direction. The *magnitude, normal to direction* method was also adopted for some of the studies as it was sufficient to the needs of some of the investigations. A uniform velocity profile was set as the inlet boundary condition similar to previous modelling investigations of pollutant dispersion in street canyons (Kumar et al., 2009; McNabola et al., 2009; Gallagher et al., 2011).

POLLUTANT EMISSIONS

Introducing pollutant emissions in a CFD simulation requires a pre-determined *species mass fraction* of the pollutants in the model. This *species mass fraction* represents a mass of a given pollutant (a ‘tracer’ gas) as a fraction of the total species mass (‘air’) in each model.

To represent pollutant emissions in the FLUENT models, literature was reviewed to determine suitable methods of simulating vehicular emissions in street canyon models. However, the selection of a suitable emissions source model, Kumar et al. (2009) stated that there is no definitive standard practice in CFD modelling. Therefore, the selection of a suitable A number of different emission source models have been used in previous 3D air pollution modelling investigations: point (Chang, 2006; Dong &

Chan, 2006), line (Meroney et al., 1996; Nagendra & Khare, 2002), surface (Baker et al., 2004; Murena et al., 2009) and volume (as a 2D area model) (Kumar et al., 2009) sources. Table 3.1 summarises the characteristics of the different source emission models.

TABLE 3.1. COMPARISON OF DIFFERENT EMISSION SOURCE MODELS.

Source Model	Advantages/ Disadvantages	Information
<i>Point</i>	Advantage(s)	Once suitably located, a point source can accurately represent tailpipe emissions for any given vehicle
	Disadvantage(s)	Most point source models use static emissions and this can misrepresent vehicle movement or turbulence
<i>Line</i>	Advantage(s)	A line source can replicate the path of a vehicle tailpipe
	Disadvantage(s)	The location of a tailpipe on a vehicle tailpipes varies, thus no specific location can be considered as definitive for all vehicles
<i>Surface</i>	Advantage(s)	Surface emission allows for the dispersion of emissions across the canyon floor in the vehicle wake
	Disadvantage(s)	The surface emissions model has not been used or validated in models which include vehicular turbulence
<i>Area</i>	Advantage(s)	Can be used as an emissions source with an associated turbulence zone to take into account vehicular turbulence and pollutant dispersion
	Disadvantage(s)	Currently limited to 2D studies, which limits the understanding of its accuracy in a 3D context

The initial factor considered to determine the most suitable emission source model for passive control investigations was ensuring the model has been used in a 3D context. Thus the point and area/volume source models were not considered as accurate for the passive control investigations. Surface emission source (Baker et al., 2004; Murena et al., 2009; Gallagher et al., 2011) and line emission source (Nagendra & Khare, 2002; Chang & Meroney, 2003; Baker et al., 2004) models are among the most used in 3D street canyon models. Surface source models have become the most common method of simulating vehicle emissions at street level in recent years, with the line source previously well established in emission source modelling. Both methods have been validated to effectively simulate vehicular emissions. However, they have been calibrated to wind tunnel experiment results, which do not necessarily justify their ability to simulate real world variation of air flow and pollutant dispersion. Some line and surface emission source models have also omitted vehicular turbulence, which

although reducing the computational costs, reduces the accuracy of street canyon simulations (Liu, 2010).

The typical patterns of pollutant dispersion in the vehicle wake were assessed (as vertical and lateral dispersion) to determine the most suitable emission source model with the omission of vehicular turbulence, which was necessary for the passive control modelling investigations. The typical dispersion tailpipe emissions pattern in the wake of an individual vehicle tailpipe is displayed in Figure 3.11.

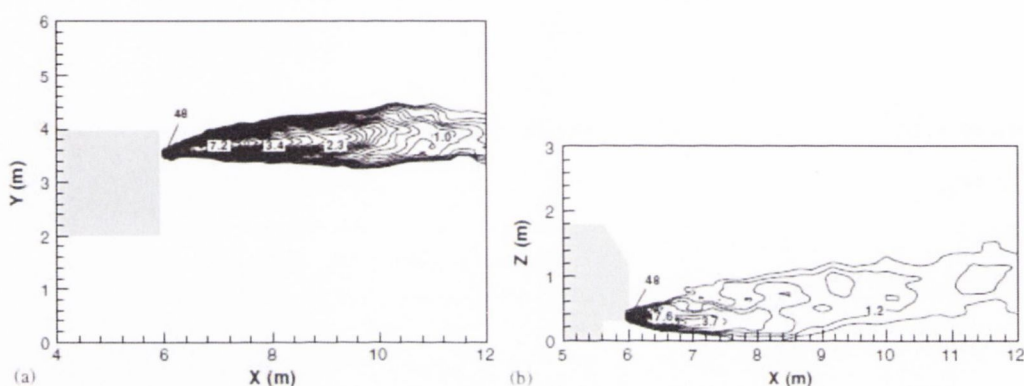


FIGURE 3.11. (A) PLAN AND (B) ELEVATION PLOTS OF TIME-AVERAGED SCALAR CONCENTRATION CONTOURS AS IN WAKE OF VEHICLE WITH A WIND SPEED OF 1.0 M/S (DONG & CHAN, 2006).

Figure 3.11 shows the pattern of dispersion behind a vehicle (Dong & Chan, 2006). This simulation assumes a line emission source would be suitable for the purpose of simulating vehicle emissions and the line emissions pattern would be observed in street canyon models. However, a number of shortcomings exist in the use of this method of simulating emissions: (i) the location of tailpipes varies between each vehicle model, therefore there is no defined location for the line emissions pathway and (ii) the lateral dispersion which occurs from multiple vehicles is neglected and a line source simplifies the emission source significantly. In addition, the variability which exists between vehicles rear spoilers, and their effects on pollutant dispersion, demonstrates the challenge of accurately locating a line emissions source which is definitive for all vehicle movements in a street canyon (McNabola, 2011).

The surface emissions source equally spreads the loading of the emissions across the road surface and therefore allows for an equal distribution of pollutants in the street. The surface emissions source model takes into account lateral dispersion across the

lanes due to vehicular turbulence from multiple vehicles (Pospisil et al., 2004). The surface emissions source has been adopted by recent investigations. The surface source model is more difficult to simulate in a wind tunnel experiment (simulated rather as a multitude of point sources) and thus has had limited validation to date using wind tunnel studies.

Comparing the two most commonly used emission source models in urban street canyon models i.e. line and surface sources both have unique benefits for introducing pollutant emissions in street canyon models. However, the surface emissions source ensures to represent the variability of the location of tailpipe emissions. The location of the surface source was chosen as the floor of the canyon ($Z = 0$) i.e. the road surface of the street canyon model. This was deemed suitable for the passive control investigations as tailpipe emissions were generally horizontal and dispersed vertically or directly downward towards the street floor. The difference in the height of the surface source (within a reasonable zone i.e. up to tailpipe height e.g. 200mm) does play a marginal role in the likely measured concentrations on the footpaths, but it was considered negligible for the comparative nature of these investigations for passive controls. The surface emission source model was therefore used in the passive control investigations, but there is scope for further investigations to determine the optimum selection of emission source models.

MONITORING POLLUTANT EMISSIONS

Monitoring lines were inserted at the centre of both footpaths in each model at heights of 1.76 m and/or 1.00 m, to represent the path of an adult and/or child walking the full length of the canyon. The centre of the footpath was chosen as it represented the typical path of the average pedestrian on the footpath in terms of personal exposure to pollutants from the road. A plot of the pollutant concentrations on the footpath for different locations along the 2.0 m footpath (0.5 m intervals from road to building) for different wind speeds is displayed in Figure 3.12.

The plot shows the pollutant concentration at the various locations across the footpath, with similar patterns observed for all wind speeds. For each of the modelling studies, the monitoring line was located along the centre of the footpaths as this was considered as representative of the average route taken by each pedestrian along the

footpath. The increase in the concentration with an increased distance from the road was due to the transport of pollutants from the road and the pollutants being trapped along the leeward wall of the canyon.

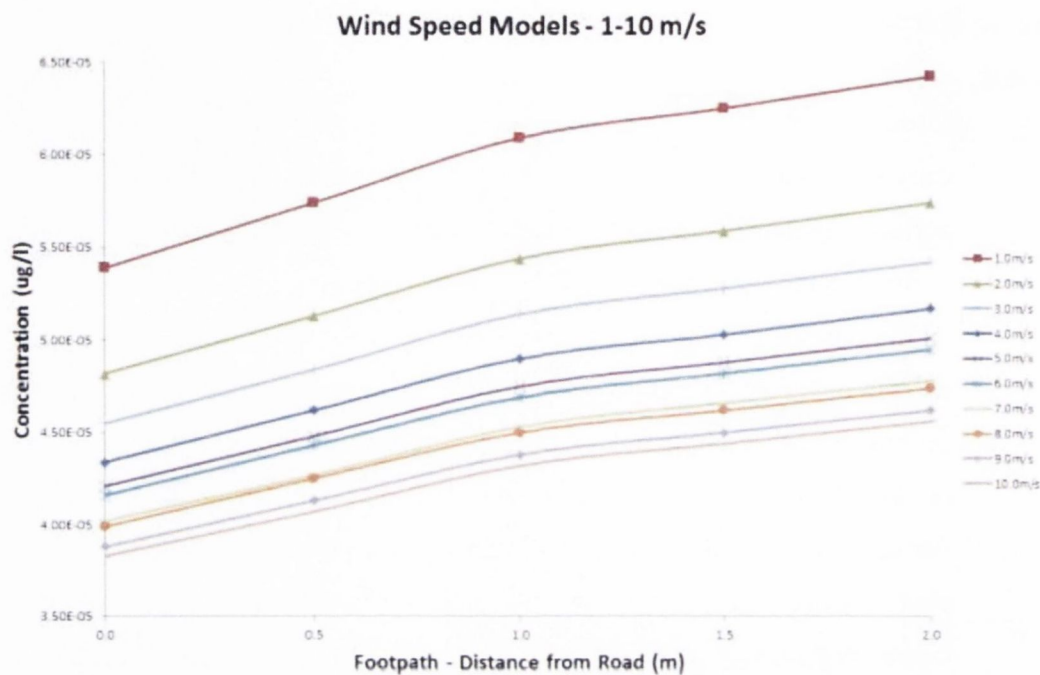


FIGURE 3.12. POLLUTANT CONCENTRATIONS ON LEEWARD FOOTPATH AT AN ADULT HEIGHT OF 1.76 M FOR DIFFERENT WIND SPEEDS (1 – 10 M/S IN 1.0 M/S INTERVALS) IN PERPENDICULAR WIND CONDITIONS.

The data output from each monitoring line recorded the average tracer concentration along each line every second. A result was obtained for each model by taking an average value of the output data. The path of the monitoring line was inserted into each model using a co-ordinate system. The data output was saved in .out format and were transferred from *WordPad* to *Microsoft Excel* for comparative analysis. The data output from these monitoring lines were also plotted in window(s) during the simulation process, which allowed for a visual inspection of the live data feed. In some model scenarios, a steady state was observed in these plots, which allowed for a reduction in the duration of time taken to run some simulations.

Point monitors are another method of extracting data on the footpath for comparison of results and are prepared in the same manner as the line monitor. However, point monitors do not take into account the full variation in pollutant concentrations along

the full length of footpath. The monitoring line measures a representative sample of air along the full length of the canyon model to account for the average concentration that an individual is exposed to as they walk the full length of the canyon.

3.3.2.4 SETTING SOLUTION PARAMETERS

Prior to solving each model, a number of criteria are required to be defined or default criteria justified to ensure each model runs smoothly and data output is accurate.

CONVERGENCE CRITERIA

Defining suitable convergence criteria for each series of street canyon models is a difficult task as a large amount of simulations are required to define the optimum *absolute criteria* values for the residuals. Therefore, the default values were chosen for the passive control modelling investigations and any adjustments to the convergence criteria were made through a manual reduction in the number of iterations at various stages of the simulation process. This allowed for a reduction in the computational running time of the models and served a similar function to altering the absolute values of the residuals.

3.3.2.5 PRESSURE & MOMENTUM

The pressure and momentum factors are considered to fall under the category of *Under-Relaxation Factors* in FLUENT. The under-relaxation factors affect the rate at which the solution changes (i.e. equation solving), which in turn controls the rate of convergence of each model. The turbulent air flow patterns in the street canyon models adopted the LES turbulence models and as such typically display unstable behaviour. Therefore, the use of reduced factors are advised in the FLUENT manual (Fluent, 2008) and based on previous passive control model investigations (McNabola et al., 2009; Gallagher et al., 2011; 2012). The default values for pressure and momentum are typically 0.3 and 0.7, respectively. These values were reduced to 0.1/0.2 and 0.3 to aid convergence as these parameters influenced the iterative solution process and altering these parameters improved the computational running time of each model.

3.4 SOLVING

Solving the model is the most time consuming element of the simulation process. Therefore, this section outlines methods of optimising the running time in the solving phase. The initialisation of each model and parallel processing provides two methods of optimising the solution runtime process, which are discussed in more detail in the following sections.

3.4.1 INITIAL CONDITIONS

Providing initial flow condition is a good approach for a new solution as it can provide faster solution convergence (Tominaga et al., 2008). This provides initial values to all cells relating to the flow criteria in the model. The initial conditions change the duration taken for the simulation to converge and do not affect the results (Fluent, 2008).

3.4.2 SOLVING MODELS

The simulation of over 200 passive control models and countless other discretization and test models on a standard desktop PC was considered extremely demanding to achieve the magnitude of output required to ensure detailed modelling investigations can be carried out. Therefore, two avenues were assessed during the duration of the PhD to increase productivity (beyond model optimisation), in terms of access to additional resources.

3.4.2.1 PERSONAL PROCESSING NETWORK

The first method of increasing output was to access the *Trinity Centre for High Performance Computing* (TCHPC), which provided powerful research computers for the purpose of reducing the running time of simulations. The TCHPC was accessed remotely on the TCD home network using Xming (X window Server) which allowed the user to open and view graphical applications on the TCHPC system. This resource was used in the early stages of the PhD, but an alternative option was sought due to several downtimes of the TCHPC resources. In addition, the resources on the TCHPC i.e. the number of cores and RAM in the systems did not provide the necessary processing speed for multiple models. Therefore, another option was considered to increase productivity through constructing a personal HPC network.

As high numbers of models were prepared and a desktop or the TCHPC systems could not run them all simultaneously, a small personal computer modelling network was constructed. Each computer was re-formatted, FLUENT installed and the network was created via a modem hub. This allowed for access to all the computers through the hub and the computers were used to simultaneously simulate multiple model scenarios. The system constructed for this research study can be seen in Figure 3.13.



FIGURE 3.13. PERSONAL HPC SYSTEM (MODEM HUB INSERT).

Depending on each model being run in parallel or not, in excess of 20 models could be run simultaneously. This was beneficial as bulk results were collected and considered more productive than staggered results over a longer period of time.

3.4.2.2 PARALLEL PROCESSING

Parallel processing is a common method of increasing computer productivity as FLUENT typically solves a model simulation on one computer core (Fluent, 2008; Kremenetsky & Kodiyalam, 2010). Most computers have a number of central processing unit (CPU) cores and therefore the full potential of most computers is not utilised. Parallel processing was used for a significant fraction of the passive control model investigations. The parallel simulation process splits up each model into several

partitioned sections and solves each section separately. The information was then shared across each of the partitioned interfaces in the model. These interfaces can be observed in Figure 3.14.

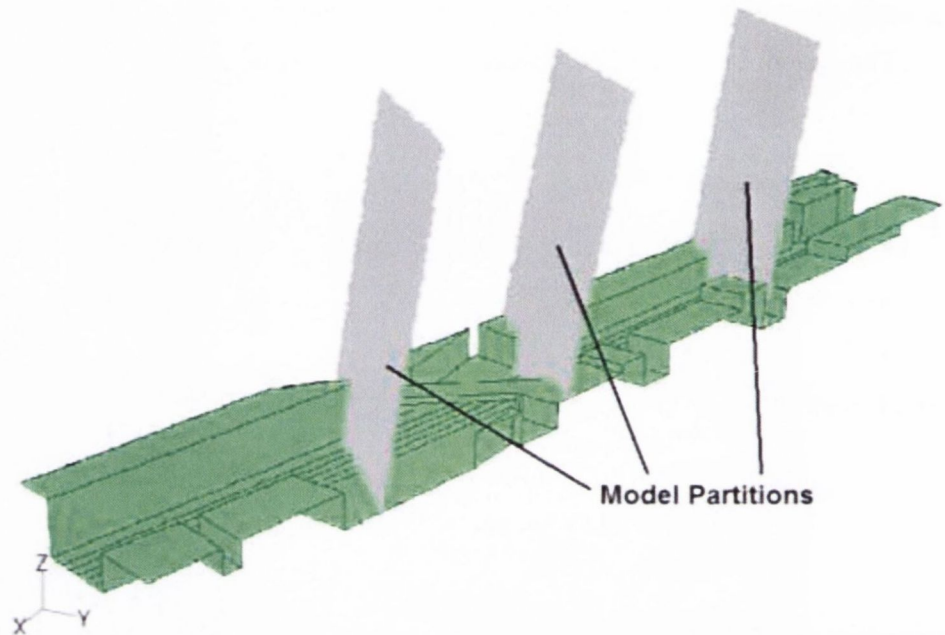


FIGURE 3.14. PARTITIONED MODEL FOR PARALLEL PROCESSING (PEARSE STREET MODEL).

Each parallel model was prepared as defined in the FLUENT Manual (Fluent, 2008). The typical desktop computer has 4 cores and these were all used for most of the modelling studies to maximise model output. Figure 3.14 displays a typical model split into four sections for parallel processing.

3.5 POST-PROCESSING

The post processing stage aims to discuss the details of the modelling output including an analysis of the convergence criteria, assessment of data output from line monitors and methods of visually inspecting air flow and pollutant dispersion in street canyon models.

3.5.1 CONVERGENCE CRITERIA

The convergence criteria set within the model defines when the model solution is solved. The concept of convergence can be adopted for any numerical problem which adopts the finite volume method. However, the convergence criteria chosen for a

problem is the biggest challenge as there is no comprehensive method of defining convergence (Fluent, 2008). This is due to the non-linear behaviour of fluid flow models, which simulate turbulent flow processes. For the passive control models, the default residuals were maintained and under-relaxation factors were changed for pressure and momentum as defined in a previous section of this chapter. The primary objective in assessing the results is to ensure that acceptable convergence criteria have been met and the results are accurate.

The rate of convergence can display significant differences in the time taken for each of the residuals to converge. Changing the under-relaxation factors can improve the iterative solution time as the convergence criteria section discussed, the values have been reduced without a loss in accuracy.

DATA EXTRACTION FROM MODELS

Data output was extracted from all models through the saved output files from the surface monitors. The results were considered acceptable in terms of convergence when the model predictions reached a relatively steady state for a moving average value of approximately 50 time steps (seconds). An example of a typical plot of data output from a monitor is shown in Figure 3.15.

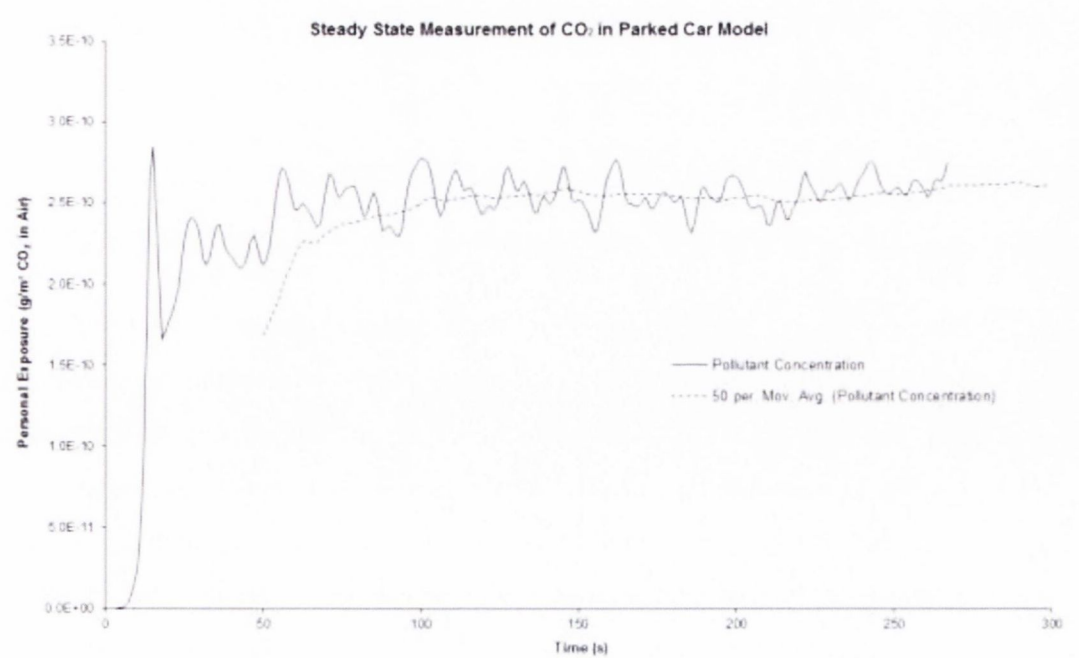


FIGURE 3.15. METHOD TO DETERMINE A STEADY STATE MEASUREMENT OF POLLUTANT CONCENTRATION ALONG FOOTPATH (PARKED CAR MODEL DATA ON WINDWARD FOOTPATH).

The plot displays a relatively clear steady-state pattern comparing the raw data to the moving average trend line with a period of 50 seconds. This method of analysis was used to identify a steady state output in all models. Where a steady state results is visible from the moving average plot, the average concentration was then calculated for each model from the time the steady state is observed to begin and end. The results in the investigations then compared the average measured concentration on the footpaths between each reference and passive control model. The difference between the reference and passive control models was then calculated to define the percentage improvement or deteriorating in air quality on the respective footpath as outlined in Figure 3.16.

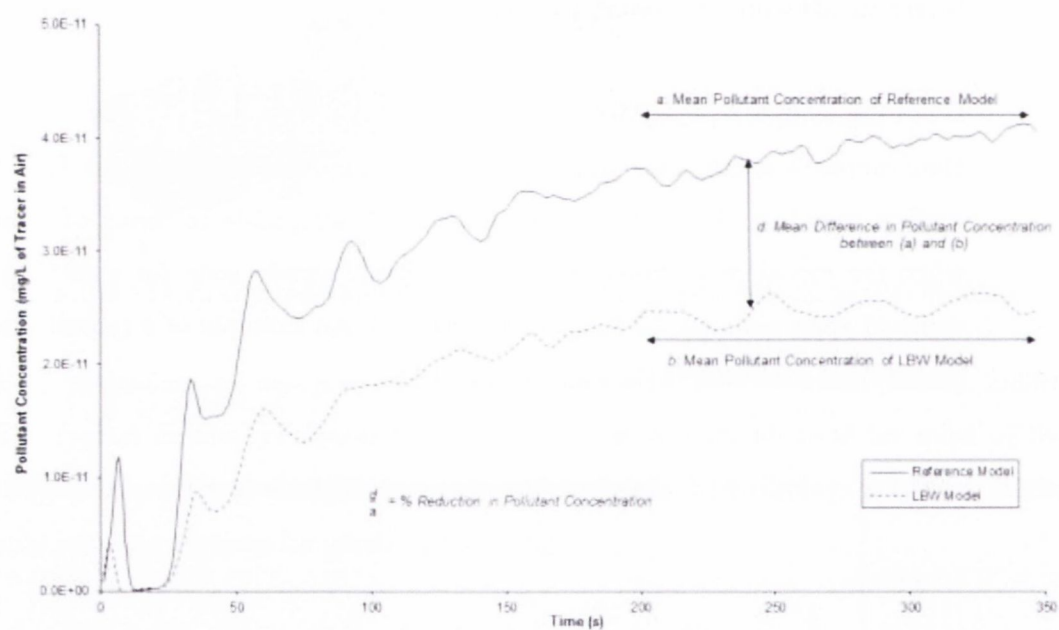


FIGURE 3.16. DETERMINING THE PERCENTAGE DIFFERENCE IN THE POLLUTANT CONCENTRATION ACHIEVED BY COMPARING A PASSIVE CONTROL MODEL TO A REFERENCE MODEL.

The calculation and analysis of the results was carried out in Microsoft Excel for all modelling investigations. The plot displays a clear reduction in the measured pollutant concentration on the footpath of the reference model compared to the passive control model. To quantify the reduction or increase in pollutant concentrations between the reference and passive control models, the percentage difference between the two average steady state concentrations were calculated. In some scenarios, an increase in the pollutant concentrations would be observed, whereby the concentration measured in the passive control model would be more than the measured concentrations in the

reference model. The equation for calculating this percentage difference is displayed in Figure 3.16.

In addition to the calculation of the average steady state concentration in the modelling investigations, the standard deviation (σ) and the minimum and maximum values were calculated over the steady state period to ensure the statistical significance of the results.

3.5.2 VISUALISATION OF RESULTS

The visualisation of results is a crucial element of the post-processing stage as there is an inherent need to understand the air flow and pollutant dispersion patterns in the models. Two main methods were adopted for the investigation of passive controls; vector or contour plots. Both methods allowed for the pollutant concentrations to be viewed in the canyon models and comparisons were carried out between the plots to identify the reasons for changes in air quality on the footpaths.

3.5.2.1 VECTOR PLOTS

The vector plot displays the flow of air and pollutant dispersion in the canyon as vectors. The vector plot is beneficial in that the arrows define the wind direction and the size of the vector shows the magnitude of the wind parameter i.e. the strength of the wind. In addition, the colour of the velocity vectors illustrate the pollutant concentration at a specific location in the model as displayed in Figure 3.17.

The differences in air flow patterns and pollutant concentrations can then be compared between models to better understand the percentage results calculated between a reference and LBW model or the same model with different boundary conditions e.g. low and high wind speeds in Figure 3.17. The benefit of the vector plots is the ability to determine the relationship between a series of models for a specific range of pollutant concentrations. It can also identify the factors that influence pollutant dispersion in street canyon models. The vector plots also give a good representation of air flow and dispersion patterns in a three-dimensional context.

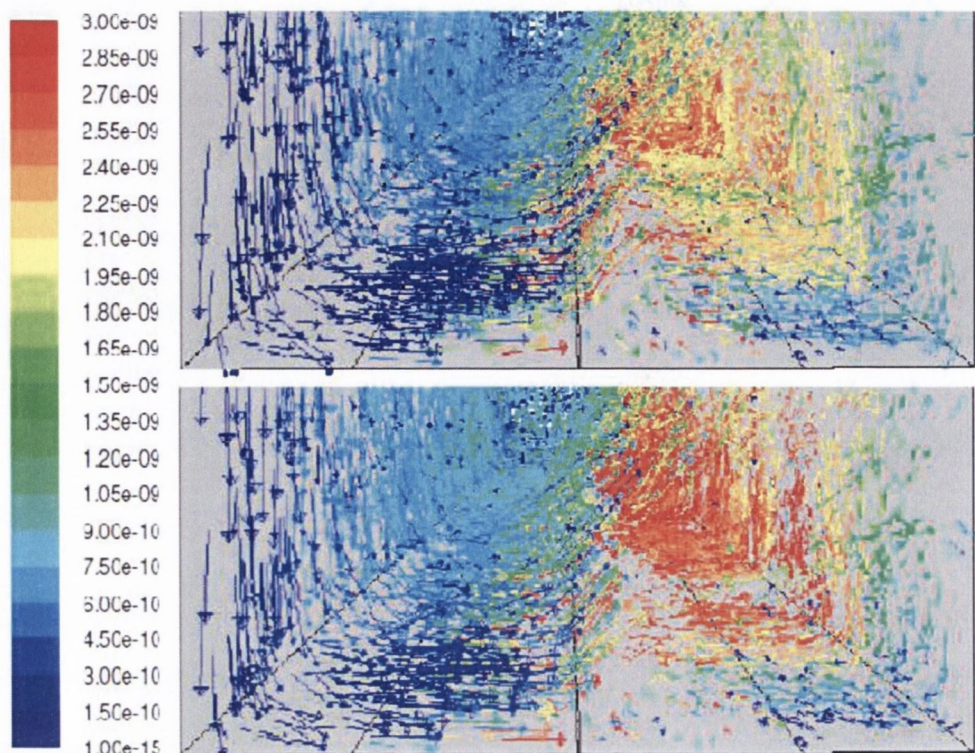


FIGURE 3.17. VECTOR PLOT OF POLLUTANT CONCENTRATIONS IN STREET CANYON MODELS WITH A LBW PASSIVE CONTROL.

3.5.2.2 CONTOUR PLOTS

The contour plot is another useful method of evaluating the air flow and pollutant dispersion patterns in a street canyon model. Figure 3.18 displays a clear pattern of pollutant concentrations on the surface of two canyon models for use in comparing the dispersion patterns in the models.

The main shortcoming of this method was the restriction to two-dimensional views (model surfaces or inserted cross-sectional iso-surface) as the three-dimensional view with contours proved to be overly complex and difficult to visually analyse. Based on the two methods used in these studies, the vector plots were considered as the most useful for analysing three-dimensional models and interpreting air flow and pollutant dispersion patterns for comparison between models.

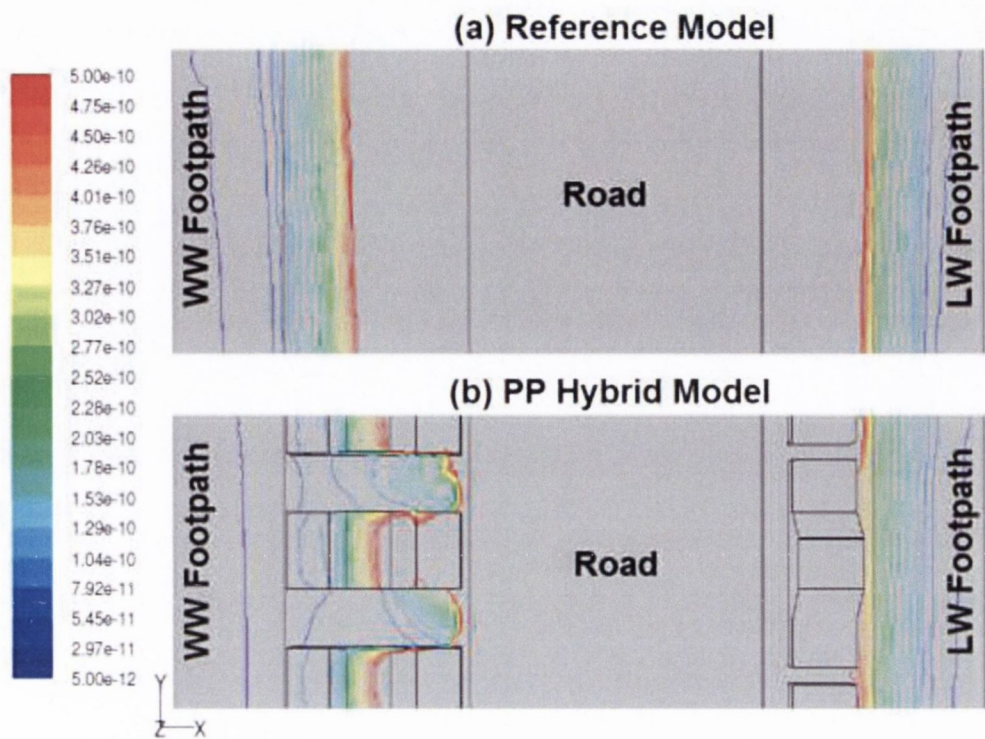


FIGURE 3.18. CONTOUR PLOT OF POLLUTANT CONCENTRATIONS ON FOOTPATHS OF A REFERENCE AND PASSIVE CONTROL MODEL.

3.5.3 PASSIVE CONTROL MODELS

3.5.3.1 HEIGHT SELECTION

The introduction of low boundary walls (LBWs) in a passive control model provides an additional element of the street canyon geometry and a series of modelling investigations were carried out to determine the optimal wall height. Four heights were investigated ranging from 0.3 m to 1.0 m. The results for the percentage difference in concentration along the centre of both footpaths in perpendicular wind conditions are shown in Table 3.2Table 3. and Figure 3.19.

TABLE 3.2. DIFFERENCE IN PERCENTAGE POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW MODELS AT 1.76 m HEIGHT IN 2 m/s WIND SPEEDS AND FOR VARYING WIND CONDITIONS.

LBW Height (m)	Parallel	Perpendicular		Total
	LW/WW	LW	WW	
0.3	19%	25%	51%	95%
0.5	33%	21%	44%	98%
0.8	37%	15%	40%	93%
1.0	62%	12%	26%	100%

The results in Table 3.2 demonstrated the potential for improved air quality on the footpaths with an increase in the height of the LBWs in parallel conditions, which was due to the LBWs effectively channelling the pollutants along the centre of the canyon and away from the footpaths. In perpendicular conditions, the increased height of the LBWs led to increased fractions of pollutants being trapped on the footpaths. The low wind speed played a part in these results and higher wind speeds in the canyon would lead to differences in the model results.

Despite the 1.0 m LBW performed the best, the 0.5 m was chosen as the optimal height for the LBW as it showed good performance in reducing pollutant concentrations on the footpaths. The 0.3 m wall was considered as a potential trip hazard and as the 0.5 m wall had also been used in previous investigations, therefore it was considered the most suitable height for the LBWs in an urban canyon environment (King et al., 2009; McNabola et al., 2009).

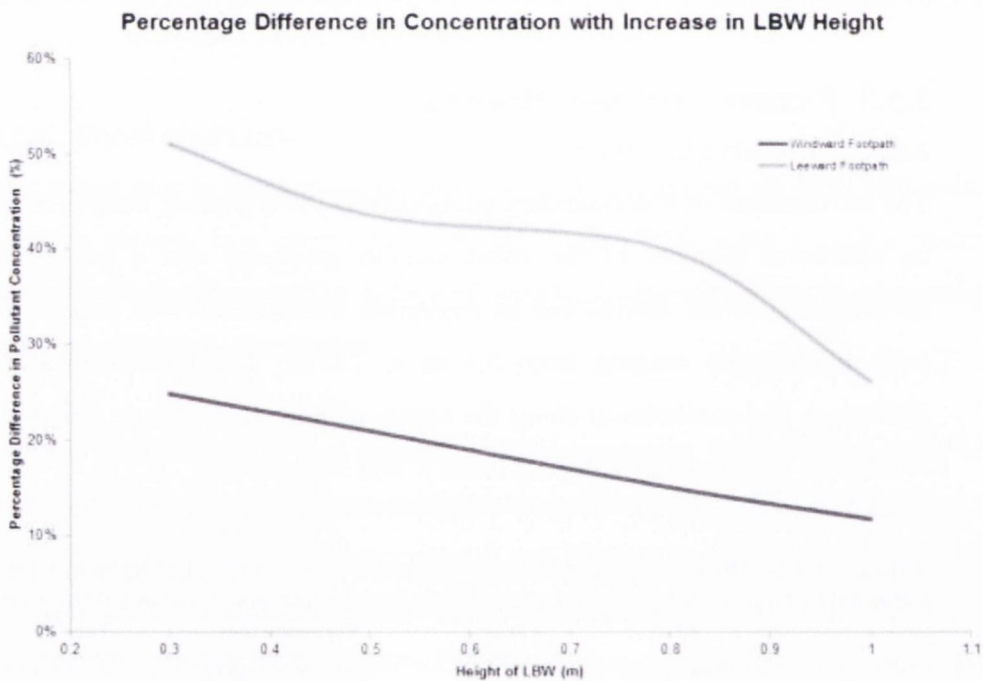


FIGURE 3.19. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW MODELS AT 1.76 M HEIGHT IN 2 M/S WINDS FOR PERPENDICULAR WIND CONDITIONS.

3.5.3.2 VARIABLE CANYON DIMENSIONS

The LBW study was extended to assess the effectiveness of the 0.5 m walls in canyons with a similar road width (7.0 m), yet different footpath widths (ranging from

2.0 m to 5.0 m). A H/W ratio of 1.0 was used for each canyon model to create a similar shaped vortex was maintained in each footpath scenario (Gallagher et al., 2011). Table 3.3 and Figure 3.20 display the results of the percentage difference in pollutant concentrations along the centre of both footpaths for a varying footpath width in different wind conditions.

TABLE 3.3. DIFFERENCE IN PERCENTAGE POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW MODELS ALONG THE CENTRE OF THE FOOTPATHS AT 1.76 M HEIGHT IN DIFFERENT WIND CONDITIONS.

Footpath Width (m)	Wind Direction			
	Perpendicular		Parallel	
	LW	WW	LW	WW
2.0	17%	41%	35%	30%
3.0	16%	42%	39%	35%
4.0	17%	37%	30%	28%
5.0	25%	42%	29%	29%

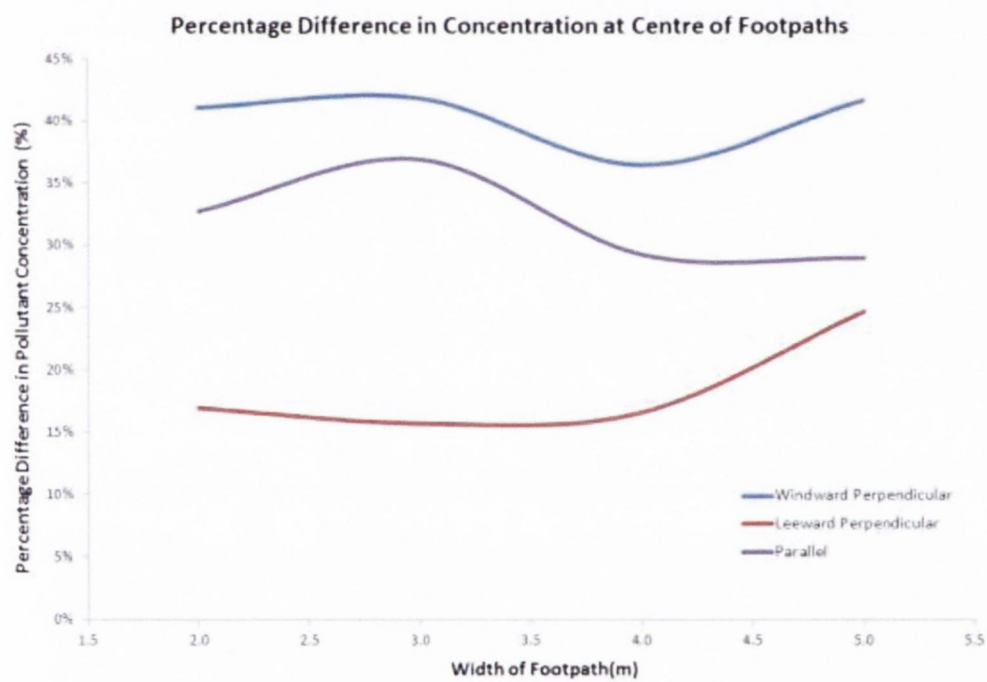


FIGURE 3.20. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW MODELS ALONG CENTRELINE OF FOOTPATHS AT 1.76 M HEIGHT IN DIFFERENT WIND CONDITIONS.

The results from Figure 3.20 show deviations in the percentage difference in pollutant concentrations on both footpaths in different wind conditions with an increase in the footpath widths. The results displayed differences of between 5% and 10% due to the

increase in the footpath width altering the shape of the primary vortex in the canyon and the turbulence created in the footpath zones. These results defined the optimal LBW height and the confidence of results for different LBW models as an effective passive control of air pollution at street level.

4. OPTIMISATION OF ON-STREET CAR PARKING AS AN ALTERNATIVE PASSIVE CONTROL IN STREET CANYONS

4.1 INTRODUCTION

Previous investigations of passive controls have included low boundary walls (LBWs) (McNabola et al., 2009), avenue trees (Gromke et al., 2008; Buccolieri et al., 2009) and noise barriers (Bowker et al., 2007; Baldauf et al., 2008; Finn et al., 2010). This chapter investigates on-street parking as an alternative method of manipulating air flow and improving local pollutant dispersion in an urban canyon environment. Parked cars are a common element within street canyons and this study aims to determine the associated benefits/drawbacks of on-street car parking. Figure 4.1 displays a selection of different parking layouts in street canyons. This study aims to analyse different configurations of on-street parking with the objective of finding the best layout to act as a passive control improving urban air quality at street level.



FIGURE 4.1. SAMPLE IMAGES OF (A) PARALLEL, (B) PERPENDICULAR, (C) CENTRAL AND (D) DIAGONAL (45°) ON-STREET PARKING LAYOUTS.

In the past, researchers have focused on the negative impacts of urban parking and planners have aimed to introduce systems to reduce urban driving and thus reduce air pollution. Steinberga & Kleperis (2004) determined that cars older than 10-12 years were previously a source of pollution even for a duration after parking and calculations, showing higher benzene and carbon oxides concentrations for people living in areas beside on-street parking. Providing parking can encourage drivers to take their vehicles into urban areas and emit pollutant emissions. The act of parking is itself a source of pollutant emissions, thus the parking layout can affect the amount of emissions from parked vehicles. Höglund (2004) found up to 40% emission reductions was evident after comparing underground garage parking to kerbside parking. These studies highlight the impacts of on-street parking, yet parked cars remain a common site in urban environments.

Therefore, this investigation focused on finding conclusive evidence for the potential of on-street parked cars as a passive control. The study aimed at finding the optimal layout of parked cars to maximise local dispersion and reduce personal pollutant exposure at street level. The study assessed a number of different on-street parking configurations and quantified their potential in different wind conditions. The investigation considered the potential reductions achievable by introducing parallel, perpendicular, 45° or central parking configurations as passive controls. The impact of car space occupancy and parking bay spacing was also investigated as were the impacts due to changing wind speed and wind direction.

4.2 METHODOLOGY

The study comprised several numerical modelling tests to assess the potential of on-street parking as a passive control in generic urban street canyons. The first four series of tests investigated the percentage reduction in pedestrian exposure to the tracer pollutant (CO₂) as a result of introducing different car parking configurations in the street canyon models. These parking regimes represented typical parking layouts which occurred in the urban environment: parallel, perpendicular, diagonal (45°) and central parking. The canyon simulations investigated differences in pollutant concentrations for varying wind speeds (ranging from 2 m/s to 16 m/s) and wind directions (0° and 90°).

After identifying the optimal parking bay layout, the effect of different occupancy rates in the parking bays was also assessed. Methods to improve the parking layouts as effective passive controls were assessed. This was carried out by reducing the parking bay dimensions to determine the optimal parking bay layout to improve air quality on the footpaths.

4.2.1 MODELLING PROCEDURE

This section describes the modelling procedures specific for the investigation of on-street parking as passive controls in conjunction with the modelling methodology outlined in Chapter 3. This was to have continuity in each of the passive control modelling studies and the comparability of output from the results of the parked car models. The procedure for each modelling case is detailed in subsequent sections of this chapter.

4.2.1.1 MODELLING SET-UP

This investigation aimed to determine the effect of different parked car configurations on air quality and pollutant transport along the footpaths. The study assessed two sets of models which differed from one another with the inclusion of parked cars in one set of models.

All street canyon models were constructed with a symmetrical H/W ratio of 1.0 to preserve a similar shaped primary eddy between each layout (Figure 4.2). The footpath and total road widths remained constant in all of the models, with a varying parking bay width in each model case. This created a canyon of different widths (W_c) in each of the case models, but the building height (H_b) equalled W_c in all model scenarios. The models were extended above the rooftop of the buildings and back from the building faces at rooftop level by a distance of $H_b/2$ or $W_c/2$, respectively. These dimensions were chosen based on previously validated modelling investigations of passive controls (McNabola et al., 2008a; Gallagher et al., 2011). The extended model height and width of the model above rooftop level allowed for air flow to enter or exit the canyon above the buildings.

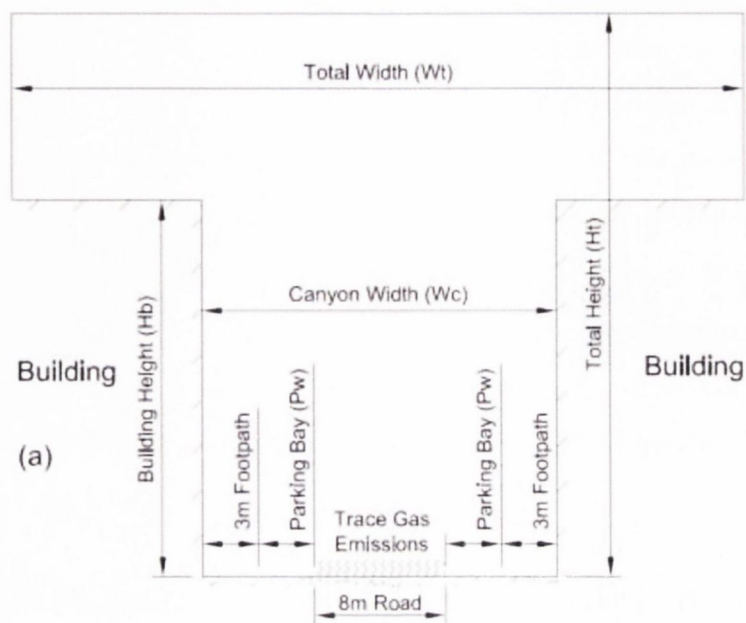


FIGURE 4.2. GENERIC STREET CANYON LAYOUT FOR CASES 1-3 WITH H/W RATIO OF 1.0 (GALLAGHER ET AL., 2011).

4.2.1.2 MESH DISCRETIZATION

A case specific mesh independence or discretization study was carried out for the parked car investigation as outlined in Chapter 3. Three grid schemes were assessed using the perpendicular parked car layout and the results are displayed in Figure 4.3.

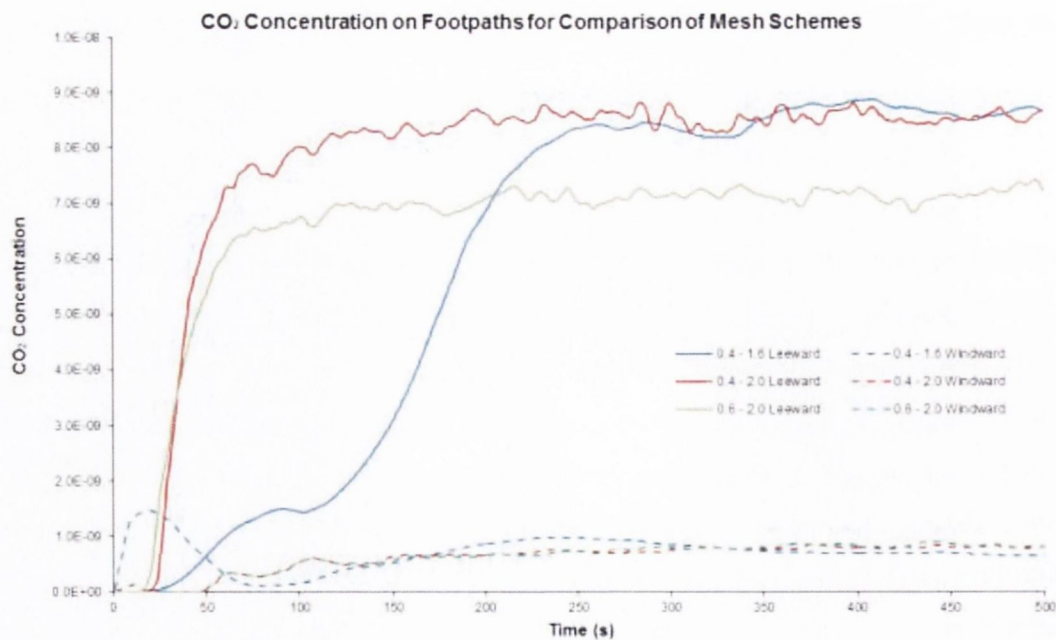


FIGURE 4.3. CONCENTRATIONS ALONG FOOTPATHS FOR DIFFERENT MESH SCHEMES.

The sensitivity test compared the results from the three models with different mesh schemes. The schemes consisted of a 0.4 m or 0.6 m triangular mesh in a paved grid configuration on the canyon floor with a 1.6 m or 2.0 m tetrahedral mesh of the model volume.

The plot showed similar concentrations on the windward footpath for all mesh schemes. The plot also showed that both 0.4 m surface mesh models (blue and red in Figure 4.3) provided a strong agreement for measured pollutant concentrations. However, a difference was noted in the 0.6 m surface mesh model (green). The optimal mesh size study considered the 0.6 m surface mesh unsuitable for the parked car modelling study. Therefore, the floor of the parked car models was meshed with 0.4 m spaced triangular mesh elements with the 2.0 m tetrahedral mesh.

4.2.1.3 MODELLING TRACER EMISSIONS

Emissions of the tracer gas (CO_2) were released from the road surface at ground level (i.e. $Z = 0$) in each model (as shown in Figure 4.2) at a fixed generic emissions rate of 1×10^{-5} kg/s. The CO_2 acts as an inert indicator pollutant to assess the dispersion of any inert gaseous pollutant common in an urban street canyon. A comparative examination was carried out to compare CO_2 (44.01 g/mol) with the tracer gas, C_2H_6 (30.07 g/mol) (Shao & Riffat, 1994; Moryń-Kucharczyk & Gnatowska, 2007; Heist et al., 2009). A 94% agreement was observed between the results for the comparative study, which was deemed satisfactory for the use of CO_2 to simulate pollutant dispersion in the reference and passive control models.

4.2.2 PARKED CAR MODEL INVESTIGATIONS

Each of the parked car cases were constructed separately and prepared in the same manner to maintain uniformity between the modelling procedures. This section outlines the details for the construction and preparation of each of the model cases in conjunction with general modelling details discussed in Chapter 3.

4.2.3 CASES 1-4 FOR DIFFERENT PARKING LAYOUTS

Each model was constructed in accordance with the measurements detailed in Table 4.1. The canyon floor was made up of two 4 m wide traffic lanes, two 3 m footpaths

(F_p) and one or two parking bays (P_w) in the street canyon. In the reference models the parking bays remained empty, while in the each of the parked car models, medium-sized cars (see Figure 4.5) were positioned into each parking space until no empty parking spaces were available (i.e. occupancy rate = 100%).

TABLE 4.1. DIMENSIONS AT STREET LEVEL IN PARKED CAR MODELS.

Case No.	Street Floor Dimensions ^a			
	F_p	Road	P_w	V_d
Case 1	3.0	8.0	3.00	0.4
Case 2	3.0	8.0	5.00	1.3
Case 3	3.0	8.0	5.65	1.3
Case 4	3.0	8.0 ^b	5.00	1.3

^a All dimensions in metres (see Figure 4.2)
^b Consisting two 4 m lanes on either side of central parking bay

The spacing between vehicles varied for each modelling study and is represented by the value of perpendicular vehicle distance (V_d) in Table 4.1. A monitoring line was inserted into each model at a breathing height of 1.76 m, to represent the path of a pedestrian walking the full length of the canyon at the centre of each footpath as defined in Chapter 3.

The models were solved for scenarios of varying wind speed and direction. The results were compared to assess the effects of variable wind conditions on air flow in an urban canyon and the effect of parked cars as a passive control of air pollution in these varying conditions. The four tests included in this study were as follows:

- Case 1 – Parallel parked cars
- Case 2 – Perpendicular parked cars
- Case 3 – Diagonally (45°) parked cars
- Case 4 – Centrally (parallel) parked cars

Illustrations of the street canyon layout and related dimensions are shown in Figure 4.4 and Table 4.2, respectively. Figure 4.4 denotes the canyon width (W_c) equals the building height (H_b) in each of symmetrical street canyon models.

The parking bay width (P_w) differed in each of the parked car models. The overall dimensions of the parked car models are shown in Table 4.2 and refer to the dimensions outlined in Figure 4.2.

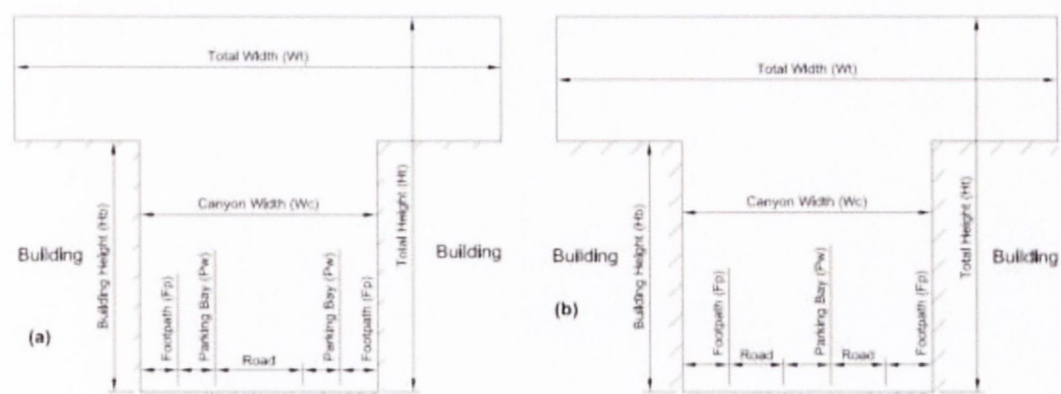


FIGURE 4.4. CROSS-SECTIONS FOR (A) CASES 1-3 AND (B) CASE 4 PARKING BAY LAYOUTS IN GENERIC STREET CANYONS.

TABLE 4.2. OVERALL DIMENSIONS OF STREET CANYONS LAYOUTS (IN METRES).

Case No.	Overall Model Dimensions			
	H_b	H_t	W_c	W_t
Case 1	20.0	30.0	20.0	40.0
Case 2	24.0	36.0	24.0	48.0
Case 3	25.3	38.0	25.3	50.6
Case 4	19.0	28.5	19.0	38.0

4.2.4 PARKED CARS LAYOUTS

The shape and design of vehicles vary hugely between makes or models and therefore for the purpose of this study a generic vehicle design was created. The dimension of the generic medium-sized car (1.7 x 4.6 x 1.8 m high) is displayed in Figure 4.5 and is used for each of the parked car models.

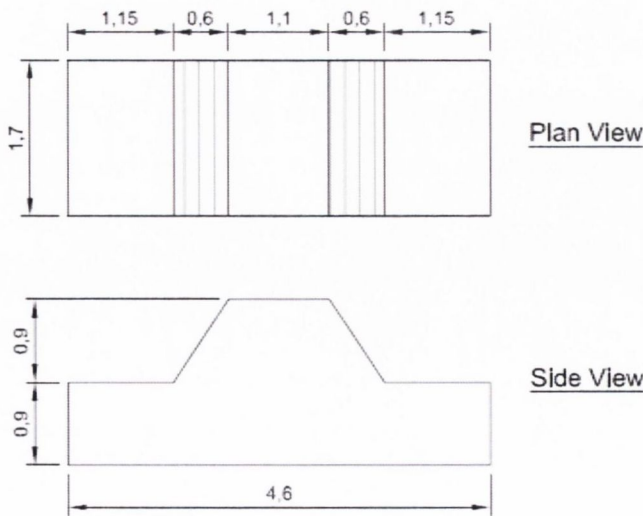


FIGURE 4.5. GENERIC VEHICLE DIMENSIONS FOR PARKED CAR MODELS (DIMENSIONS IN METRES).

Different layouts for on-street parking bays were required for each of the model cases. The layouts displayed in Figure 4.6 show the parking bay layouts and associated dimensions for the four cases.

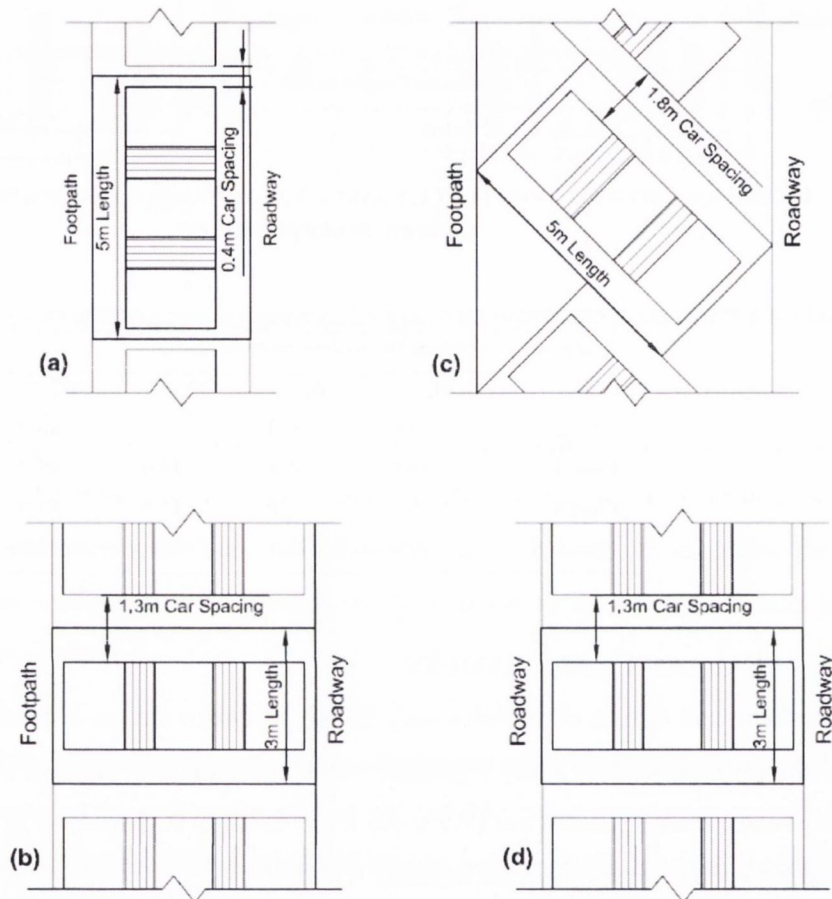


FIGURE 4.6. PLAN VIEW FOR (A) PARALLEL, (B) PERPENDICULAR, (C) 45° DIAGONAL AND (D) CENTRAL ON-STREET PARKING LAYOUTS.

4.2.5 VARYING WIND CONDITIONS

Wind speed and direction influences the dispersion patterns of air pollutants in an urban canyon (Ghenu et al., 2008; Hu et al., 2009). Therefore, a range of different wind speeds and directions were investigated to assess their effects on air flow and pollutant dispersion. Four different wind speeds were chosen to represent the range of speeds likely to occur within an urban canyon environment. These wind speeds ranged from the lower end of the spectrum with 2 and 4 m/s winds to high wind speeds of 8 and 16 m/s and were simulated using a uniform wind profile in preference to a logarithmic wind profile. In addition, air flow was simulated parallel and

perpendicular to the direction of traffic flow in the canyon for each wind speed. The two wind directions were selected as they would simulate the most extreme conditions for wind direction.

4.2.6 PARKING SPACE OCCUPANCY RATES

Based on the outcome of the modelling results for the four parked car studies, one of the cases (the case with the best overall reduction in personal pollutant exposure) would be chosen for further analysis to assess the effect of different occupancy rates in the parking bays. This part of the modelling study aimed to determine the relationship between the percentage difference in pollutant concentrations and a range of car occupancy rates. The number of cars which accounted for full capacity in the parking bays on the 200 m stretch differed for each modelling case. Case 1 consisted of 40 parallel parked cars, compared to 39 cars for the 45° diagonal layout and 66 cars in the perpendicular and central parking layouts.

A range of suitable occupancy rates were selected to allow an even number of cars to remain in each model. The occupancy rates chosen were 10%, 25%, 50%, 75%, 90% and 100% and were to be compared to the reference model with an occupancy rate of 0%. Using a random number generation tool in Microsoft Excel, the selection of vehicles in the parking bays to be removed was carried out at random. This allowed the selection process for creating the different occupancy rate models to be carried out in an unbiased manner. The cars on the leeward (LW) and windward (WW) sides of the canyon were numbered.

This process was repeated until a number of vehicles in the model were removed to match the desired occupancy rates e.g. 4 out of 40 vehicles would be removed to correspond to a 90% occupancy rate in the parking layout. This random number generator was used for each separate parking bay configuration. This was to replicate the random pattern that would be considered normal in a canyon with respect to car parking behaviour. The occupancy rates were investigated for the same conditions as the previous cases, i.e. the range of different wind speeds and directions.

4.2.7 PARKING BAY OPTIMISATION

A reduction of the spacing between the parked cars by 10 or 20% could improve the effectiveness of parked cars as a passive control. The parking layouts had investigated a width of 3.0 m, and as some guidelines have stated that a minimum width of between 2.4 m and 2.5 m can be used, these reductions of the parking bay width would assess the effects on air quality (IStructE, 2002; Laois County Council, 2007; Rochford District Council, 2010). In addition, the introduction of a hybrid parking layout (a combination of two different parking layouts on adjacent sides of the road) could provide optimised conditions for reduced pollutant concentration on both footpaths. The two combinations investigated in this study were (i) parallel and perpendicular parking bays and (ii) parallel and diagonal parking bays. These were chosen as parallel parking provided consistent pollutant reductions on the leeward footpath, unlike the perpendicular and diagonal layouts, and these layouts provided the best reduction of pollutant concentrations on the windward footpath.

The effects of reducing spacing between vehicles and introducing hybrid parking layouts were also assessed. This aimed to provide additional information to urban planners to improve the effectiveness of current parking regimes as more effective passive control options.

4.3 MODELLING RESULTS

This section outlines the results of the modelling investigation for (i) the four parking bay regimes, (ii) the parking bay occupancy rate models (iii) the optimised parking bay layouts.

4.3.1 CASE 1: PARALLEL PARKING

The model layout of the parallel parked cars at street level is illustrated in Figure 4.7. In addition, the results for the Case 1 investigation of the parallel parking layout are presented in Table 4.3.

The results show that the presence of parallel parked cars provided an improvement in air quality compared to the absence of parked cars on both footpaths in all wind conditions. In the perpendicular wind model, improvements in air quality of up to

35% and 49% were calculated on the leeward and windward footpaths, respectively. For a parallel wind direction, a symmetrical layout was constructed for Case 1 (to reduce the computational running time) as the average concentrations were determined to be the same on both footpaths in the reference and parallel car model. The average reduction in pedestrian exposure was calculated to be up to 33% in the parallel wind models.

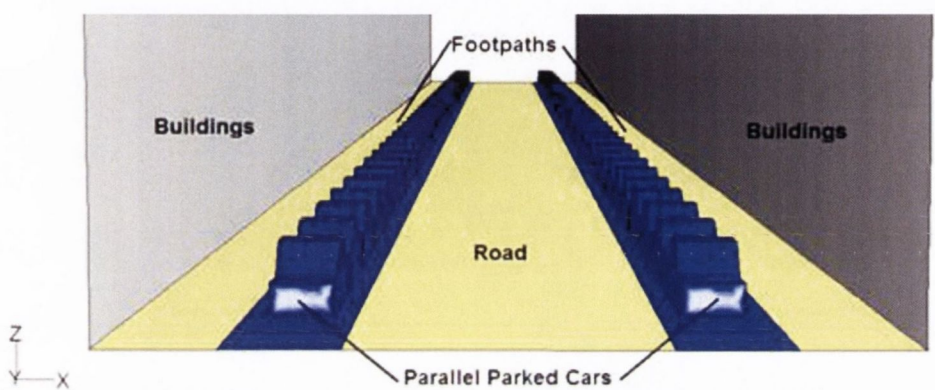


FIGURE 4.7. FLUENT GRAPHIC OF PARALLEL PARKED CARS IN STREET CANYON.

TABLE 4.3. REDUCTIONS IN CO₂ CONCENTRATIONS BETWEEN PARALLEL PARKED CARS & REFERENCE MODELS.

Wind Direction	90°		0°
Wind Speed (m/s)	Leeward	Windward	Average
2	35%	46%	33%
4	34%	47%	33%
8	33%	48%	32%
16	31%	49%	32%
Mean	33%	48%	32%

4.3.2 CASE 2: PERPENDICULAR PARKING

A combination of positive and negative results was identified in Case 2. Negative percentages constituted an increase to the predicted pollutant concentrations between models. The layout of the perpendicular parked cars is displayed in Figure 4.8. Table 4.4 also shows the results of the Case 2 investigation for perpendicular parked cars.

The results shows that the presence of perpendicular parked cars caused a reduction in the pollutant concentration of up to 41% on the windward footpath and an average increase of 35% on the leeward footpath. The improvement in air quality on the

windward footpath was similar to the percentage differences calculated for the footpath LBW models in the next chapter. In parallel wind conditions, an average reduction in personal exposure of up to 30% on both footpaths was found between the reference and perpendicular car models. A substantial difference of 18% in the percentage difference in pollutant concentrations were calculated between low and high wind speeds, suggesting the influence of wind was more significant in parallel wind conditions.

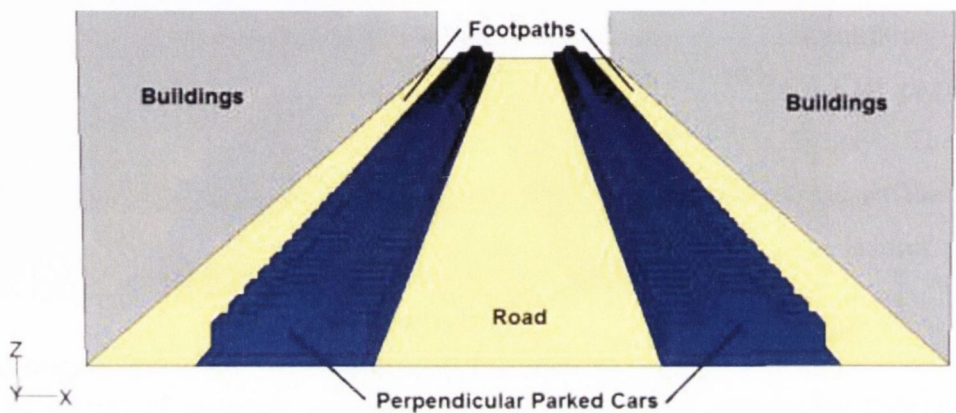


FIGURE 4.8. FLUENT GRAPHIC OF PERPENDICULAR PARKED CARS IN STREET CANYON.

TABLE 4.4. REDUCTIONS IN CO₂ CONCENTRATION BETWEEN PERPENDICULAR PARKED CARS AND REFERENCE MODELS.

Wind Direction	90°		0°
Wind Speed (m/s)	Leeward	Windward	Average
2	-37%	41%	12%
4	-36%	41%	19%
8	-35%	39%	25%
16	-34%	37%	30%
Mean	-35%	40%	22%

Note: A negative percentage corresponds to an increase in the pollutant concentration.

4.3.3 CASE 3: 45° DIAGONAL PARKING

Figure 4.9 and Table 4.5 presents the layout and results for the Case 3 investigation for 45° diagonally parking cars. Improvements and deteriorations in air quality were measured in some of the parked car models in Case 3. In addition, the 45° parking configuration did not display a symmetrical layout and therefore separate results were attained on both footpaths in parallel wind conditions.

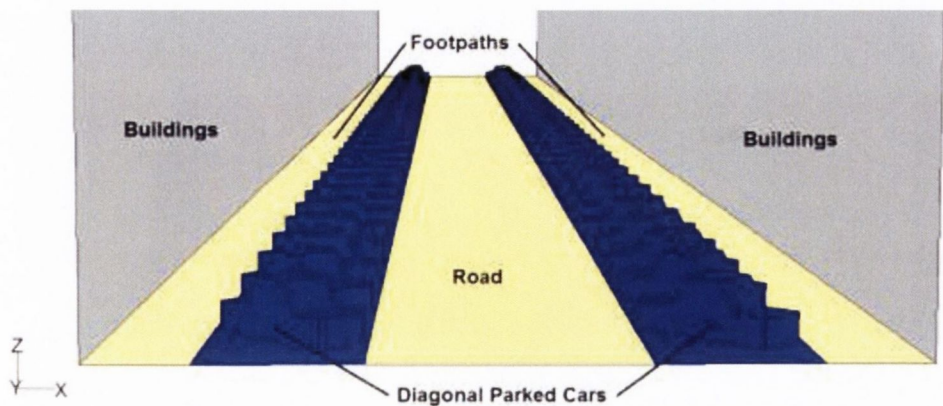


FIGURE 4.9. FLUENT GRAPHIC OF 45° DIAGONAL PARKED CARS IN STREET CANYON.

TABLE 4.5. REDUCTIONS IN CO₂ CONCENTRATION BETWEEN 45° DIAGONAL PARKED CARS AND REFERENCE MODELS.

Wind Direction	90°		0°	
Wind Speed (m/s)	Leeward	Windward	Leeward	Windward
2	-23%	47%	-8%	-288%
4	-25%	49%	-3%	-275%
8	-26%	53%	0%	-249%
16	-28%	56%	5%	-233%
Mean	-26%	51%	-2%	-261%

Note: A negative percentage corresponds to an increase in the pollutant concentration.

For a perpendicular wind flow, the data showed that the introduction of 45° parked caused an average increase of 26% in personal exposure of pollutants compared to their absence on the leeward footpath. Pollutant reduction was observed on the windward footpath of up to 56% for perpendicular winds. The presence of parked cars was found to provide a 2% increase in pedestrian exposure compared to their absence on the leeward footpath and a very significant increase of up to 288% on the windward footpath due to the channelling effect of the diagonal parked cars in parallel wind conditions.

4.3.4 CENTRAL PARKING

The layout of parked cars in the central parking bay is illustrated in Figure 4.10. Table 4.6 displays the results of the Case 4 investigation for centrally parked cars. In a similar manner to the previous cases, a combination of positive and negative results was identified for Case 4.

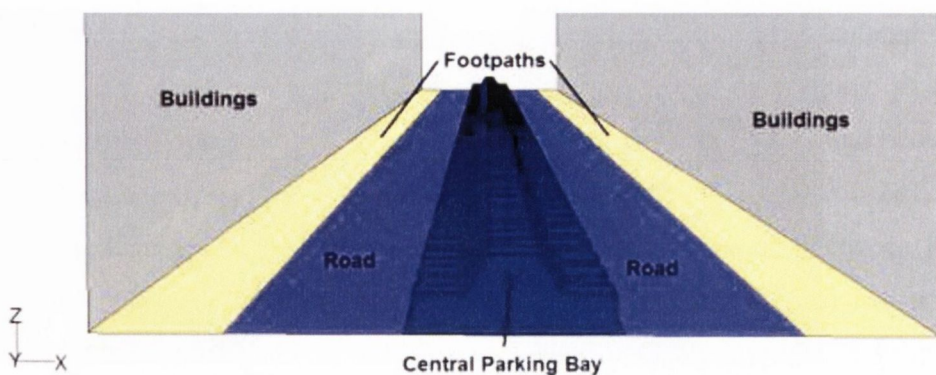


FIGURE 4.10. FLUENT GRAPHIC OF CENTRALLY PARKED CARS IN STREET CANYON.

TABLE 4.6. REDUCTIONS IN CO₂ CONCENTRATION BETWEEN CENTRALLY PARKED CARS AND REFERENCE MODELS.

Wind Direction	90°		0°
Wind Speed (m/s)	Leeward	Windward	Average
2	-24%	30%	23%
4	-24%	29%	23%
8	-24%	25%	24%
16	-25%	23%	24%
Mean	-24%	27%	23%

Note: A negative percentage corresponds to an increase in the pollutant concentration.

The results in Table 4.6 show that the presence of perpendicular parked cars in the central parking bay of the canyon provided a decrease in pollutant concentration of up to 30% on the windward footpath and an increase of up to 25% on the leeward footpath in perpendicular winds. In parallel wind conditions, an average improvement in air quality of 23% was calculated between the reference and centrally car models.

4.3.5 VARYING WIND CONDITIONS

The results in the parked cars models demonstrated changes in air quality for different wind speeds and directions. The parallel and perpendicular wind direction primarily clearly influenced the dispersion of pollutants within the canyon. The parked cars acted as an effective baffle wall in parallel wind conditions for most parking scenarios. In addition, the larger spacing presented between the road and footpath by the parking bays further improved air quality. In perpendicular winds, reductions in pollutant concentrations were mainly observed on the windward footpath in the parked cars models, with less substantial reductions or increases on the leeward

footpath. This was due to the wind direction at street level transporting pollutants away from the windward footpath and towards the leeward footpath (Figure 4.11).

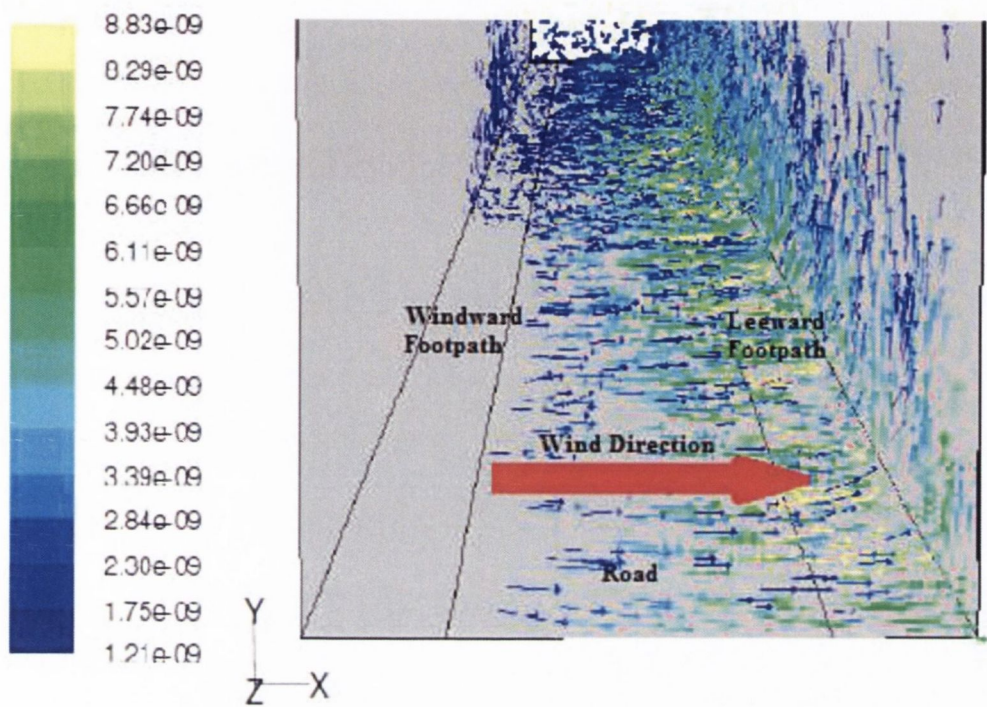


FIGURE 4.11. DISPERSION OF POLLUTANTS AT STREET LEVEL FROM WINDWARD FOOTPATH TO LEEWARD FOOTPATH.

Changes in wind speed influenced the potential of the parked cars as passive controls of air pollution. The increase in wind speed displayed small changes in the percentage difference in pollutant concentrations on the footpaths for all cases, with the exception of a 55% difference on the windward footpath for parallel wind conditions in the diagonally parked cars model. This was due to the significant influence of the diagonally parked cars to alter the natural air flow patterns in the canyon in comparison to the other parking layouts.

The common finding of the four parking studies in both wind directions was the linear behaviour of the associated improvements or deteriorations in air quality with varying wind speed as shown in Figure 4.12. The results allow for the potential interpolation of the percentage improvement or deterioration in air quality on the footpath in specific wind conditions.

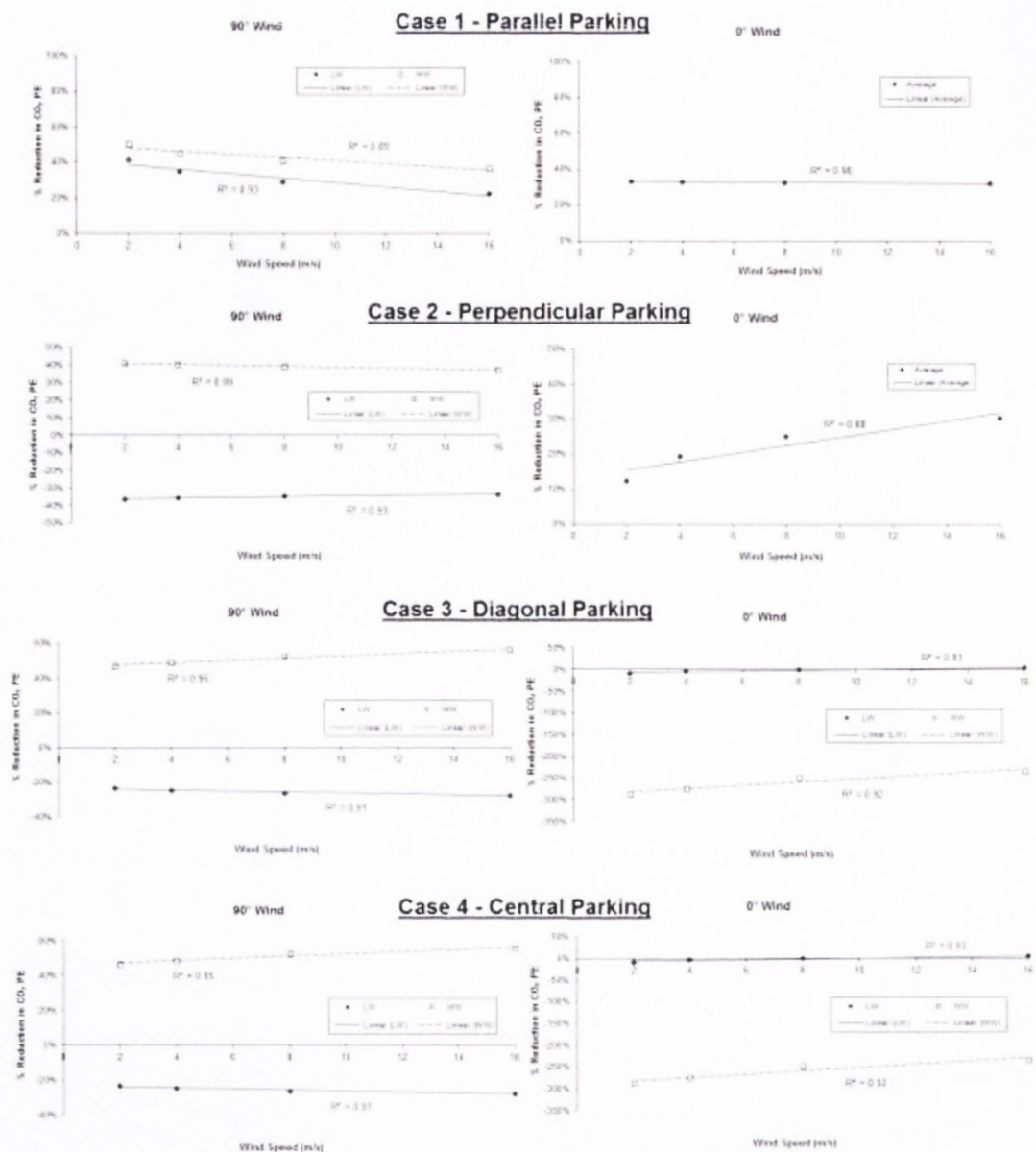


FIGURE 4.12. PERCENTAGE DIFFERENCE IN CO₂ CONCENTRATION ON FOOTPATHS BETWEEN THE REFERENCE AND PARKED CAR MODELS IN VARYING WIND CONDITIONS.

4.3.6 PARKING BAY OCCUPANCY RATES

In addition to the spacing width between vehicles, the occupancy rate of the parking bay(s) was considered to be influential to the level of reduction of pollutant concentrations on the adjacent footpaths. As Case 1 proved the best overall passive control (in terms on consistency on both footpaths), this parking bay layout was investigated further to determine the effect of different parking occupancy rates on pollutant concentrations. The parallel parking layouts provided reductions of up to 33% and 49% between the reference models and the 100% occupancy models for

parallel and perpendicular wind conditions, respectively. The potential to maintain pollutant concentration reductions on both footpaths was investigated and the results are outlined in this section. Figure 4.13 displays the findings from an assessment of the different parking occupancy rates in parallel wind conditions.

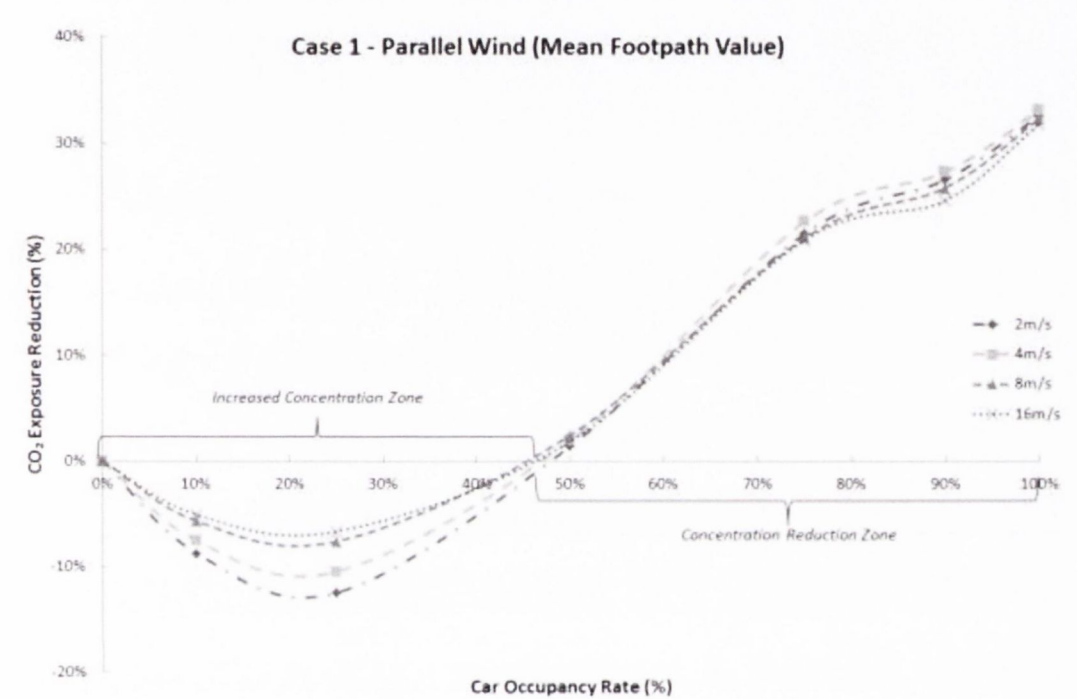


FIGURE 4.13. PLOT OF AVERAGE FOOTPATH POLLUTANT CONCENTRATION VS. OCCUPANCY RATES IN PARALLEL WIND CONDITIONS.

From Figure 4.13, deteriorations in air quality occurred from a 0% to a 45% parking space occupancy with a maximum deterioration in occurring for an occupancy rate of approximately 22.5%. This was followed by an incremental reduction in pollutant concentrations for subsequent increased parking occupancy rates. For the low parking occupancy rates, the parked cars did not effectively channel air flow along the road and segregate the clean air on the footpath with the polluted air in the road. The low occupancy rate of vehicles in the parking bays allowed paths to exist between the road and footpaths and pollutants to be transported to the footpaths. The parked cars that were present in the canyon trapped some pollutants (up to an occupancy rate of 22.5%) and caused deteriorations in air quality on the windward footpath. The larger occupancy rates led to a larger fraction of clean air being trapped on the windward footpath and the results then displayed relatively steady improvements from the worst air quality conditions for the 22.5% occupancy rate model. The plotted results show

the influence of wind speed on pollutant reduction with respect to low occupancy rates. The plots of occupancy rates against percentage pollutant exposure for a perpendicular wind conditions are displayed in Figure 4.14 and Figure 4.15.

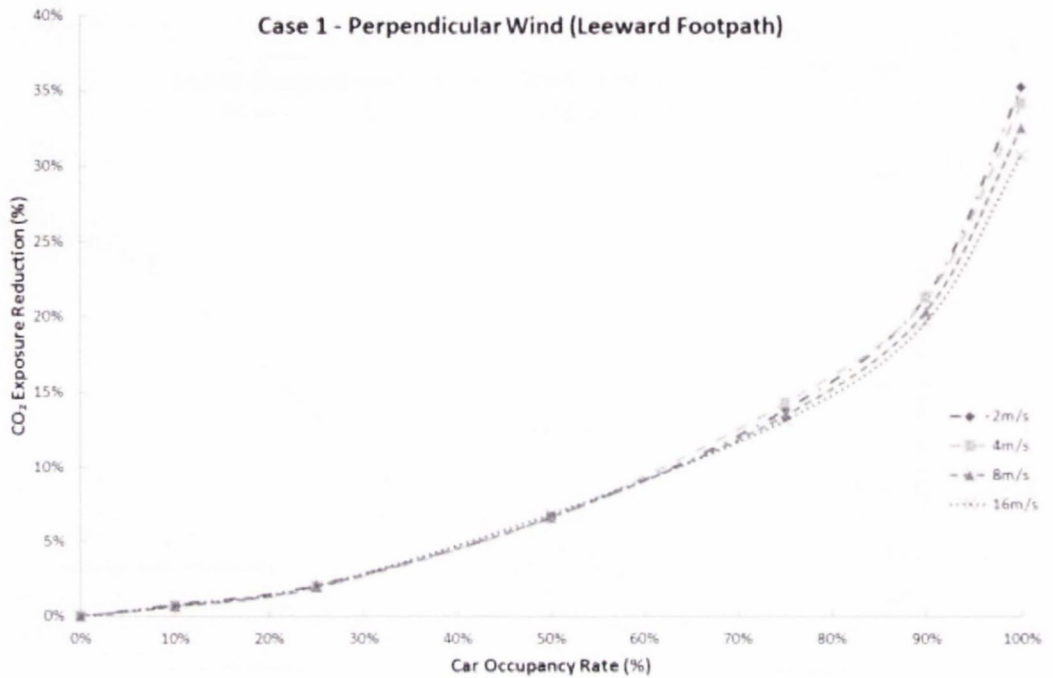


FIGURE 4.14. PLOT OF AVERAGE LEEWARD FOOTPATH POLLUTANT CONCENTRATION VS. OCCUPANCY RATES IN PERPENDICULAR WIND CONDITIONS (GALLAGHER ET AL., 2011).

Air quality on the leeward footpath was influenced by the occupancy rates of the adjacent parking bay. An exponential reduction in pollutant concentrations was noted in Figure 4.14 across all occupancy rates from 0% to 100%, with the most significant reduction evident between the 90% and 100% occupancy rates. As the gaps between vehicles equals less than 10% of the parking bay length, it becomes less influential as the parking bay occupancy rate increases.

The results from both figures indicate a relationship between the occupancy rates of cars in the parking bays to the percentage reduction of pollutant concentrations for all wind speeds. Improvements in air quality were observed with an increase in the occupancy rate on both footpaths for perpendicular winds. Figure 4.15 shows the plot of the windward footpath results for varying parking occupancy rates and wind speeds.

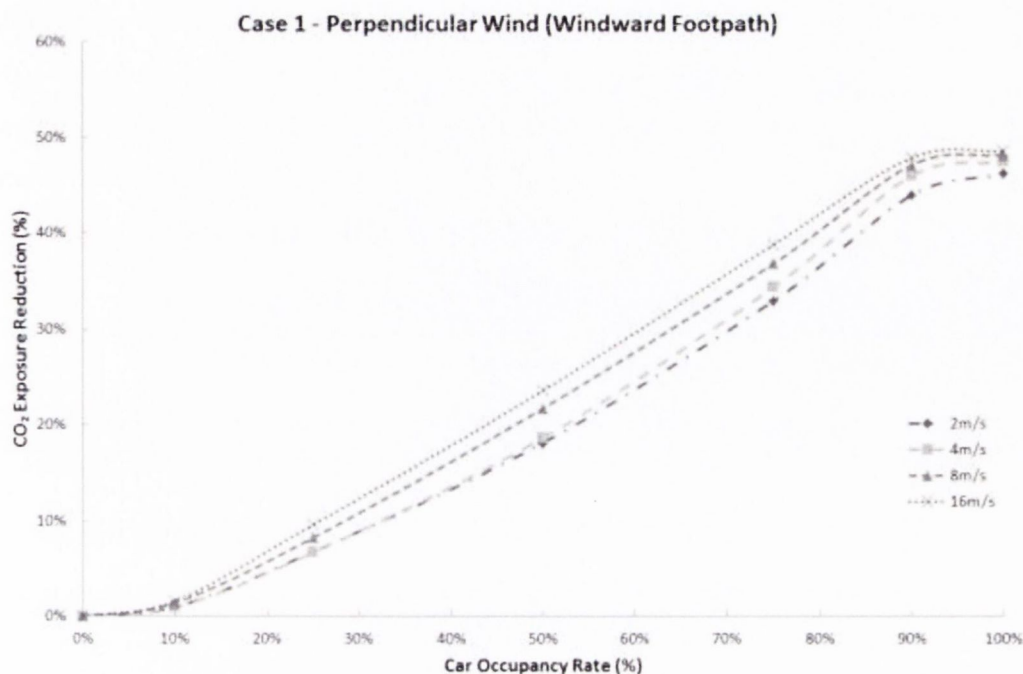


FIGURE 4.15. PLOT OF AVERAGE WINDWARD FOOTPATH POLLUTANT CONCENTRATION VS. OCCUPANCY RATES IN PERPENDICULAR WIND CONDITIONS (GALLAGHER ET AL., 2011).

The plot presents a visible sigmoid or s-curve pattern and demonstrates the curvilinear improvements between 10% and 90% with negligible difference between low (0% to 10%) and high (90% to 100%) occupancy rates. This shows that the extreme parking bay occupancy rates did not significantly affect the potential of parked cars as a passive control. The curvilinear relationship found in this study displayed steady improvements in air quality as the occupancy rate incrementally increased. The gaps that exist in the parking bays do affect air quality on the footpaths, but it can be seen from the results that the effect on air quality can be estimated even with a random pattern of parked cars.

4.3.7 PARKING BAY OPTIMISATION

4.3.7.1 REDUCED PARKING BAY WIDTH

The primary difference between a LBW and row of parked cars acting as a passive control is the voids that exist between the parked cars. These voids act as channels, transporting pollutants from the road to the footpath. This section presents the results for a reduction in the parked bay width to identify the effects of reducing the spacing between vehicles in accordance with minimum parking space guidelines (IStructE, 2002; Rochford District Council, 2010). This reduction could potentially improve air

quality on the footpaths. The initial 3.0 m parking bay equated as the 0% space reduction model results, with the 2.7 m and 2.4 m bays equalling the 10% and 20% reduced spacing models, respectively. Table 4.7 and Table 4.8 outline the results for a reduction in the parking bay widths for perpendicular, diagonal and central parking bay layouts in parallel and perpendicular wind directions, respectively.

TABLE 4.7. REDUCTIONS IN CO₂ CONCENTRATION BETWEEN PARKED CARS AND REFERENCE MODELS WITH INCREMENTAL PARKING BAY WIDTH REDUCTIONS IN PARALLEL WIND CONDITIONS.

Spacing Reduction (%)	Perpendicular	Diagonal (45°)		Central
	Average	LW	WW	Average
0%	25%	0%	-249%	24%
10%	30%	50%	-363%	23%
20%	43%	64%	-391%	21%

Note: A negative percentage corresponds to an increase in the pollutant concentration.

Improvements and deteriorations in air quality were noted on both footpaths for the parallel wind model. An improvement in air quality of 18% (i.e. 43% - 25%) was calculated on the footpaths for the perpendicular parked car models with a 20% reduction in the parking bay width. The diagonal layout provided mixed results with improvements of up to 64% on the leeward footpath, yet a deterioration of air quality of 142% on the windward footpaths from the reduction of the parking bay widths. The central parking bay displayed only very small differences in air quality on the footpaths, with deteriorations in air quality of 3% with a reduction in the parking bay widths. Table 4.8 displays the results of reducing the parking bay width for the three parking layouts for a perpendicular wind direction.

TABLE 4.8. REDUCTIONS IN CO₂ CONCENTRATION BETWEEN PARKED CARS AND REFERENCE MODELS WITH INCREMENTAL PARKING BAY WIDTH REDUCTIONS IN PERPENDICULAR WIND CONDITIONS.

Spacing Reduction (%)	Perpendicular		Diagonal (45°)		Central	
	LW	WW	LW	WW	LW	WW
0%	-35%	39%	-26%	53%	-24%	25%
10%	-29%	43%	-4%	61%	-26%	29%
20%	-17%	44%	2%	63%	-26%	31%

Note: A negative percentage corresponds to an increase in the pollutant concentration.

Improvements in air quality were observed on almost all leeward footpaths with the reduced parking widths in the parked car models, with the exception of the diagonal parking bay layout, where a small increase (2%) was calculated on the leeward

footpath. Improvements in air quality of 18% (i.e. 35% – 17%) and 28% were measured on the leeward footpaths with the 20% reduction in the parking bay width for the perpendicular and diagonal parking layouts. Further reductions were observed on the windward footpath for all three parking layouts, with reductions of between 5% and 10% for a reduction in the spacing between parked vehicles. The diagonal layout provided the biggest improvement in air quality on both footpaths after reducing the width of the parking bays.

Depending on the specific results for each parking bay layout, a reduction in the parking bay widths could benefit by (i) improving air quality on the adjacent footpath and (ii) increasing the number of parking bays and/or allow for a change in the parking layout while maintaining the same number of parking bays. However, as full parking occupancy is required to achieve the results from the individual scenarios, this is needed to be taken into account to assess parking demand in a given street canyon. This was to ensure full occupancy and maximum effectiveness of the parked cars as passive controls.

4.3.7.2 HYBRID PARKING LAYOUTS

As the results from the individual parking cases exhibited distinctive results on both footpaths, hybrid mixed parking layouts were investigated. These two layouts consisted of a parallel parking bay on the leeward side of the street and either a perpendicular or diagonal parking bay on the windward side of the street. The parallel parking layout was located on the leeward footpath for both hybrid layouts as it was the only layout shown to present improvements in air quality on the footpath in the individual case models for both wind directions. Table 4.9 shows the results of the hybrid parking layouts in parallel and perpendicular wind conditions.

TABLE 4.9. REDUCTIONS IN CO₂ CONCENTRATION BETWEEN PARKED CAR AND REFERNECE MODELS FOR HYBRID PARKING LAYOUTS.

Parking Layout	90°		0°	
	LW	WW	LW	WW
Parallel & Perpendicular	4%	46%	-12%	61%
Parallel & Diagonal (S-N)	2%	35%	19%	-58%
Parallel & Diagonal (N-S)			-177%	33%

Note: A negative percentage corresponds to an increase in the pollutant concentration.

The results showed mixed results for both hybrid models. Reductions of 35% and 46% were calculated on the windward footpath between the reference and hybrid models for the parallel-diagonal (Par-Diag) and parallel-perpendicular (Par-Perp) layouts, respectively. The results showed that the Par-Perp hybrid parking layout performed better overall compared to the Par-Diag layout.

The parallel wind direction models demonstrated improvements and deteriorations in air quality for both hybrid parking layouts. The Par-Perp model layout displayed a small increase of 12% in the pollutant concentrations on the leeward footpath and a 61% improvement in air quality on the windward footpath. As the Par-Diag hybrid layout presented distinctive wind patterns for southerly and northerly wind directions, both wind models were modelled and the results showed different effects on both footpaths. Similar trends were observed in the Par-Diag with increases of 177% and 58% on the left footpath and reductions of 19% and 33% on the right footpath based on the oncoming wind direction. The hybrid models did not display consistent reductions in pollutant concentrations on both footpaths in parallel or perpendicular wind conditions.

4.4 DISCUSSION

This section discusses the results of the individual parking car layouts, the parking bay occupancy rate scenarios and the methods used to optimise the parking bay layouts.

4.4.1 CASE 1: PARALLEL PARKING

Despite the fact that the parallel parked cars present a temporary and non-continuous boundary between the footpath and traffic emissions (while parked at full occupancy) significant reductions in pedestrian exposure were found. In this study, large and consistent reductions in exposure were found for both wind directions. An explanation for the reductions created by parked cars in comparison to a previously investigated passive control such as low boundary walls (LBWs) (King et al., 2009; McNabola et al., 2009) include the presence of gaps between cars: in cross section they present a much wider and taller boundary than the solid LBW. Pollutants emitted at street level are presented with a much longer pathway between source and receptor as they must travel a larger distance around, over or under the cars, resulting in a greater degree of

pollutant dispersion. Figure 4.16 shows a plot of air flow patterns in the canyon and the dispersion of the tracer pollutant in a reference and parked cars model. The plots illustrate the resultant velocity vectors of the molar concentration of the tracer gas (CO_2) in kmol/m^3 .

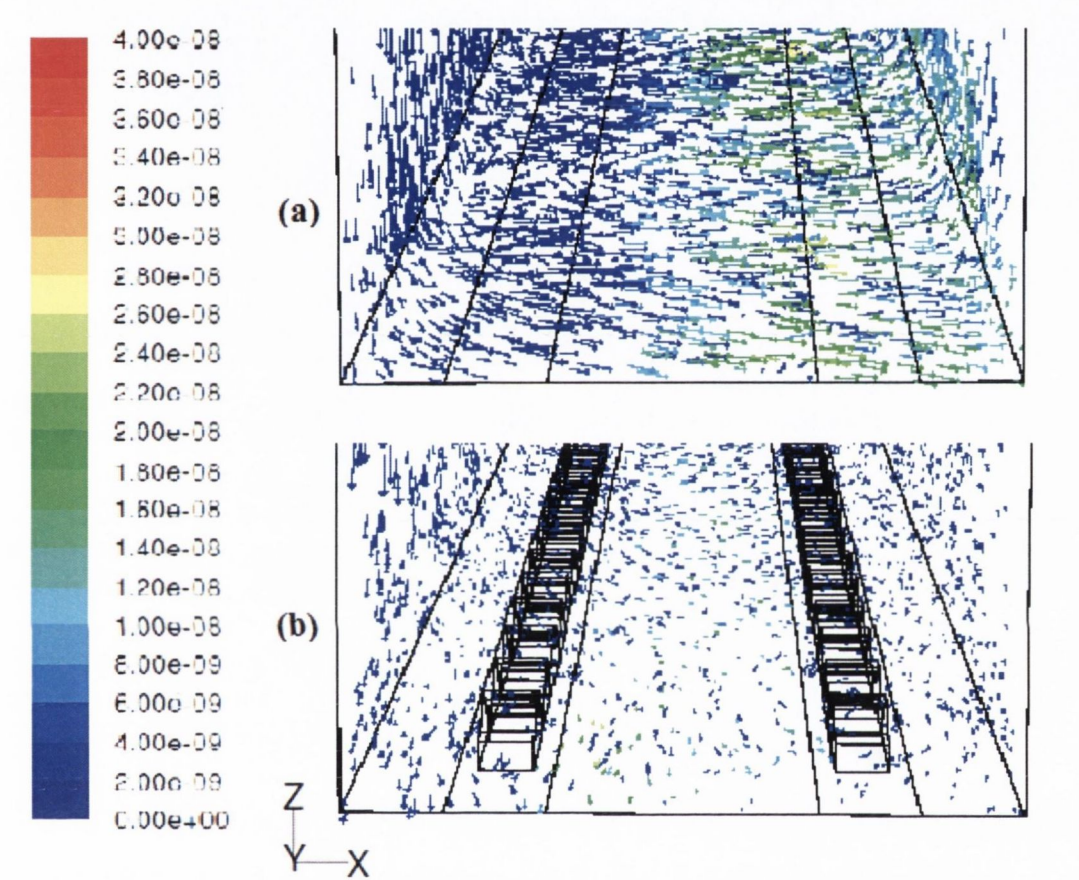


FIGURE 4.16. RESULTANT VELOCITY VECTORS PLOT OF THE CONCENTRATION FOR A 4 M/S PERPENDICULAR WIND IN CASE 2 FOR THE (A) REFERENCE MODEL AND (B) PARALLEL PARKED CARS MODEL.

Previous investigations have shown the height of a boundary wall has a significant influence on its effectiveness as a passive control on air pollutant dispersion (King et al., 2009) and parked cars present a boundary which was typically higher than most boundary walls in urban areas (waist height versus shoulder height in broad terms). For a perpendicular wind, the parked cars alter the natural air flow patterns in the canyon in a similar fashion to LBWs. Figure 4.17 illustrates the direction of air flow for the primary and secondary vortices within a street canyon in perpendicular wind conditions. The plot identifies that the direction of air flow through the canyon and the

typical direction of pollutant transport at street level is from the windward side to the leeward side of the canyon.

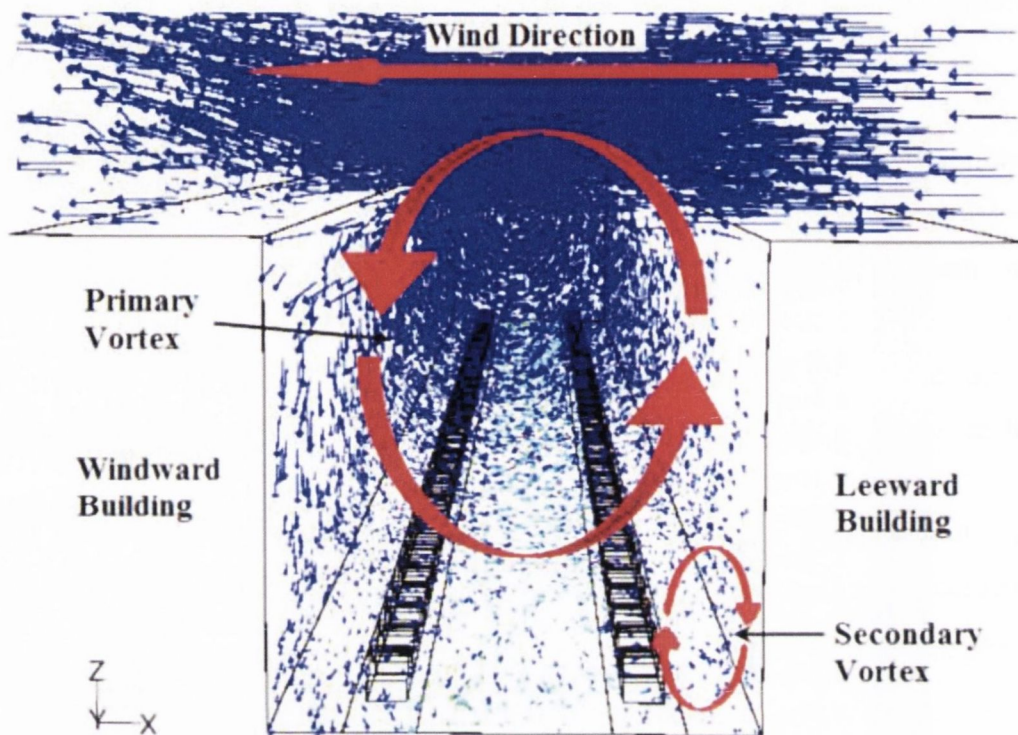


FIGURE 4.17. RESULTANT VELOCITY VECTORS PLOT OF THE POLLUTANT CONCENTRATIONS IN THE CASE 1 MODEL IN PERPENDICULAR WIND CONDITIONS (GALLAGHER ET AL., 2011).

Secondary vortices were created on both footpaths in the canyon. As air enters the canyon on the windward side of the street, this clean air is circulated on the windward footpath. The transport of clean air from roof level and the parallel parked cars acting as a baffle wall improved air quality on the windward footpath and reduced the pollutant concentration by up to 49%. The boundary created by the parallel parked cars reduced pollutant concentrations on the leeward footpath by up to 35% with only a small deterioration in air quality for increasing wind speeds. The parked cars provided an effective baffle wall in parallel wind conditions and improved air quality by up to 33%.

In perpendicular winds, the rate of reduction was not as significant on the leeward footpath as the primary vortex carries pollutants towards the footpath and the secondary vortices in this region enhanced mixing with the clean air. Small wind channels were also created on the leeward footpath as the air travelled through the 0.4

m spacing between the vehicles. This air diverged when it reached the footpath; producing additional secondary eddies as the air dispersed in both clockwise and anti-clockwise directions. The increase in wind speed caused an incremental deterioration in air quality on the leeward footpath. The deterioration was due to the increased infiltration of pollutants into the leeward footpath in the high wind speed models.

4.4.2 CASE 2: PERPENDICULAR PARKING

The perpendicular parked car models displayed similar patterns and differences in percentage pollutant concentrations to Case 1, yet presented a wider parking bay than the parallel parking bay. The spacing between vehicles was 1.3 m in width (as shown previously in Figure 4.6), and this void contributed to approximately 43% of the total canyon length. The effect of this larger void space for the perpendicular parked cars configuration reduced the potential for pollutant reduction compared to Case 1. Larger pathways for emissions were presented due to the larger voids between the parked vehicles, allowing more pollutant to potentially travel directly between the road and the footpaths in Case 2. The alignment of the perpendicular parked car promoted pollutant flow towards the footpath as the wind flowed over the car with more ease compared to the parallel parked cars layout for perpendicular wind conditions.

The increase in pollutant concentrations on the leeward side highlighted the reduced effectiveness of the perpendicular parked car layout as a passive control system. The large void spaces between vehicles caused deterioration in air quality of up to 37%. The increase in pollutant concentrations was incremental to the reduction of the wind speed, as higher wind speeds promoted dispersion in the large voids between the cars and reduced the time taken for pollutants to escape from street to roof level. In comparison to the LBW investigation, the perpendicular parked cars displayed similar reductions on the windward footpath. However, the parked cars model demonstrated larger increases in pollutant concentrations on the leeward footpath due to the non-continuous boundary offered by the perpendicular parked cars.

The larger spacing between parked cars in the Case 2 layout reduced their effectiveness as a baffle wall in comparison to Case 1. This led to an increased fraction of pollutants being transported from the road to the footpath. A reduction of up to 41% was calculated on the windward side of the canyon and provides evidence

that the perpendicular parked cars acted as an effective baffle wall for pollutants travelling against the natural flow of air in a canyon.

The orientation and spacing of perpendicular parked cars promoted increased turbulence and transport pathways for pollutants to disperse across the footpaths in parallel wind conditions. This large void spacing induced a significant difference in the reduction of pollutant concentrations on both footpaths ranging from 12% to 30% for low to high wind speeds, respectively. An increase in wind speed enhanced pollutant mixing in the canyon and reduced the infiltration of pollutants towards the footpath zones. This increased the effectiveness of the perpendicular parked car in parallel wind conditions.

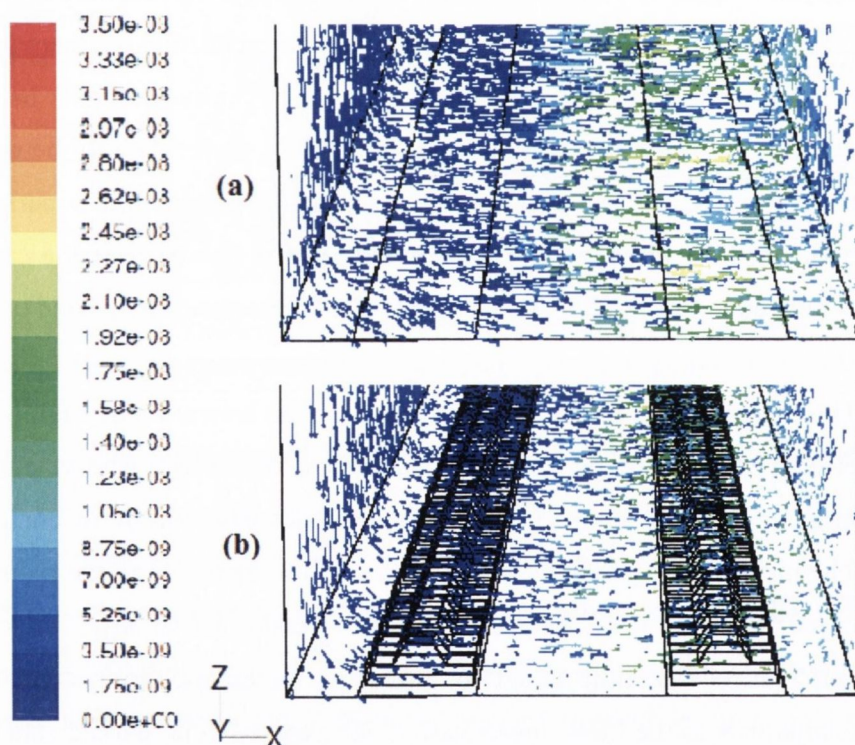


FIGURE 4.18. RESULTANT VELOCITY VECTORS PLOT OF THE CONCENTRATION FOR A 4 M/S PERPENDICULAR WIND IN CASE 2 FOR THE (A) REFERENCE MODEL AND (B) PERPENDICULAR PARKED CARS MODEL.

The difference in air quality between Case 1 and Case 2 highlighted the clear influence of parking bay widths on pollutant infiltration from the road to the footpath. This highlights the clear benefits associated with increased distance between the pollutant source and receptor. Figure 4.18 shows the resultant velocity vector plot of

the concentration of the tracer pollutant to compare the typical dispersion patterns between the perpendicular parked cars and reference models.

4.4.3 CASE 3: 45° DIAGONAL PARKING

In Case 3, the 45° parked car configuration provided an alternative layout to the conventional parallel and perpendicular parking cases. It required the widest parking bay in comparison to the Cases 1 and 2, and similarly it disturbed the natural air flow patterns in the canyon models for both parallel and perpendicular wind conditions. Another reason for considering the 45° parking layout was due to it being considered the safest parking layout due to the ability for a pedestrian to scan for oncoming traffic and the driver to see a pedestrian much earlier than with other parking configurations (Berger, 1975; Retting et al., 2003).

In perpendicular winds, an increase in pollutant concentrations of up to 28% was found on the leeward footpath, due to the channelling of a fraction of pollutants from the road to the footpath. The diagonal parking layout provided a 56% reduction in pollutant concentrations on the windward footpath, the most substantial improvement in air quality of the parked car layouts. Higher wind speeds caused a small deterioration in air quality on the leeward footpath and marginal improvements in air quality on the windward footpath for perpendicular wind conditions. In a similar manner to the Case 2, improvements in air quality were similar to the LBW models on the windward footpath. However, the diagonally parked cars did not provide an effective baffle on the leeward side of the canyon in comparison to the parallel parked cars due to the large voids between the parked cars.

The most notable differences in pollutant concentrations on the leeward and windward footpaths were due to the increased dispersion from the 45° parked cars. The parked cars altered the natural air flow through the canyon. In parallel wind conditions, the 45° parked cars channelled the wind from the road to the windward footpath, significantly increasing the pollutant concentration by as much as 288%. The opposite effect was observed on the leeward footpath, as the 45° parked cars obstructed direct air flow from the road to leeward zone of the canyon. The increased wind speed in the 45° parking models increased pollutant dispersion and reduced the fraction of

pollutants that infiltrated the parked car boundary into the windward footpath. The dispersion patterns for the reference and parked car models are shown in Figure 4.19 for Case 3 as velocity vector plots of the pollutant concentrations.

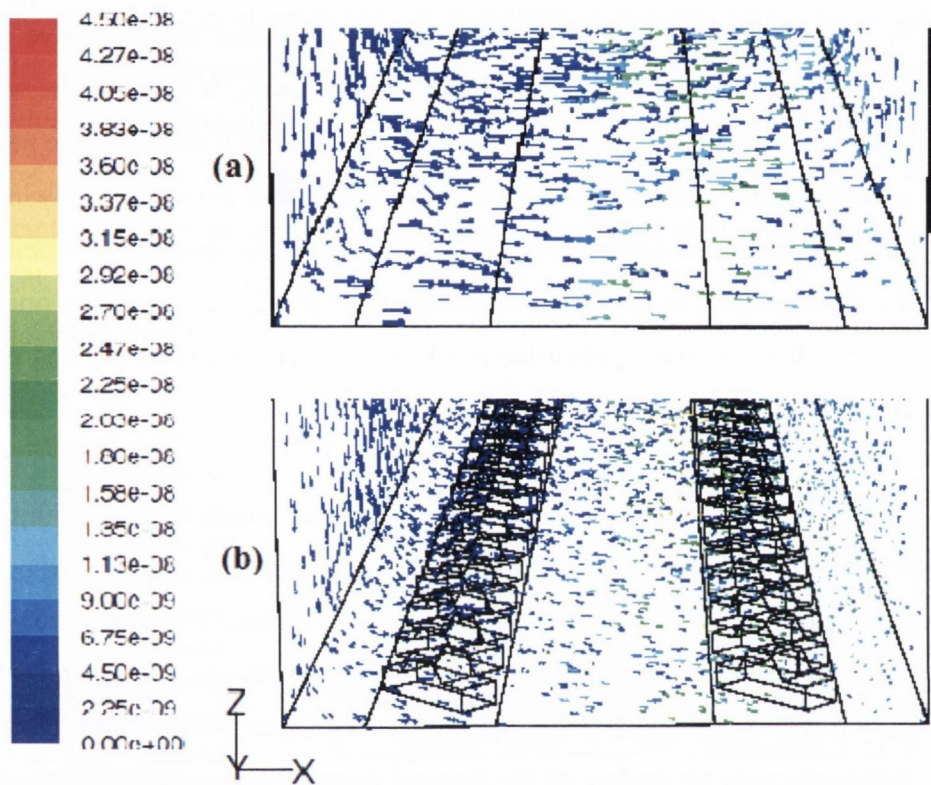


FIGURE 4.19. RESULTANT VELOCITY VECTORS PLOT OF POLLUTANT CONCENTRATIONS IN CASE 2 (A) REFERENCE AND (B) 45° PARKED CARS MODEL FOR PERPENDICULAR WIND CONDITIONS.

The increase in wind speed influenced the flow and spatial distribution of pollutants by reducing the effectiveness of the 45° parked cars on the windward footpath and inversely improving air quality on the leeward footpath.

4.4.4 CASE 4: CENTRAL PARKING

The central parking model layout reduced the pollutant concentration in parallel wind conditions, but led to both reductions and increases in perpendicular wind models. The layout differed from the previous three cases and therefore it can only be compared to the other cases in terms of performance acting as a passive control. The central parking bay provided a different pattern of air flow to the previously investigated layouts as shown in Figure 4.20.

The parked cars were laid out in a similar manner to Case 2 with spacing between vehicles of 1.3 m in width (as shown previously in Figure 4.6), with the void contributing to approximately 43% of the total canyon length. The large void space for the centrally parked cars reduced the potential for pollutant reduction compared to Case 1. Larger pathways were presented between the diagonally parked cars for emissions to be transported between the road and the footpaths.

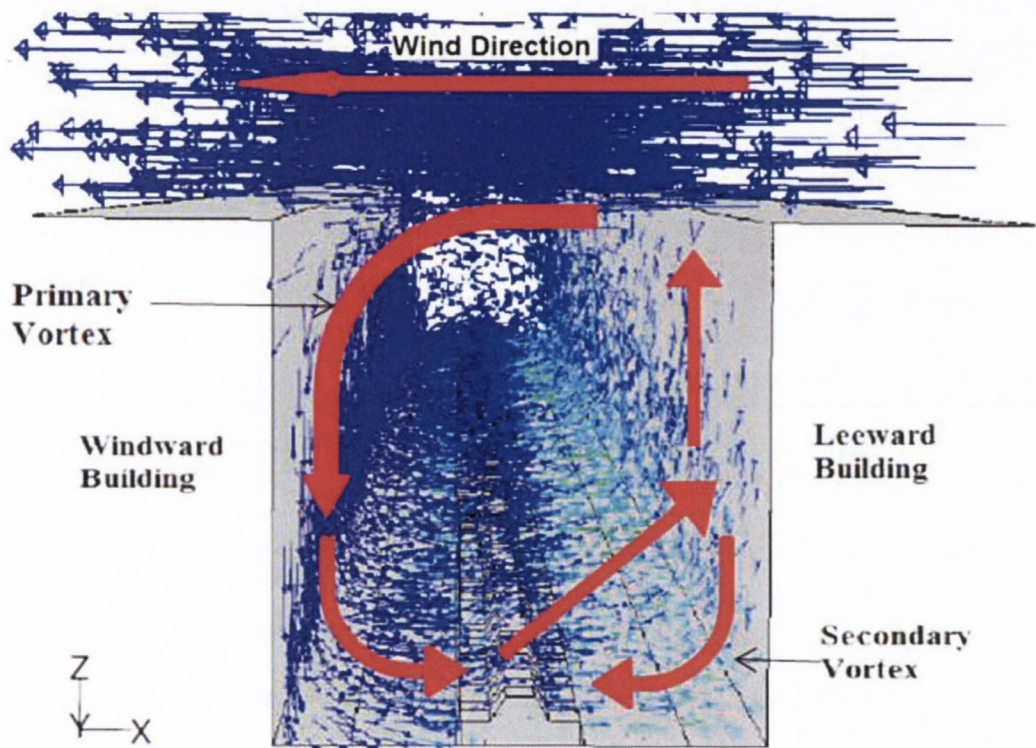


FIGURE 4.20. RESULTANT VELOCITY VECTORS PLOT OF POLLUTANT CONCENTRATIONS IN STREET CANYON FOR A CASE 4 MODEL IN PERPENDICULAR WIND CONDITIONS.

The deterioration in air quality on the leeward side highlighted the reduced effectiveness of the central parked car layout with an increase in pollutant concentrations of up to 25%. The increase in pollutant concentrations was incremental to an increase of the wind speed. This was due to the higher wind speeds transporting increased concentrations of pollutants to the leeward footpath. The spacing width of cars in this layout did not have any notable influence over the effectiveness of the centrally parked car acting as a baffle wall in comparison to the other cases. This was due to the location of the parked cars in comparison to the other cases; the spacing between vehicles allowed pollutants to transport between the traffic lanes, but this did not directly affect air quality on the footpaths. A reduction of up to 30% on the

windward sides gives evidence that the parking layout alters the natural air flow pattern in the canyon. The increase in wind speed improved air quality on the windward footpath. This was due to the influence of increased wind speeds creating a turbulent zone on the windward side of the street. This transported increased pollutant concentrations towards the windward footpath.

The centrally parked cars displayed less substantial reductions in pollutant concentrations on both the footpaths. On the windward footpath, the lack of a boundary along the interface between the road and footpath caused a reduction in the effectiveness of the central parking bay. The circulation of pollutants within the second primary vortex in the leeward zone of the canyon prevented the effective reduction of pollutants on the leeward footpath. In comparison to the previous cases, the differences in percentage reductions in pollutant concentration in Case 4 showed the influence of the parking bay location on pollutant dispersion in a street canyon. Figure 4.21 shows the resultant velocity vector plot of the tracer pollutant concentrations to compare the typical dispersion patterns between the central parked car model and reference model.

The location of the central parked cars promoted increased turbulence in the street canyon in parallel wind conditions. The reduction in pollutant concentrations was not as significant as in previous cases due to the parked car layout acting as a baffle wall in a different location i.e. in the centre of the canyon. In a similar manner to the perpendicular wind conditions, the spacing between vehicles did not significantly affect the percentage reduction in pollutant concentrations on the footpaths as the measured reductions were linear for different wind speeds. Changes in wind speed did not affect the percentage difference in pollutant concentration between the reference and central parked car models in parallel wind conditions.

The introduction of parallel parked cars in the central parking bay was not investigated, but would offer an alternative to the perpendicular parked cars in the parking bay. The perpendicular parked cars provided more spaces and provided a safer option for individuals getting in or out of the car away from moving traffic compared to the parallel parking layout. However, the parallel parking layout

provided the best overall reductions and could provide a better alternative to perpendicular parked cars for the central parking bay layout.

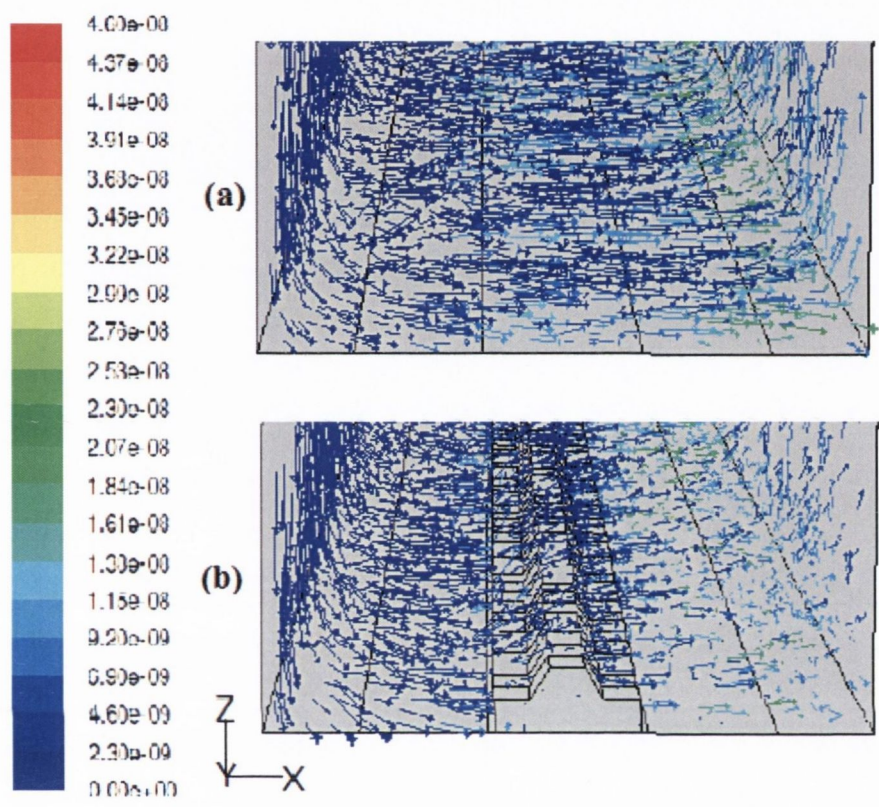


FIGURE 4.21. RESULTANT VELOCITY VECTORS PLOT OF THE CONCENTRATION FOR A 4 M/S PERPENDICULAR WIND IN CASE 2 FOR THE (A) REFERENCE MODEL AND (B) CENTRAL PARKED CARS MODEL.

4.4.5 VARYING WIND CONDITIONS

From the individual case models, changes in wind speed and direction clearly influence air flow and pollutant dispersion in different ways. The parallel wind model allows the parked cars to act as an effective baffle wall as air flows along the canyon floor and the baffle maintains clean air on the footpath and polluted air in the road. The small differences between each of the wind speed models is related to increased turbulence in the parking bay zones, which can further reduce or increase the effects of the parked cars. As stated in the results section, the diagonal parked cars display unique results as the orientation of the parked cars alters the direction of air flow in parallel winds.

In perpendicular wind conditions, the air flow in the canyon displayed one of two patterns due to the introduction of the parked cars; the circular primary vortex in Cases 1-3 and the two primary vortices created in Case 4. The two air flow patterns had distinct effects on pollutant dispersion in the canyon. As stated in the results section, the perpendicular wind direction caused typical reductions on the windward footpath and increases or less substantial reductions on the leeward footpath. The perpendicular wind benefits the windward footpath in the parked cars models as the clean air is trapped in the zone and the parked cars act as an effective baffle to trap pollutants in the street. However, the increased concentrations of pollutants in the street combined with the air flow towards the leeward zone causes additional pollutants to be transported to this zone and these pollutants are trapped on the footpath. The orientation of the parked cars affect the direction of transported pollutants out of the canyon and the results indicate that these differences were also influenced by the wind speed. The wind speed created stronger vortices in the canyon which: (i) improved the fraction of pollutants transported out of the canyon, (ii) increased turbulence at street level, (iii) increased the fraction of pollutants transported to roof level and released from the canyon vortices and (iv) re-circulated increased fraction of pollutants towards the windward footpath. These effects varied between the parked cars models and were responsible for small incremental improvements and deteriorations in air quality on the footpaths in perpendicular wind conditions.

4.4.6 PARKING BAY OCCUPANCY RATES

The results from the occupancy rate models demonstrated that the percentage of occupied parking bays influences the ability for parallel parked cars to act as a passive control. In the parallel parking layout, the percentage gap width between vehicles and the percentage open space in the parking bay were two criteria which defined the ability of the parked cars to act as an effective passive control of air pollution in the street canyon models. The gap width and open space percentage differed in the parking layout models as the spacing between vehicles varied for each of the parking regimes. In the parallel parking layout, the smallest difference in the gap width and open space percentages were calculated in comparison to the other parking layouts. The gaps in the parallel parking layout (0.4 m every 5.0 m long bay) were much smaller than the perpendicular and diagonal layouts (1.3 m every 3.0 m long bay).

This was responsible for the negative impact on air quality in some of the parked car models as influence of the gap width for varying occupancy rates.

The results demonstrated how different parking occupancy rates influence air quality in a distinctive manner for varying wind conditions. However, there cannot be a direct correlation made for the different parking layouts with similar percentage gap widths. In comparing the results between the different parking layouts, the ability for the parked cars to channel the air in the street is a function of (i) the length of the section of passive control i.e. parked car, (ii) the regularity of occupied parking bays and (iii) the length of the gap between parked cars. Thus, the comparable improvements in air quality for a gap width of approximately 43% in the parallel and perpendicular parking models were 10% and 22% in parallel wind conditions. The parallel layout performs poorer as although there are narrower spaces between vehicles, the results demonstrate that fewer, wider gaps have a more substantial impact than a large quantity of small gaps.

The results of the parking bay occupancy study presented different patterns of pollutant infiltration on the leeward and windward footpaths for the parallel parked car layout of Case 1. Relationships were identified between the number of parked cars and the potential reduction of pollutants on both footpaths. In parallel wind conditions, deterioration in air quality was noted on the adjacent footpaths for the 10% and 25% occupancy rates. From this point, there was a relatively steady improvement in air quality occurring from a 25% to 100% occupancy rate. The increase in pollutant concentration for low occupancy rates was due to the influence of individual cars directing pollutants towards the footpath and promoting enhanced mixing with the clean air on the footpath and the polluted air from the road. A plan view of the velocity vectors along the canyon floor is shown in Figure 4.22 and demonstrated the effects of air flow and pollutant transport along the canyon floor for different parking occupancy rates.

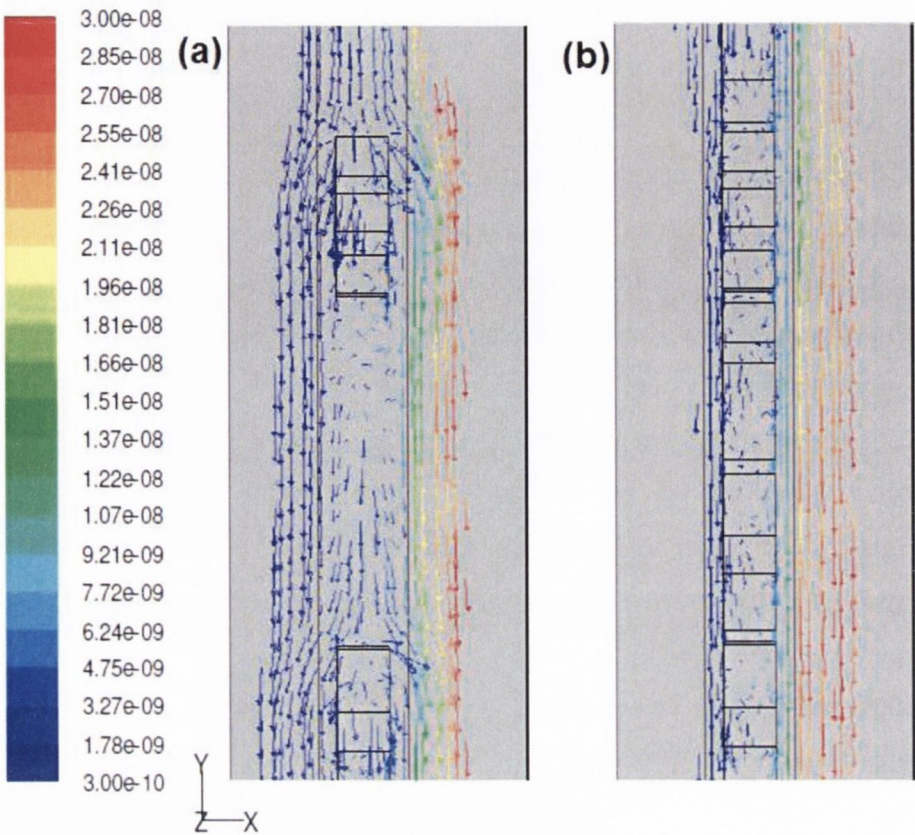


FIGURE 4.22. RESULTANT VELOCITY VECTORS PLOT OF POLLUTANT CONCENTRATIONS FOR PARKING OCCUPANCY MODELS WITH A 8 M/S PARALLEL WIND SPEED WITH (A) 25% AND (B) 75% OCCUPANCY RATES.

This highlighted the negative impact on air quality associated with low parking occupancy rates, as marginal increases in pollutant concentrations were measured on the footpaths in these scenarios. As discussed in Case 1, the parked cars trap clean air transported down from roof level along the windward footpath and increased pollutant dispersion on the leeward footpath. Figure 4.23 displays a velocity vector plot of pollutant concentrations in street canyon models with occupancy rates of 25% and 75% for perpendicular wind conditions.

From visual comparison of the two cases, larger pathways were displayed in the lower occupancy model (Figure 4.23(a)) compared to the high occupancy model (Figure 4.23(b)). This was due to a reduction of the pollutant transport pathways between the road and the footpath. On both footpaths, lower occupancy rates demonstrated wider pathways between the pollutant source on the road and the footpath. In parallel wind conditions small wake zones were created after the vehicle, reducing the effect of spacing between the parked cars. However, the wake zone between the parked cars

could not maintain the baffle wall effect and minimised the reduction of pollutants transported from the road to the footpath.

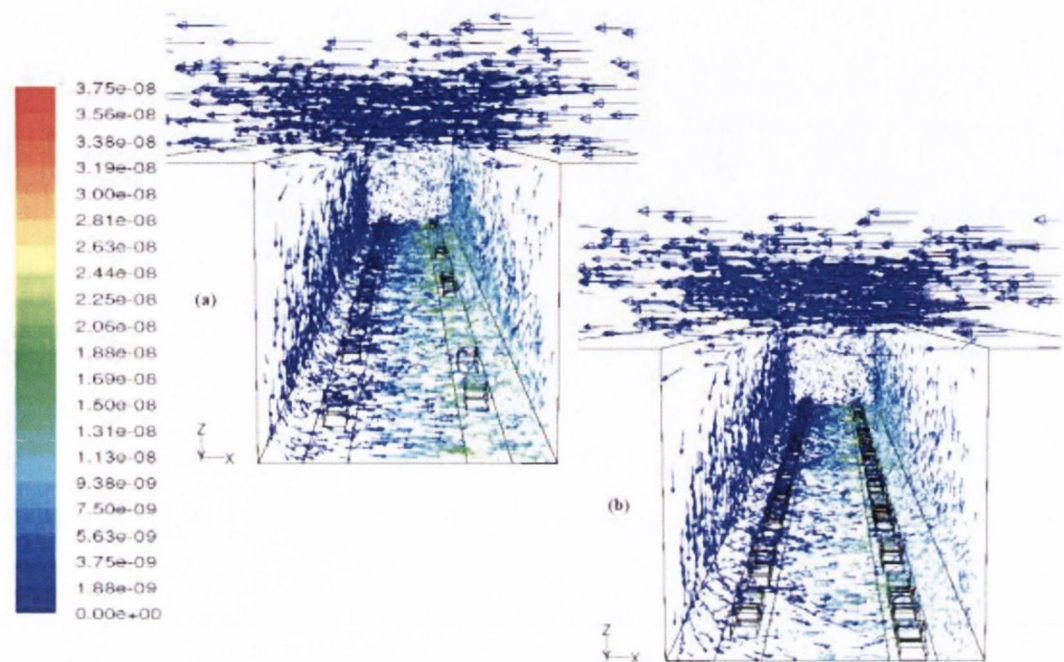


FIGURE 4.23. RESULTANT VELOCITY VECTORS PLOT OF POLLUTANT CONCENTRATIONS FOR PARKING OCCUPANCY MODELS WITH A 4 M/S PERPENDICULAR WIND SPEED WITH (A) 25% AND (B) 75% OCCUPANCY RATES.

The change in occupancy rate on the leeward side on the canyon proved to have an exponential relationship from an empty parking bay (0% occupancy rate) to a full parking occupancy rate of 100%. Low occupancy rates provided very little reduction in pollutant concentrations, compared to the substantial improvements in air quality which occurred with occupancy rates greater than 75%. On the windward footpath, an s-curve pattern was evident (Figure 4.15), which best describes the pattern for the percentage pollutant reductions against increasing occupancy rates. The percentage difference of pollutant infiltration on the windward footpath was not significantly different between the lower and higher ranges of occupancy rates i.e. between 0% to 10% and 90% to 100%. However, a curvilinear pattern of pollutant reduction was observed between the 10% and 90% occupancy rates. The plots of occupancy rates against the percentage pollutant reduction did not display any significant influence of changes in wind speed.

In each of the case models, an increase in pollutant concentration was found in the roadway as the parked cars acted as a baffle wall and impeded pollutant transport in the roadway. This was considered an unavoidable impact of parked cars as a passive control, which aims to protect pedestrian health. This may impact negatively on both vehicle passengers and cyclists; therefore further research is required to identify the impact of parked cars as a passive control on these groups.

4.4.7 PARKING BAY OPTIMISATION

4.4.7.1 REDUCED PARKING BAY WIDTH

The results from the optimised modelling cases illustrated how the vehicle spacing affected the transport of pollutant concentrations from the road to the footpath. Figure 4.24 to Figure 4.26 display the profile plots of pollutant concentrations along the street canyon floor for two different parking bay widths in parallel wind conditions. The plots show the original parking bay spacing of 3.0 m from the previous cases and parking bays reduced by 20% in width to 2.4 m, a minimum width set by a number of parking bay design guidelines (IStructE, 2002; Laois County Council, 2007; Rochford District Council, 2010). Figure 4.24 illustrates the plan view of two perpendicular parking bays with the initial and reduced parking bay widths.

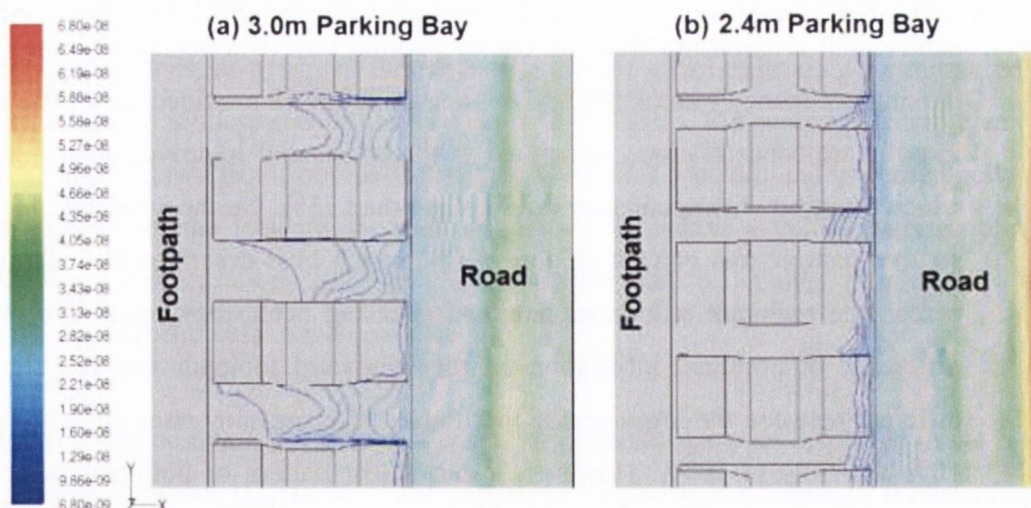


FIGURE 4.24. CROSS-SECTIONAL PLAN VIEW OF PERPENDICULAR PARKING LAYOUTS WITH CONTOURS OF TRACER CONCENTRATIONS FOR A (A) 3.0 M PARKING BAY AND A (B) 2.4 M PARKING BAY IN 8 M/S PARALLEL WINDS.

The results from the optimisation models for the perpendicular parking bay layout demonstrated a percentage improvement in air quality on the footpath with an

incremental reduction of the parking bay widths. A 20% reduction in the bay width from 3.0 m to 2.4 m improved air quality on the footpaths by 18%. Figure 4.24 shows the rate of pollutant infiltration between the parked cars for both parking bay widths, and illustrates the reduced fraction of pollutants allowed to be channelled between the vehicles. The plots display a small increase in the pollutant concentration on the road. Figure 4.25 shows the plan view of the two diagonal parking bays with bay widths of 3.0 m and 2.4 m and the pollutant dispersion patterns along the canyon floor.

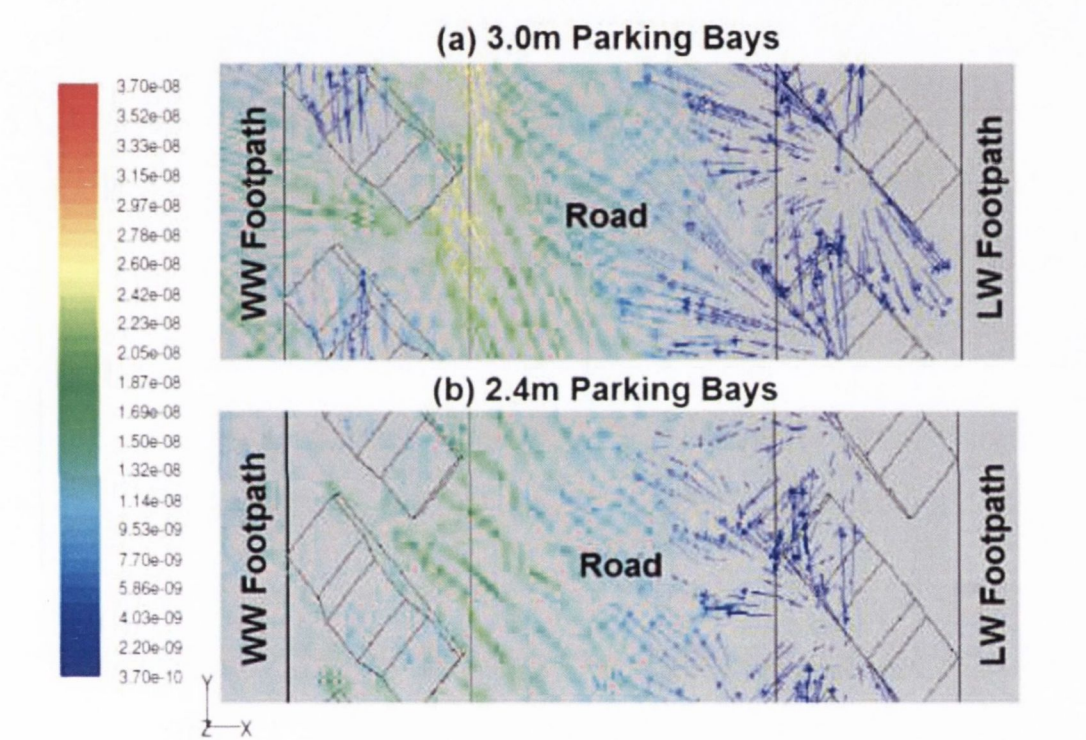


FIGURE 4.25. CROSS-SECTIONAL PLAN VIEW OF DIAGONAL PARKING LAYOUTS WITH VELOCITY VECTORS OF TRACER CONCENTRATIONS FOR A (A) 3.0 M PARKING BAY AND A (B) 2.4 M PARKING BAY IN 8 M/S PARALLEL WINDS.

The reduced spacing of the parking bays in the diagonal layout demonstrated changes in the percentage differences in pollutant concentrations on both footpaths. In parallel wind conditions, the wind was travelling from north to south and was channelled between the cars on the windward (WW) footpath. The results showed a further deterioration in air quality from 249% to 391% with a reduction in the parking bay width. The benefit of reduced bay width was counteracted by a 24% increase in the number of channels (67 to 83 spaces) along the canyon floor to transport pollutants from the road to the footpath.

The results on the leeward footpath displayed significant improvements in air quality with the reduction of the spacing between the parking bays. The initial parking bay width of 3.0 m showed no change in air quality, yet 10% and 20% reductions in the parking bay widths led to substantial improvements in air quality on the leeward footpath of 50% and 64%, respectively. The plan view of the two central parking bays with bay widths of 3.0 m and 2.4 m is shown in Figure 4.26 and displays the profile contours of pollutant concentrations along the street canyon floor.

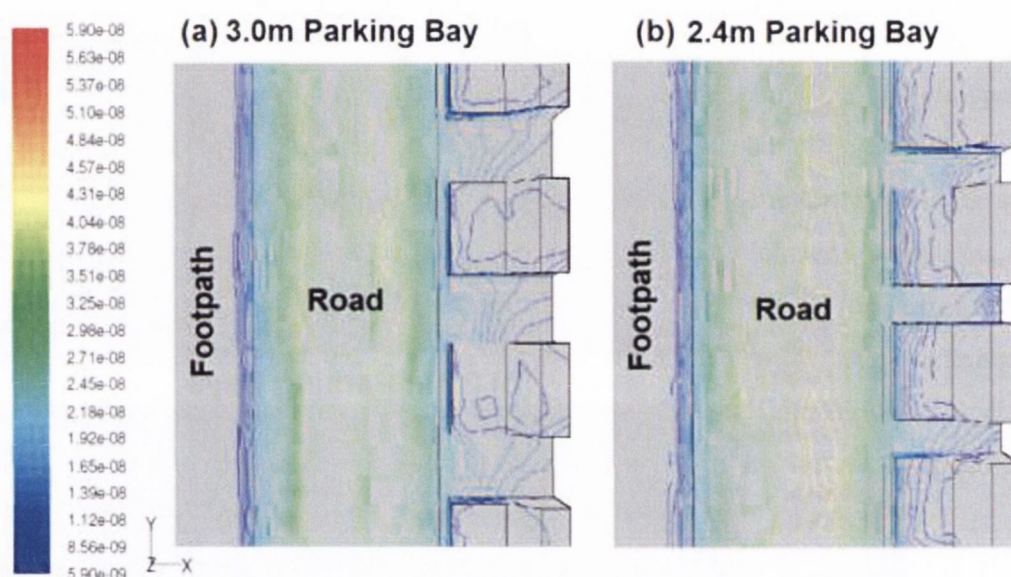


FIGURE 4.26. CROSS-SECTIONAL PLAN VIEW OF CENTRAL PARKING LAYOUTS WITH CONTOURS OF TRACER CONCENTRATIONS FOR (A) 3.0 M PARKING BAY AND A (B) 2.4 M PARKING BAY IN 8 M/S PARALLEL WINDS.

Only a small 3% deterioration in air quality (from 24% to 21%) was noted on the footpaths. This was considered to be due to the reduction in the width of the parking bays and increased turbulence, which caused a small change in lateral dispersion patterns. The difference in pollutant concentrations across the street floor is not considered notable and this is evident from Figure 4.26. These changes were notably insignificant as the central parking bay did not influence air flow and pollutant dispersion along the footpaths in parallel wind conditions.

Reductions in the parking bay width also marginally increased dispersion in the perpendicular wind models as narrower parking bays improved air quality on both footpaths for the other three parking layouts. Figure 4.27 to Figure 4.29 display the plots of pollutant concentrations along the street canyon floor in perpendicular wind

conditions for the different parking bay widths. Figure 4.27 shows the plan view of two perpendicular parking bays with the initial and reduced parking bay widths for a perpendicular wind.

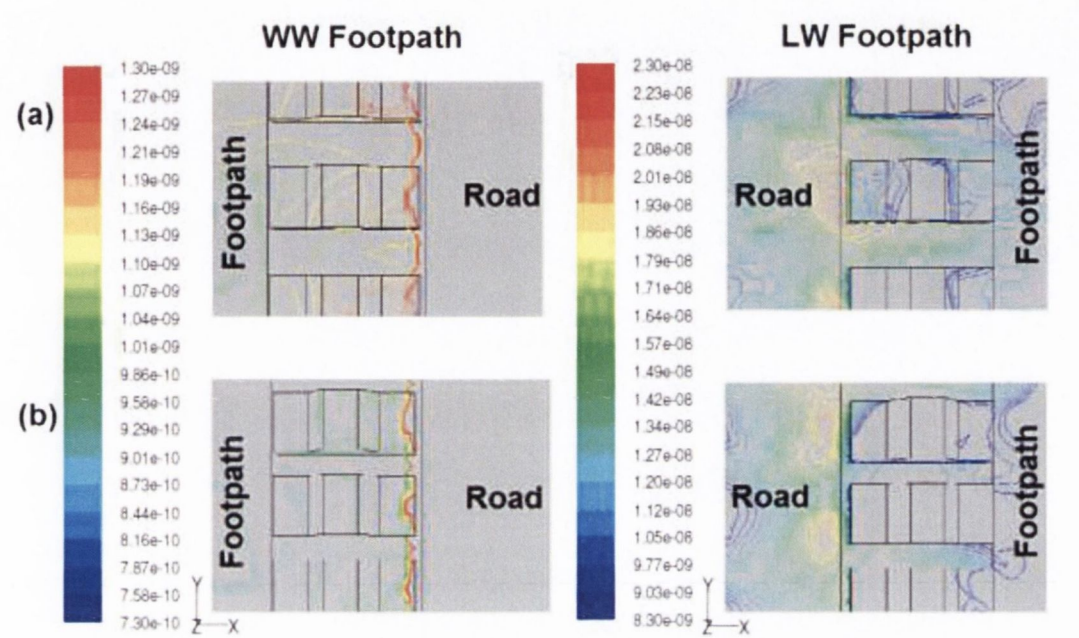


FIGURE 4.27. CROSS-SECTIONAL PLAN VIEW OF PERPENDICULAR PARKING LAYOUTS WITH CONTOURS OF TRACER CONCENTRATIONS FOR A (A) 3.0 M PARKING BAY AND A (B) 2.4 M PARKING BAY IN 8 M/S PERPENDICULAR WINDS.

A reduction in the spacing between the parking bays improved conditions by 18% and 5% on the leeward and windward footpaths, respectively. The percentage difference in pollutant concentration increased from 39% to 44% on the windward footpath, as the narrower channel width between the parked cars reduced the fraction of the pollutants transported from the road to the footpath. Figure 4.27 also shows the contoured pollutants on the leeward side of the canyon floor which demonstrated the clear improvements in air quality due to the reduced parking bay width from 3.0 m to 2.4 m. Figure 4.28 displays the profile contours of pollutant concentrations along the canyon floor for the diagonal layouts with different parking bay widths.

The results from the diagonal parking bay layouts models displayed improvements in air quality on both footpaths with an incremental reduction of the parking bay widths. The reduction in the bay width improved air quality on the leeward and windward footpaths by 28% and 10%, respectively. Figure 4.28 shows improved air quality on

the windward footpath in the 2.4m spacing parking bay model and a reduction in the fraction of pollutants transported to the leeward footpath in the same model.

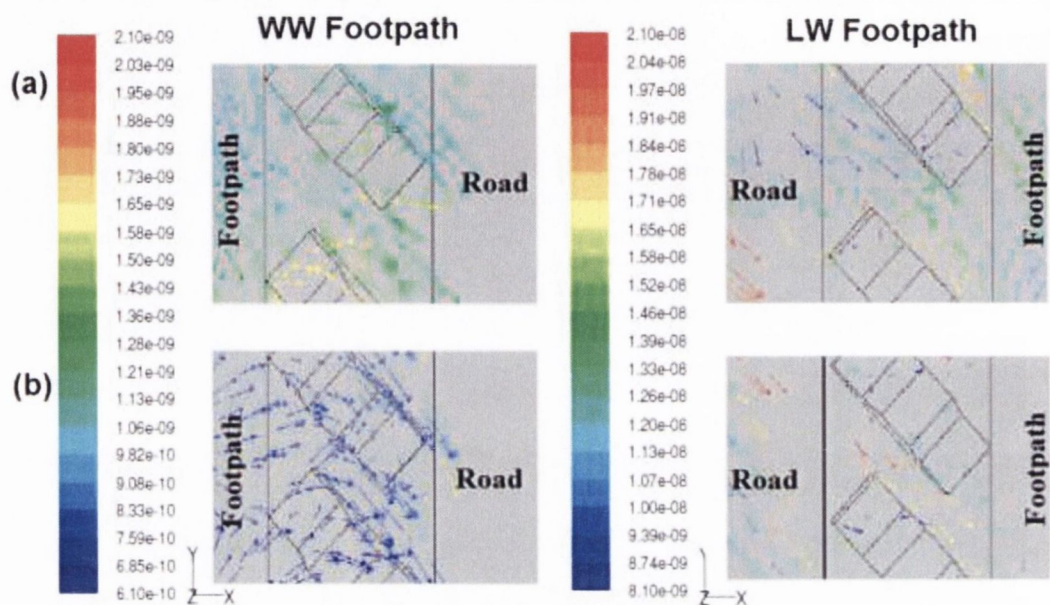


FIGURE 4.28. CROSS-SECTIONAL PLAN VIEW OF DIAGONAL PARKING LAYOUTS WITH VELOCITY VECTORS OF TRACER CONCENTRATIONS FOR A (A) 3.0 M PARKING BAY AND A (B) 2.4 M PARKING BAY IN 8 M/S PERPENDICULAR WINDS.

The plan view of the two central parking bays with widths of 3.0 m and 2.4 m and the pollutant dispersion patterns along the canyon floor is shown in Figure 4.29.

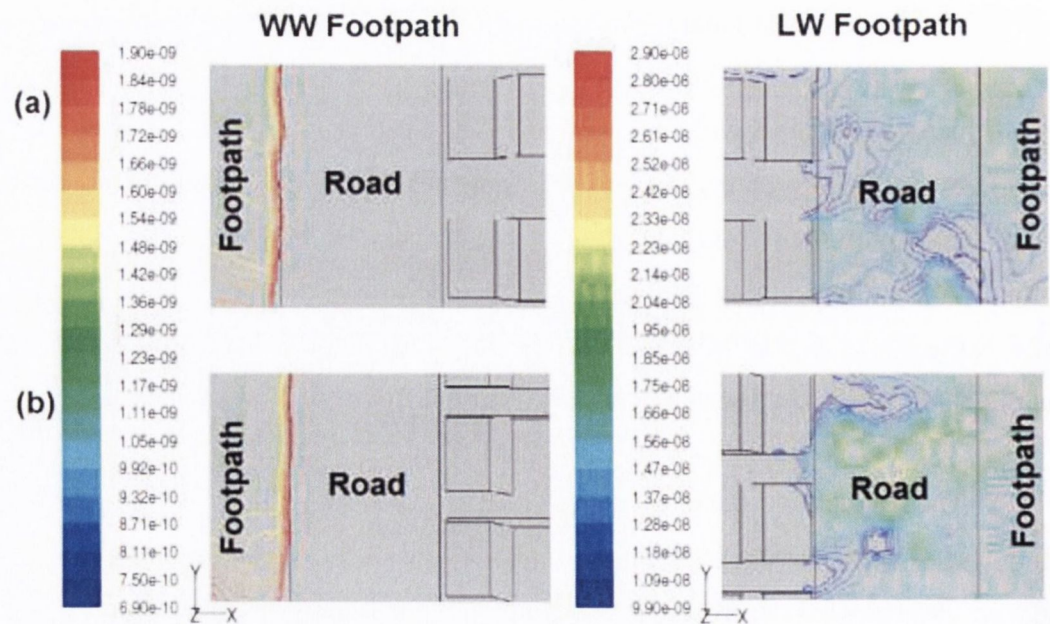


FIGURE 4.29. CROSS-SECTIONAL PLAN VIEW OF CENTRAL PARKING LAYOUTS WITH CONTOURS OF TRACER CONCENTRATIONS FOR A (A) 3.0 M PARKING BAY AND A (B) 2.4 M PARKING BAY IN 8 M/S PERPENDICULAR WINDS.

The reduced spacing of the parking bays in the central parking layout demonstrated insignificant changes in the percentage difference calculated from the measured concentrations on both footpaths. In perpendicular wind conditions, the results displayed a level of deterioration in air quality on the leeward footpath of 2% and a 6% improvement in air quality on the windward footpath with a reduction in the parking bay width. Figure 4.29 displays the contour patterns of pollutant concentrations on both footpaths for the 3.0 m and 2.4 m width parking bays and they did not illustrate any notable differences in a similar manner to the calculated results. The results suggest that reduction in the parking bay widths for the central parking layout does not significantly affect air quality on the footpaths.

4.4.7.2 HYBRID PARKING LAYOUTS

The hybrid parking layouts aimed at optimising street parking to further improve air quality on both footpaths. Firstly, the results from the parallel and perpendicular hybrid model can be viewed from Figure 4.30 and Figure 4.31. Figure 4.30 displays the contour plots of concentrations on the canyon floor for the reference and Par-Perp hybrid layout models in perpendicular wind conditions.

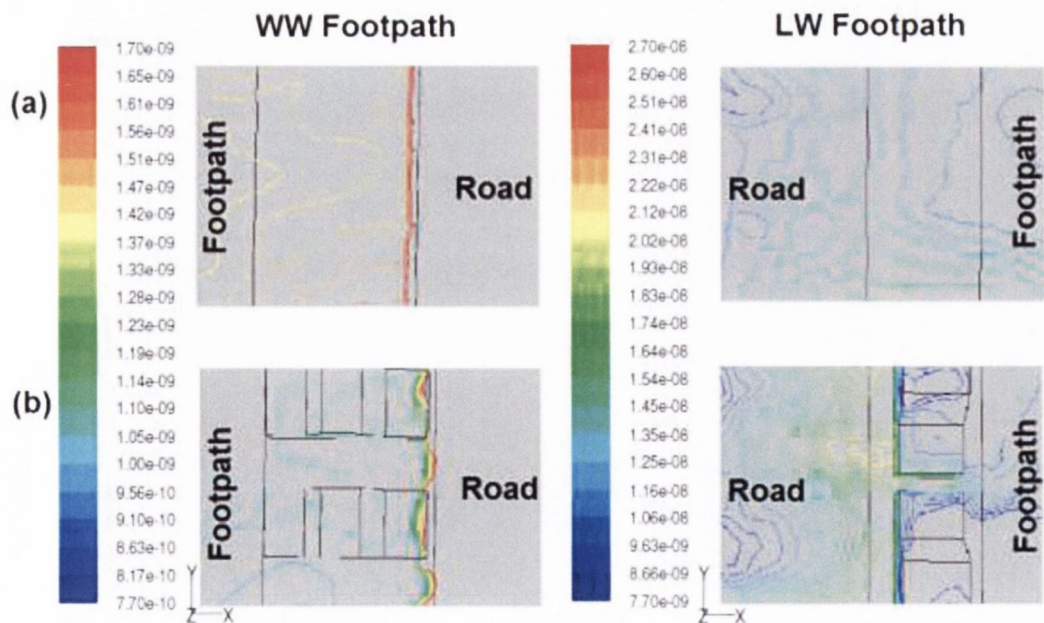


FIGURE 4.30. CROSS-SECTIONAL PLAN VIEW OF (A) REFERENCE AND (B) PAR-PERP HYBRID PARKING LAYOUT WITH CONTOURS OF TRACER CONCENTRATIONS IN PERPENDICULAR WIND CONDITIONS.

The pollutant concentration reduced by 46% and 4% with the introduction of the Par-Perp parked cars on the windward and leeward footpaths, respectively. The perpendicular parked cars on the windward side of the canyon displayed a significant improvement as it prevented the transport of pollutants from the road to the footpath. Unlike the parallel parking case, the parallel parked cars were not as effective a passive control on the leeward side of the canyon. This was due to an increased fraction of air being channelled between the perpendicular cars from the windward side of the canyon and subsequently transporting more pollutants towards the leeward footpath than in the parallel case. The parallel parked cars provide a baffle effect along the windward footpath which reduced the magnitude of the velocity vectors travelling across the floor of the canyon. The results suggested that the Par-Perp hybrid layout was not as effective in improving air quality on both footpaths as the perpendicular parking bay had a negative impact on air quality on the opposite leeward footpath. The concentration contour plots on the canyon floor for the reference and Par-Perp hybrid layout models in parallel wind conditions are shown in Figure 4.31.

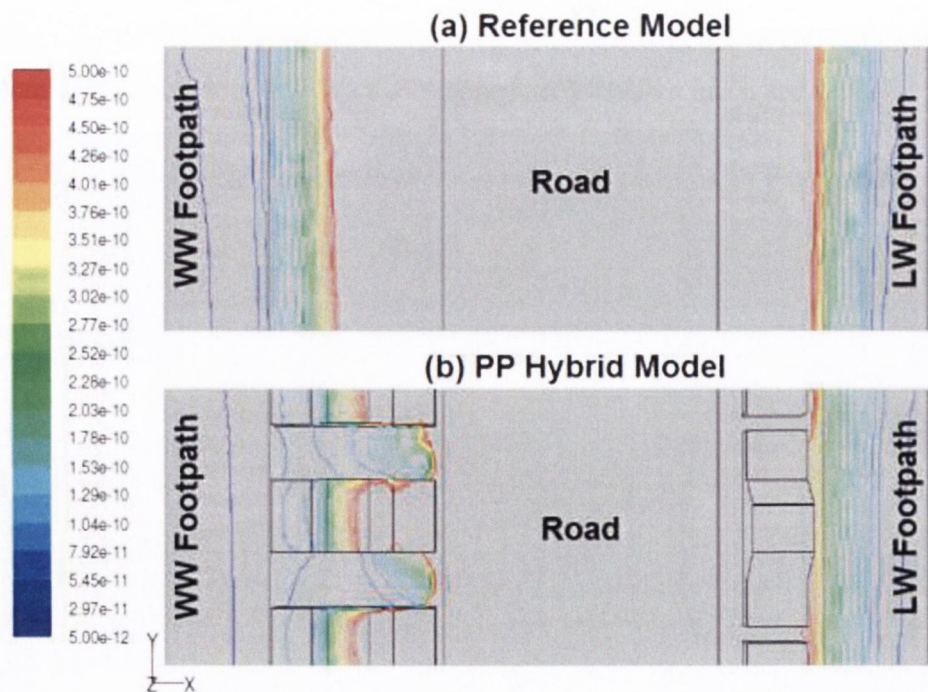


FIGURE 4.31. CROSS-SECTIONAL PLAN VIEW OF (A) REFERENCE AND (B) PAR-PERP HYBRID PARKING LAYOUT WITH CONTOURS OF TRACER CONCENTRATIONS IN PARALLEL WIND CONDITIONS.

The Par-Perp layout improved air quality on the windward footpath by 61% as the perpendicular parked cars provided a barrier between the pollutants transported from the road to the footpath. The perpendicular parked cars adjacent to the windward footpath in Figure 4.31(b) prevented the pollutants penetrating the footpath and channelled more pollutants along the road. In parallel wind conditions, the parallel parked cars on the leeward side of the canyon were found to trap pollutants and a 12% increase in the pollutant concentration was noted on the leeward footpath between the reference and Par- Perp hybrid layout. Unlike the previous parallel parking layout in case 1, the parallel parking displays an increase in this scenario due to the increased turbulence at street level caused by the perpendicular parked cars. The perpendicular parked cars increased lateral dispersion (X-direction in Figure 4.31) in a similar manner to the Par-Perp layout, which allowed increased fractions of pollutants to infiltrate the leeward footpath.

The Par-Diag hybrid parking layout displayed mixed results on both footpaths in different wind conditions. The contour plots of pollutant concentrations on the floor of the canyon for the Par-Diag hybrid layout models are shown in Figure 4.32 and Figure 4.33. The plan of contour concentrations in the Par-Diag hybrid models for perpendicular wind conditions is shown in Figure 4.32.

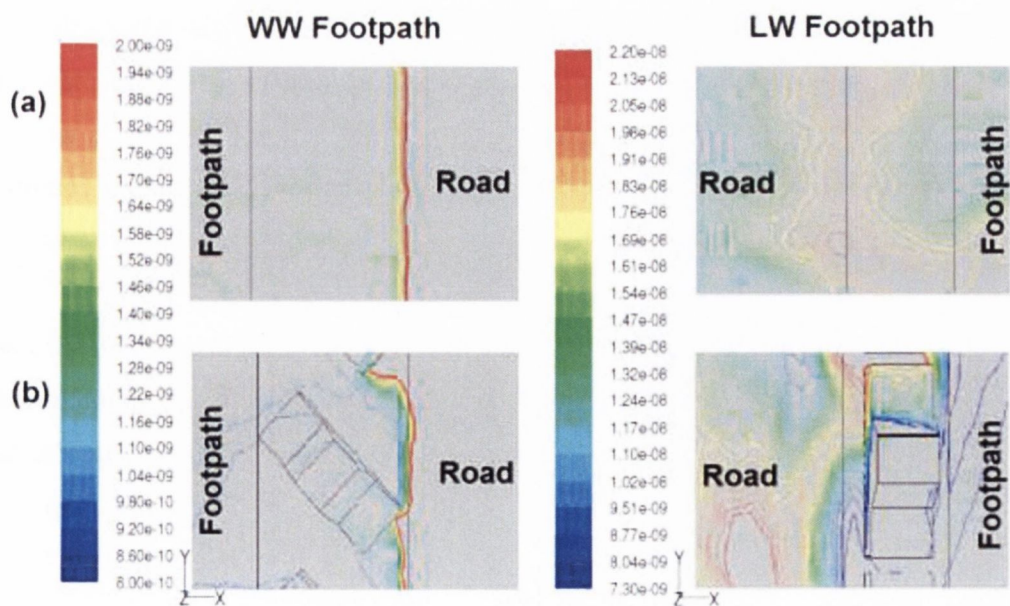


FIGURE 4.32. CROSS-SECTIONAL PLAN VIEW OF (A) REFERENCE AND (B) PAR-DIAG HYBRID PARKING LAYOUT WITH CONTOURS OF TRACER CONCENTRATIONS IN PERPENDICULAR WIND CONDITIONS.

In perpendicular wind conditions, reductions of 35% and 2% were calculated for the Par-Diag parking layout on the windward and leeward footpaths, respectively. The diagonally parked cars demonstrated an improvement in air quality on the windward side of the canyon as it reduced the transport of pollutants from the road to the footpath. The parallel parked cars provided the same improvement in air quality on the leeward side of the canyon as the parallel parking case model. The diagonally parked cars increased dispersion in the centre of the canyon and reduced the magnitude of the velocity vectors which maintained the effectiveness of the parallel parked cars acting as a baffle wall on the leeward footpath. The Par-Diag hybrid model provided a reduction on the leeward footpath, yet air quality on the windward footpath was not significantly affected by the diagonal parked cars. The contour plots of concentrations on the canyon floor for the reference and Par-Diag hybrid layout models in parallel wind conditions is shown in Figure 4.33.

Unlike the Par-P hybrid layout, the Par-Diag layout provided different results depending on the direction of the parking layout. The S-N (south to north) wind direction (Figure 4.33(b)) showed an improvement in air quality on the leeward footpath of 19% and a 58% increase in the pollutant concentration measured on the windward footpath. As the air travelled through the canyon, the diagonally parked cars channelled air away towards the windward footpath. Deteriorations in air quality became evident on the windward footpath as the parallel parked cars did not act as an effective baffle due to the diagonal winds, leading to a 58% increase in pollutant concentrations on the footpath. As an increased fraction of pollutants were transported away from the road, the parallel parked cars improved air quality conditions on the leeward footpath by 19%.

The N-S (north to south) wind direction (Figure 4.33(c)) displayed a substantial 177% increase in the pollutant concentration on the leeward footpath and a 33% improvement in air quality on the windward footpath. The reduction in pollutant concentrations on the windward footpath was due to the channelling effect of the diagonal parked cars transporting pollutants away from the footpath. The channelling effect transported a substantial fraction of pollutants towards the leeward footpath, leading to significant deterioration of air quality on the footpath. The parallel parked

cars did not provide an effective baffle as the wind travelled diagonally across the canyon.

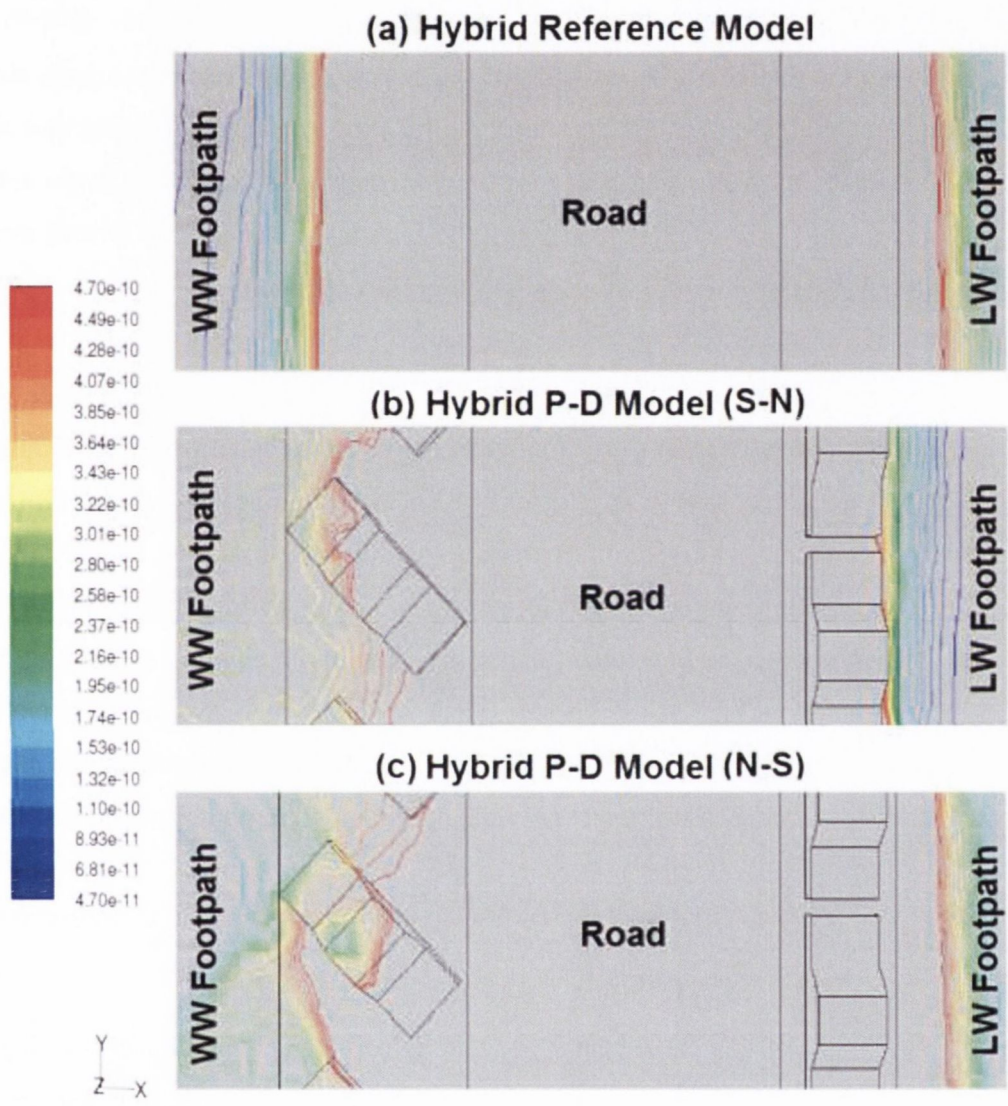


FIGURE 4.33. CROSS-SECTIONAL PLAN VIEW OF (A) REFERENCE, (B) PAR-PERP HYBRID S-N AND (C) PAR-DIAG HYBRID N-S PARKING LAYOUTS WITH CONTOURS OF TRACER CONCENTRATIONS IN PARALLEL WIND CONDITIONS.

Overall, the hybrid parking models displayed poor results compared to the early case models. The parallel parking bays provided poor results in the hybrid models compared to the parallel case for improved air quality on the footpaths for the different wind conditions. Therefore, the hybrid models would only be considered suitable in certain locations if specific wind conditions could be guaranteed most of the time.

4.4.8 APPLICABILITY OF STUDY

City parking is part of the urban landscape and has not been considered at any time with regards to the potentially positive impacts that it has on air quality in the urban environment. Each of the modelling investigations within this chapter aimed at drawing comprehensive evidence of the effects of on-street parking on air quality in urban street canyons. This research can be used to identify the most suitable parking layout for a given street based on predominant wind conditions to provide good air quality on the footpaths. In addition, the findings can be used to retrofit urban canyon where parking currently exists to improve current conditions.

Current parking guidelines vary based on local authorities and other government bodies. Therefore, this study highlights the potential benefits of introducing a specific parking layout in a street canyon which can improve air quality. However, other factors remain with regards to urban air pollution and parking, namely the additional air pollution created from the physical act of parking. This factor is directly proportional to the level of difficulty associated with entering and exiting the parking bay. Urban parking also promotes urban driving, which also has negative impacts on urban air quality. Therefore, the focus for the direction and applicability for the findings of this study is to provide optimal parking information for changing or retrofitting current parking layouts in urban street canyons.

4.5 CONCLUSIONS

The results of this parked car study highlighted the potential benefits of a parking bay in street canyons acting as a baffle wall to control pollutant flow and improving air quality on pedestrian footpaths. The following conclusions summarise the findings from the results and discussion sections.

Parallel parked cars (Case 1) provided the best overall option for improving air quality on the footpaths in comparison to its three counterpart parking layouts. Improvements in air quality were evident in all model scenarios, with minimum reductions of 31% and 46% in parallel and perpendicular wind conditions. Reductions and increases in pollutant concentrations were observed on the footpaths in the perpendicular, 45° and central parked car model layouts. Wind speed provided no significant influence to

improve the percentage reduction of pollutants on the footpaths for either wind directions in any of the cases.

The investigation of different occupancy rates found that low occupancy rates can actually be detrimental to pollutant concentrations on the footpaths in parallel winds. In perpendicular wind conditions, exponential and sigmoidal patterns of reduction were observed for increased occupancy rates on the leeward and windward footpaths, respectively.

The investigation of different parking bay spacing and hybrid parking layouts aimed to optimise the current parking regimes. A reduction in the spacing between vehicles improved air quality on the footpaths in the parked car models. However, the results of the Par-Perp and Par-Diag displayed mixed results in a similar manner to some of the previous cases as reductions and increases in pollutant concentrations were measured on the footpaths.

This investigation demonstrated the benefits of on-street car parking to reduce pedestrian personal exposure on footpaths, highlights the optimal parking layout in different prevailing wind conditions and the effects of parking occupancy rates to achieve maximum pollutant reduction. The findings can be used to modify current car parking regimes in urban canyons to reduce the potential pathways for pollutants from the road to the footpath, based on the knowledge of the optimal parking configuration and prevailing wind directions.

There is a need to further evaluate the potential of parked cars as a passive control by carrying out real world investigations. The generic study provides a good basis for understanding the influence of parked cars on air flow and pollutant dispersion and will provide guidance for real world case studies. The results obtained from this study and through future investigations can be incorporated into future urban planning strategies, to introduce or redesign urban parking bays and urban air quality at street level.

5. INVESTIGATING THE EFFECTIVENESS OF LOW BOUNDARY WALLS AS A PASSIVE CONTROL IN ASYMMETRIC STREET CANYONS.

5.1 INTRODUCTION

Previous research of passive controls has focused on symmetric street canyons (McNabola et al., 2009; Gallagher et al., 2011); however, in reality the majority of streets in the urban environment do not conform to such a regular pattern. Therefore, this study focuses on the performance of passive controls in reducing personal exposure from vehicular pollutants in asymmetrical street canyons (Figure 5.1) for varying meteorological conditions. This chapter investigates the effect of low boundary walls (LBWs) as a passive control in generic asymmetric street canyons. It also examines the difference between emission source models used to simulate pollutant emissions (Nagendra & Khare, 2002; Chang & Meroney, 2003; Baker et al., 2004; Murena et al., 2009; Gallagher et al., 2011) and the introduction of vehicular turbulence (Karim et al., 1998; Jicha et al., 2000; Solazzo et al., 2008) to determine the effects of these variable parameters on the potential of passive controls.



FIGURE 5.1. PHOTOGRAPHS OF DIFFERENT SHAPED STREET CANYONS (CLOCKWISE FROM TOP LEFT; PHILADELPHIA, DUBLIN, DUBAI & PARIS).

This study will assess the effects of LBWs in asymmetric canyons with H_1/H_2 ratios (i.e. the relationship between the height of the leeward and windward buildings as shown in Figure 5.2) ranging from 0.5 to 1.5 using the surface source emission model from previous investigations and the Pearse Street calibrated modelling investigation (Baker et al., 2004; Cai et al., 2008; Murena et al., 2009). The results will be compared to a series of line source emission models before and after the inclusion of static vehicles in the street canyon to introduce a degree of vehicular turbulence.

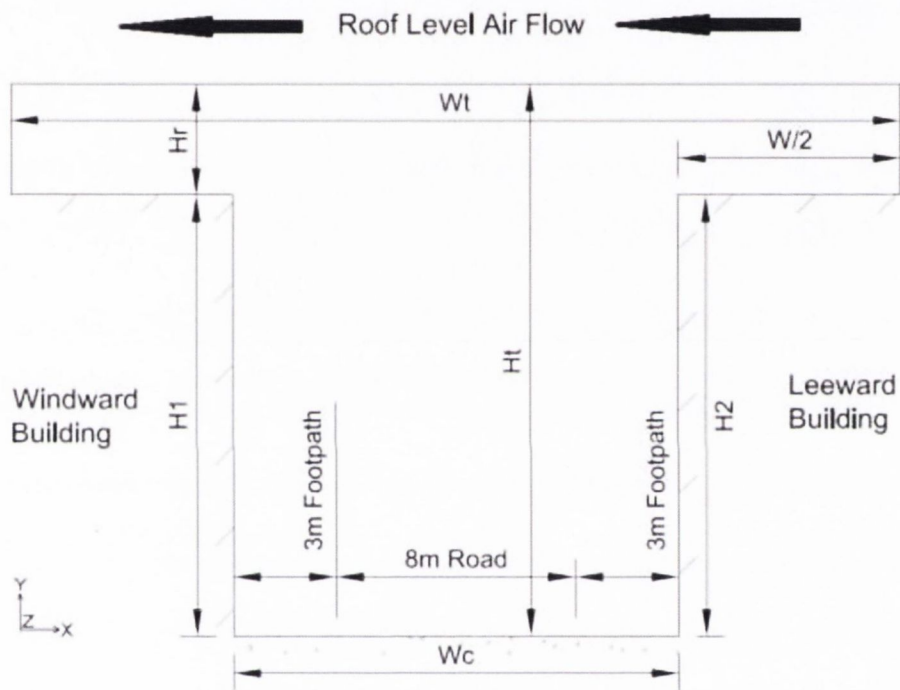


FIGURE 5.2. ILLUSTRATION OF ASYMMETRIC REFERENCE MODEL LAYOUT.

5.2 METHODOLOGY

The methodology section introduces the different modelling investigations carried out within the scope of this chapter. It will also outline the rationale behind the investigations and how each of the studies link together as part of the asymmetrical street canyon study. Firstly, the methodology for constructing the street canyon models is outlined, followed by the three modelling cases to be investigated for asymmetrical canyons: (i) the effect of footpath and central LBWs, (ii) comparing two distinct emissions source models and (iii) introducing static vehicles to represent vehicular turbulence in a street canyon.

5.2.1 MODELLING SET-UP

Each study comprised two numerical modelling cases to estimate the effects of introducing a passive control on air flow and pollutant dispersion in asymmetrical urban street canyons. The study assessed two sets of three-dimensional models which differed from one another with the inclusion of LBWs in one set of models. These were strategically located to increase localised dispersion and potentially reduce pollutant concentrations on the footpaths. This method was used in this study to endeavour that an accurate comparison was made between each reference and passive control model.

The cases investigated the percentage reduction in pedestrian exposure of an inert virtual tracer pollutant (SF_6) for a range of asymmetrical canyon configurations with vehicular emissions represented as a source across the road surface (Gromke, 2011a; Hagler et al., 2011; Salim et al., 2011b; Richmond-Bryant & Reff, 2012). Two sets of models were constructed for each H_1/H_2 ratio; the first set consisted of a reference model (200 m in length (+Z direction)) without passive controls and the second set consisted of a near-identical model, containing LBWs on the outer edge of both footpaths or in the centre of the canyon. The models were constructed for different asymmetric ratios based on the dimensions shown in Table 5.1, which is illustrated in conjunction with Figure 5.2.

TABLE 5.1. DIMENSIONS OF ASYMMETRIC STREET CANYON MODELS (ALL DIMENSIONS IN METRES).

Asymmetric Ratio	Building Height		Canyon Width		Canyon Height	
	H_1	H_2	W_c	W_t	H_r	H_t
0.5	7.0	14.0	14.0	28.0	7.0	21.0
0.6	8.4	14.0	14.0	28.0	7.0	21.0
0.7	9.8	14.0	14.0	28.0	7.0	21.0
0.8	11.2	14.0	14.0	28.0	7.0	21.0
0.9	12.6	14.0	14.0	28.0	7.0	21.0
1.0	14.0	14.0	14.0	28.0	7.0	21.0
1.1	15.4	14.0	14.0	28.0	7.7	21.7
1.2	16.8	14.0	14.0	28.0	8.4	22.4
1.3	18.2	14.0	14.0	28.0	9.1	23.1
1.4	19.6	14.0	14.0	28.0	9.8	23.8
1.5	21.0	14.0	14.0	28.0	10.5	24.5

The leeward building height (H_2) equals to the width of the canyon floor (W_c) of 14 m in all of the models, for both the reference and LBW models. The total width of the model of 28 m was calculated as the canyon width multiplied by a factor of 2. This was to account for a 7 m rooftop width on each side of the canyon similar to a previous investigation by McNabola et al. (2009). The windward building height, H_1 is proportional to the leeward building height, H_2 , as the H_1/H_2 ratio varied in the model configurations from 0.5 to 1.5 in 0.1 intervals to allow a detailed investigation of asymmetrical canyons. Figure 5.2 displays a typical cross section of a reference street canyon model with a H_1/H_2 ratio of 1.0, consisting of a road containing two 4 m wide traffic lanes and two 3 m footpaths.

The pollutant concentrations measured in both configurations were compared to yield the percentage difference between the two models as previously described in Chapter 3. Each model was run with an inlet wind velocity of 8 m/s to identify the different formations of primary and secondary vortices in a perpendicular wind direction (-X direction) to the canyon floor for models of varying H_1/H_2 ratios. This study focused on perpendicular wind conditions as canyon asymmetry affects pollutant dispersion to a lesser degree than in parallel wind conditions. The parked cars investigation (see Chapter 4) found that wind speed had only a small influence on the percentage reduction on pollutant dispersion in a street canyon between reference and LBW models (Gallagher et al., 2011), therefore only one low (2 m/s) and one high (8 m/s) wind speed was used in this study.

5.2.2 ASYMMETRY MODEL SENSITIVITY STUDY

Prior to simulating air flow and pollutant dispersion in the generic street canyon models, several discretization tests were carried out as part of the sensitivity analysis specific to the canyon asymmetry investigation. This study consisted of in excess of 50 model simulations, therefore the sensitivity study aimed to optimise the running time of each model. The findings of the sensitivity study are detailed in this section and provide accuracy for the model output as part of the asymmetric canyon investigation.

5.2.2.1 OPTIMISED GRID SCHEME

Mesh discretization analysis was carried out for the asymmetry canyon study in accordance with the details outlined in the Chapter 3. To find the most suitable grid mesh for this study, a series of models were also created with different size meshes. It was noted that as the air flowed down into the canyon it reached the windward footpath and subsequently travelled along the street floor (right to left in Figure 5.2) to the leeward footpath. The concentrations measured on the windward footpath were found to be very similar for all mesh schemes. The finer mesh schemes were required on the leeward footpath to provide accurate measurements in each of the asymmetry models. Based on the results, a tapered surface grid mesh was selected for the canyon floor with a uniform volumetric mesh (Gallagher et al., 2012). The tapered mesh was suitable for a series of perpendicular wind models only, as the investigation of several wind conditions would require a uniform fine mesh across the canyon floor. The measured concentrations for the different mesh schemes on both footpaths are shown in Figure 5.3.

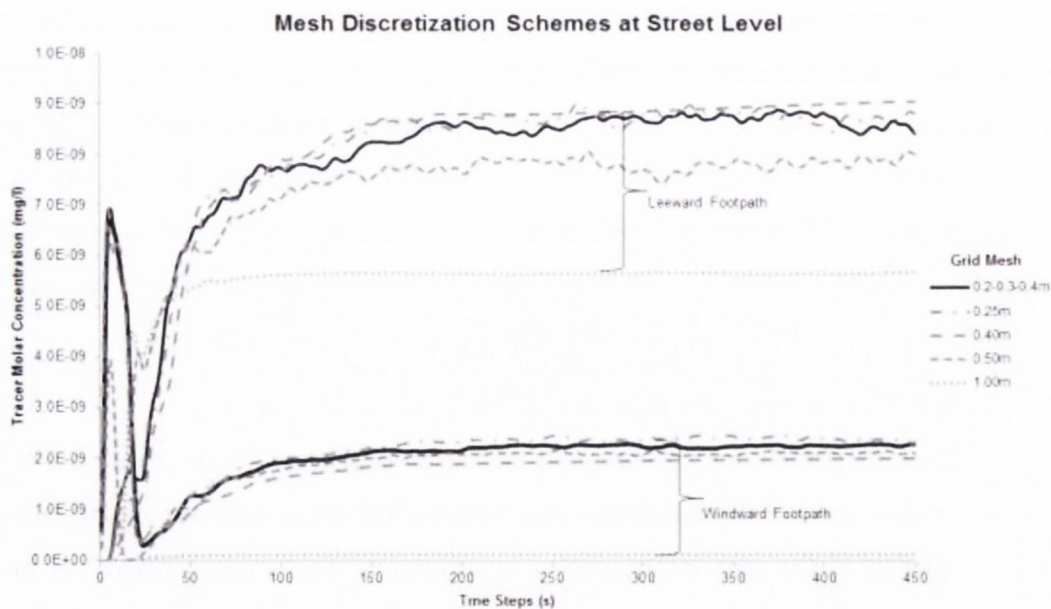


FIGURE 5.3. LEEWARD AND WINDWARD FOOTPATH CONCENTRATIONS OF TRACER GAS FOR MODELS WITH VARYING MESH DISCRETIZATION SCHEMES.

The canyon floor in each asymmetrical model was meshed with triangular mesh elements of 0.2 m on the leeward footpath, 0.3 m on the road surface, 0.4 m on the windward footpath and the overall volume was meshed with a 1.0 m tetrahedral mesh.

The virtual tracer emissions were released from the road surface at ground level (i.e. $Z = 0$) in the asymmetrical canyon models.

5.2.2.2 OPTIMISED HEIGHT EXTENSION ABOVE BUILDING ROOFTOP

A series of model configurations were also examined with extended heights above the rooftop of the buildings of H_r (see Figure 5.2; H_r equals to the maximum height of H_1 or H_2 multiplied by an extended height factor, X) to allow air flow to enter or exit the canyon above the buildings. Values of H_r (see Figure 5.2) where $X = 0.25, 0.5, 1.0$ & 2.0 times the greater value of H_1 or H_2 were examined. Figure 5.4 illustrates the plot of the measured pollutant concentrations on the footpaths for each of the model configurations.

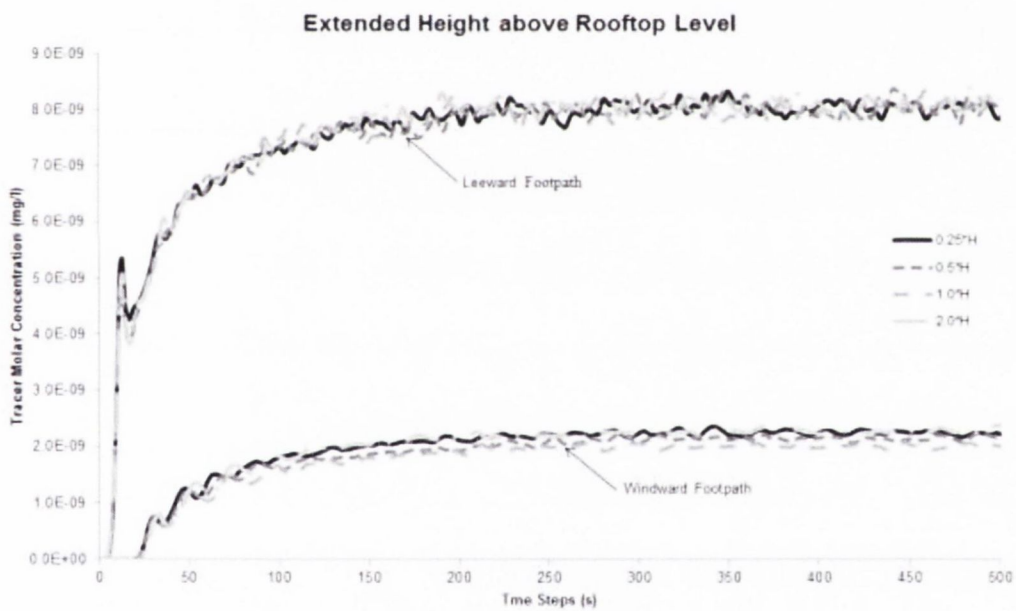


FIGURE 5.4. LEEWARD AND WINDWARD FOOTPATH CONCENTRATION OF TRACER GAS FOR MODELS WITH VARYING EXTENSION HEIGHT ABOVE ROOFTOP.

After an analysis of the model data output, it was identified that a reduction in the extended roof height did not affect the results observed at street level within each model configuration. Therefore, $0.25H$ was selected for this study as it minimised the volume for each model and further optimised the computational timeframe requirements.

5.2.2.3 OPTIMISED ITERATIONS PER TIME STEP PROCEDURE

To optimise the computational running time of a typical model configuration, an analysis of the data output of iterations per time step was carried out. The objective of this analysis was to identify the point at which iteration values converged to a degree where the number of iterations could be reduced per time step at different stages during the model simulation process. The default convergence criteria in Fluent are typically set for absolute values for several individual residuals. The manual reduction of iterations can reduce the running time of models without a loss of accuracy and provides an alternative solution to a sensitivity analysis of a wide range of residuals in turbulent models. The results from the iterative tests are displayed in Table 5.2.

TABLE 5.2. ITERATIONS PER TIME STEP TEST TO OPTIMISE MODEL COMPUTATIONAL RUNNING TIMES (DISPLAYED AS PERCENTAGE OF ITERATION VALUE DIVIDED BY FINAL ITERATION VALUE).

Time Step (s)	No. of Iterations				
	25	50	75	95	100
1	88.41%	90.21%	71.85%	1.00%	<u>0.00%</u>
10	2.60%	-0.83%	-0.13%	<u>0.00%</u>	-
20	-0.03%	0.01%	<u>0.00%</u>		
50	0.02%	<u>0.01%</u>	-	-	-
250	<u>-0.00%</u>	-	-	-	-

Table 5.2 presents the differences between the measured concentrations at a specific iteration per time step (e.g. 25 iterations) as a percentage of the concentration at the final iteration per time step (i.e. 100 iterations). As the number of time steps (seconds) increased the required number of iterations per time step were reduced at different stages in the simulation process. As the air flow pattern in the canyon stabilised, the number of iterations per time step was reduced as convergent results were noted for reduced iterations as per the underlined iterations in Table 5.2. For example, during the first time step of the model simulation process, significant differences (72% to 90%) were measured between the iterative values at 25, 50 and 75 iterations. This was due to the changes taking place in the model as the air flow pattern began to develop. A reduction in the number of iterations was considered acceptable when a convergence rate of over 99.95% (values less than 0.05% in Table 5.2) was noted. The results identified the allowance for a reduction in iterations at different stages in the simulation process to reduce the cumulative running time of the models.

5.2.2.4 DATA EXTRACTION FROM MODELS

In addition to the monitoring line inserted in the centre of both 3.0 m footpaths at a height of 1.76 m in all the investigations, a monitoring line was inserted at 1.00 m to represent the path of a child walking the full length of the canyon. This was to assess the differences in pollutant concentration exposure due to the height of an individual. The data output was collected and results calculated as outlined in the Chapter 3. In addition, the average pollutant concentrations for each monitoring line which was used to calculate the percentage differences in concentration are presented in Appendix A for all model scenarios.

5.3 ASYMMETRY MODEL INVESTIGATIONS

A series of modelling investigations were carried out consisting of different canyon geometry, wind conditions and emission source configurations. This section defines each of the modelling investigations carried out within the asymmetry study.

5.3.1 ASYMMETRIC CANYON MODELS

5.3.1.1 FOOTPATH LBW MODELS

The first modelling cases were constructed with different configurations of 0.5 m high LBWs at street level. The 0.5 m was selected based on the findings of previous modelling investigations and additional LBW tests which are discussed in Chapter 3 (McNabola et al., 2008a; King et al., 2009; McNabola et al., 2009). This initial set of models consisted of two footpath LBWs located at the outer edge of both footpaths in the canyon (Figure 5.5(a)). The H_1/H_2 ratio varied from 0.5 to 1.5 in intervals of 0.1 as described in the Section 5.2.1. The dispersion of air pollution was simulated with surface emission source models and for inlet velocity speeds of 8 m/s. This study aimed to define changes in pollutant concentrations as percentage differences to identify improvements or deteriorations in air quality with the implementation of footpath LBWs.

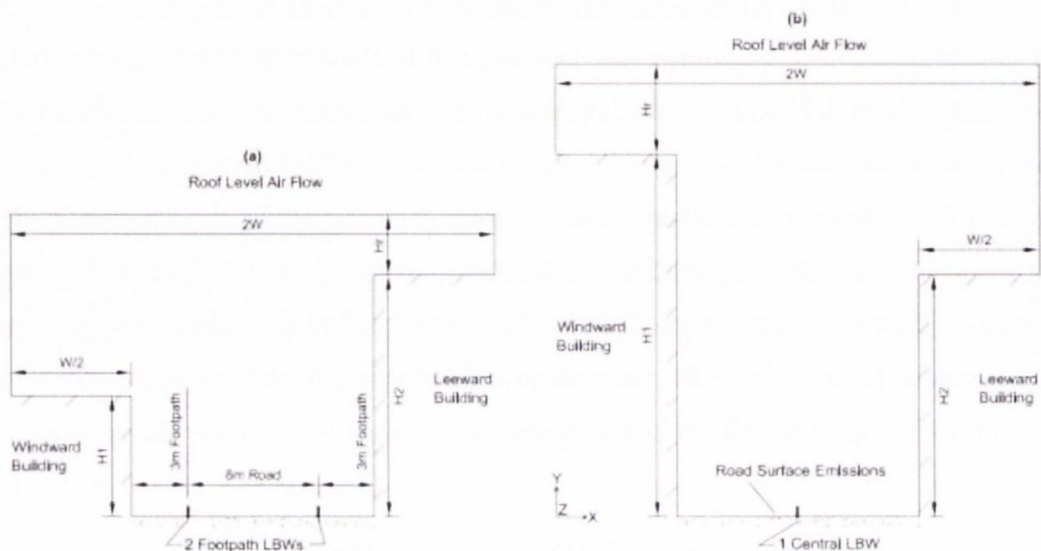


FIGURE 5.5. CROSS SECTION OF THREE-DIMENSIONAL ASYMMETRICAL CANYON MODELS FOR (A) $0.5 H_1/H_2$ WITH TWO FOOTPATH LBWs AND FOR (B) $1.5 H_1/H_2$ WITH ONE CENTRAL LBW.

5.3.1.2 FOOTPATH AND CENTRAL LBW LAYOUTS

An extension of the footpath LBW model study was carried out, with a second case configuration constructed having an individual LBW in the centre of the canyon between the two traffic lanes (Figure 5.5(b)). A condensed series of models were simulated for this case with the H_1/H_2 ratio varying in this case from 0.5 to 1.5 in 0.5 intervals. The results for this set of asymmetric models allowed for a comparison between the two sets of LBW models. The LBW models were run at the same inlet wind velocity as the reference models. The models compared air flow and dispersion patterns between the high and low wind speed models of 8 m/s and 2 m/s, respectively.

5.3.2 EMISSIONS SOURCE MODELS

5.3.2.1 COMPARISON OF EMISSION SOURCE TYPES

This section compared asymmetric canyon layouts for different LBW configurations with two distinct methods of simulating vehicle emissions. As outlined in Chapter 3, the line source (Figure 5.6(b)) represented the path of a typical vehicle tailpipe along the centre of each lane in the street canyon, while the surface emission source (Figure 5.6(a)) represents the dispersed emissions due to vehicular turbulence in the canyon. The surface emission source simplifies pollutant dispersion in the wake of moving vehicles, while the line source omits this form of dispersion. Therefore, this section

aims to compare the two emissions source models (maintaining the same pollutant emission rate as a species mass fraction over time) to consider whether both methods can be used to assess the effects of passive controls.

The asymmetrical models assessed canyons with H_1/H_2 ratios of 0.5, 1.0 and 1.5. This was to determine the effect of different asymmetric configurations and vehicular emission sources on modelling output. The models were prepared in a similar manner to the previous asymmetrical cases with the emissions source differing between the two models (Figure 5.6).

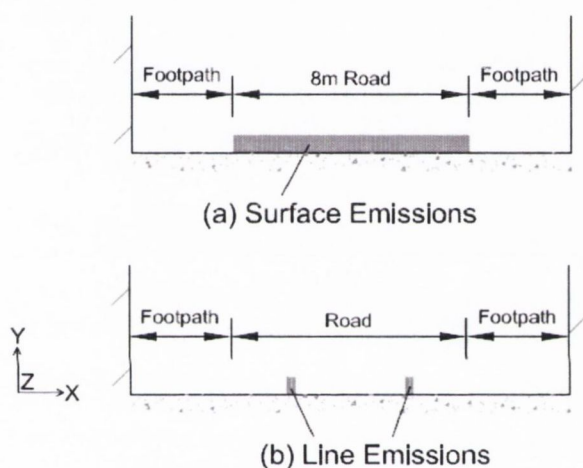


FIGURE 5.6. CROSS SECTIONS OF STREET CANYON LAYOUT SHOWING (A) SURFACE AND (B) LINE SOURCE EMISSIONS.

5.3.2.2 LINE EMISSIONS SOURCE AND STATIC VEHICLES

The inclusion of static vehicles in addition to line source emissions was to examine the effect of idle conditions as a simplified alternative to moving vehicles in the reference and LBW models. The duration of the simulation parallel processing for each model in the asymmetry studied ranged from two to three days to a week and the addition of moving vehicles would have increased the running time by ten-fold. In addition, as the study compared the results from the reference and LBW models, the omission of turbulence due to moving vehicles from all scenarios was not considered to have any considerable effect on the comparative results.

In a similar manner to the previous cases, this investigation modelled street canyons with H_1/H_2 ratios of 0.5, 1.0 and 1.5 to assess the effect of vehicular turbulence in the

different asymmetrical canyons. Each model was also run with inlet wind velocities of 2 m/s and 8 m/s perpendicular to the canyon floor (-X direction) to assess the different dispersion patterns of vehicular turbulence with a line emission source in models of varying H_1/H_2 ratios. The spacing between both static vehicles remained constant for each modelling study and was represented by the value of vehicle spacing (V_s) from Figure 5.7.

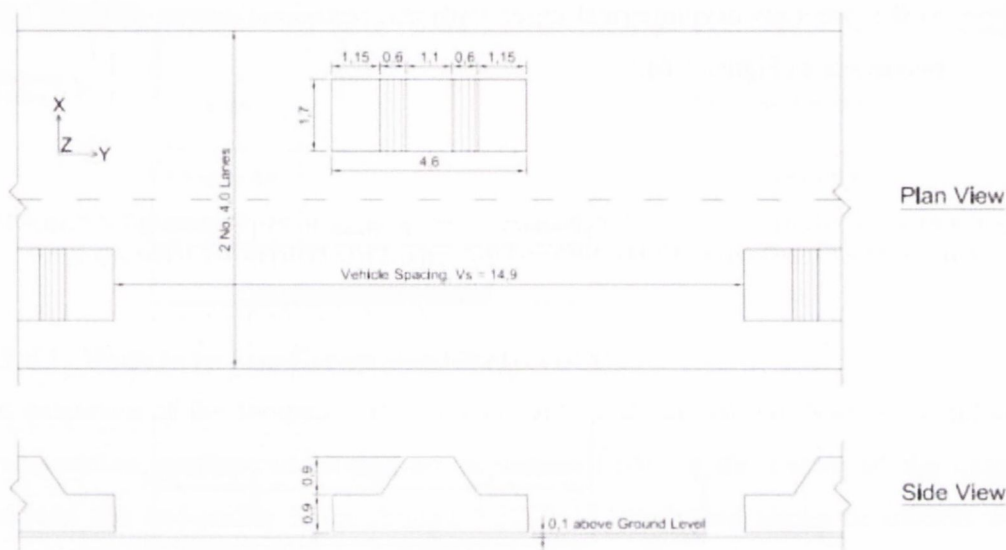


FIGURE 5.7. PLAN AND CROSS-SECTIONAL ELEVATION OF STATIC VEHICLE LAYOUT IN STREET CANYON.

The vehicle spacing was determined as the optimal safe distance between vehicles travelling at a speed of 30 km/hr. This speed was chosen to represent the urban traffic speed limit in an urban street canyon. The models were prepared and results were extracted in a similar manner to the previous cases within this study.

5.4 RESULTS

5.4.1 ASYMMETRIC CANYON MODELS

5.4.1.1 FOOTPATH LBW MODELS

The results of the investigation for the asymmetrical canyon models of varying H_1/H_2 ratios are presented in Figure 5.8 and Figure 5.9. The plots compare the pollutant concentrations for the reference and footpath LBW models and are presented as a percentage difference for each H_1/H_2 ratio at heights of 1.00 m and 1.76 m, respectively. The results showed that the presence of two footpath LBWs provides

varied results on both footpaths. Figure 5.8 displays the results on the leeward footpath as the percentage difference between the reference and LBW models for the different asymmetrical canyon models.

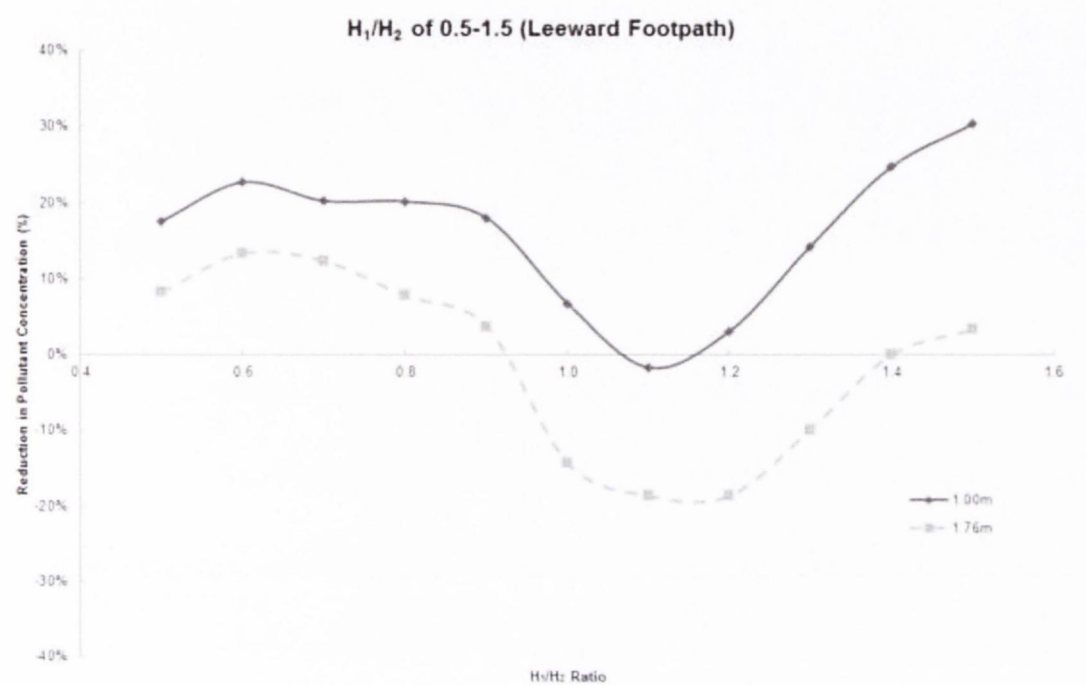


FIGURE 5.8. PLOT OF AVERAGE PERCENTAGE POLLUTANT CONCENTRATION ON LEEWARD FOOTPATH IN DIFFERENT H_1/H_2 RATIO CANYONS AT RESPECTIVE HEIGHTS (GALLAGHER ET AL., 2012).

The results varied on the leeward footpath (Figure 5.8) with an initial 8% reduction of pollutant concentration in the 0.5 H_1/H_2 ratio model at a height of 1.76 m. The difference reduced with increases in the H_1/H_2 ratio up to 1.1, where an increase in the pollutant concentration of 19% was calculated between the model configurations. An upward trend was identified from the 1.1 H_1/H_1 ratio model, reaching a reduction in the pollutant concentration of 3% in the 1.5 H_1/H_2 ratio model. A similar pattern of reductions and increases was noted for the percentage differences between the reference and footpath LBW model configurations at a child height of 1.00 m. The percentage reduction in pollutant concentration ranged from 18% for the 0.5 H_1/H_2 ratio model, to an increase of 2% for an asymmetric ratio model of 1.1 and a maximum reduction of 30% in the 1.5 H_1/H_2 ratio model. Figure 5.9 shows the results for the percentage difference in pollutant concentrations between the reference and footpath LBW models on the windward footpath.

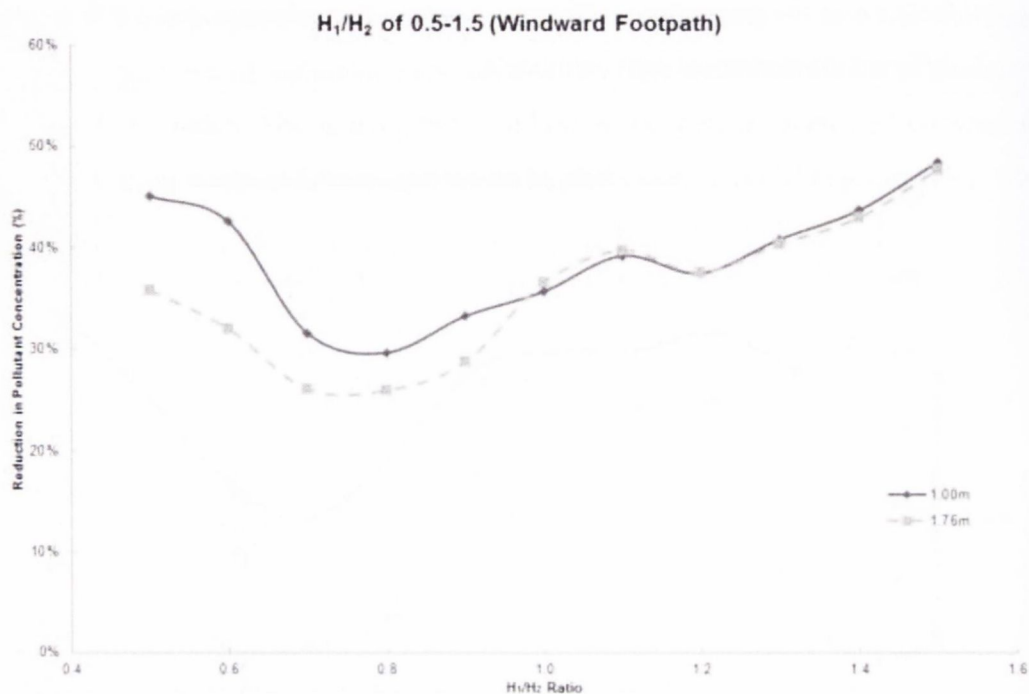


FIGURE 5.9. PLOT OF AVERAGE PERCENTAGE POLLUTANT CONCENTRATION ON WINDWARD FOOTPATH IN DIFFERENT H_1/H_2 RATIO CANYONS AT RESPECTIVE HEIGHTS (GALLAGHER ET AL., 2012).

On the windward footpath, the results (displayed in Figure 5.9) showed reductions in the pollutant concentration for all H_1/H_2 for all asymmetrical ratios. At an adult height of 1.76 m, the reductions calculated ranged from a minimum of 26% in the 0.8 H_1/H_2 ratio model with incremental increases in the reduction to 40% and 48% for an asymmetric ratio of 0.5 and 1.5, respectively. The percentages reduction at child height of 1.00 m ranged from a minimum of 30% in the 0.8 H_1/H_2 ratio model. More significant reductions were calculated for both reduced and increased H_1/H_2 ratios from 0.8 to 0.5 and 1.5 with reductions of 50% and 48%, respectively.

STEADY STATE ANALYSIS OF RESULTS

The average pollutant concentrations were calculated for all asymmetric reference and LBW models as defined in the post-processing section of Chapter 3. To establish the accuracy of the moving average data and to determine the statistical significance of the results for the asymmetric canyon models, values for the average relative concentration and standard deviation (σ) were plotted. Figure 5.10 and Figure 5.11 illustrate the plots of average relative concentration measured on both the leeward and

windward footpaths at a height of 1.00 m for the reference and footpath LBWs models in canyons with different asymmetric ratios. The difference between the two sets of results clearly shows that the presence of passive controls alters air flow and pollutant dispersion. This is indicated by the differences in the results for the models with (LBW model) and without (reference model) passive controls. The plots also include error bars denoting twice the calculated standard deviation (2σ) i.e. a 95% confidence interval that the average concentration sits within this zone. Figure 5.10 shows the results for the pollutant concentration on the leeward footpath for the reference and LBW models at a height of 1.00 m.

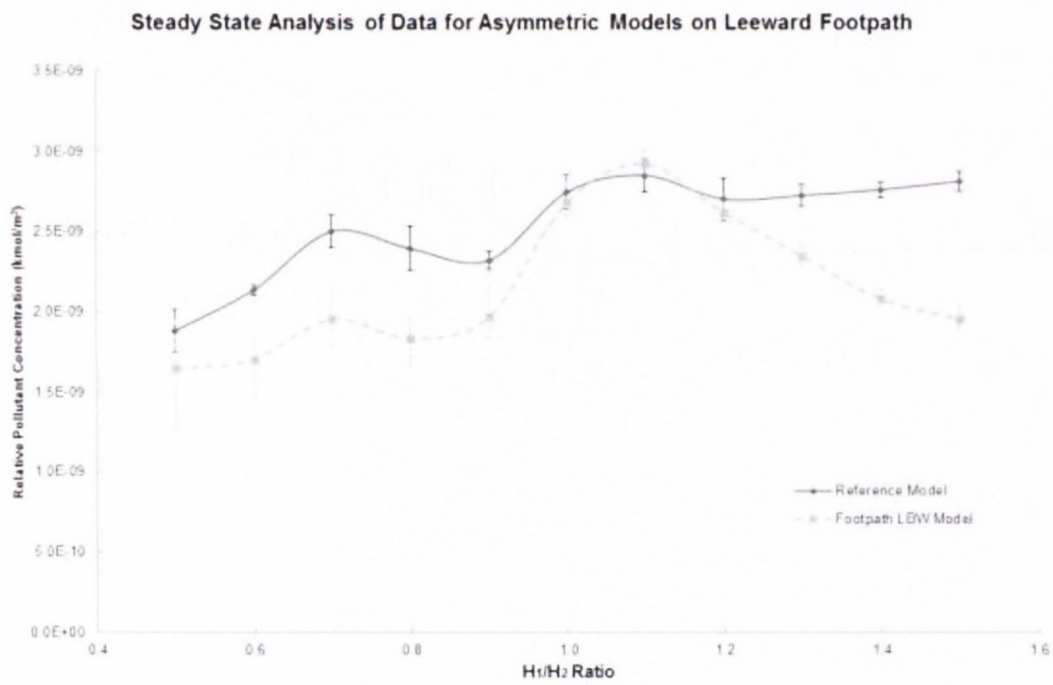


FIGURE 5.10. PLOT OF AVERAGE RELATIVE CONCENTRATION VS. ASYMMETRIC H_1/H_2 RATIO IN REFERENCE AND LBW CANYON MODELS ON LEEWARD FOOTPATH AT 1.00 METRE HEIGHT.

The plot of the average relative concentration on the leeward path demonstrates a general upward trend in the reference models for varying H_1/H_2 . The average concentration marginally increases with an increase of the asymmetric ratio in the canyon. The footpath LBW model shows an upward trend in the pollutant concentration on the leeward footpath between H_1/H_2 ratios of 0.5 to 1.1, with a downward trend evident with an increasing asymmetric ratio of 1.1 to 1.5. In general, the LBWs on both footpaths provide an effective passive control by reducing the concentration on the leeward footpath in most of the asymmetric canyon models.

From a visual inspection of the error bars in Figure 5.10, it is evident that there is a significant amount of variability in some models with different asymmetrical canyon ratios. The scale of the error bars reduce as the H_1/H_2 ratio increases for the measured concentrations on the leeward footpath. In most model scenarios, the error bars do not overlap, demonstrating that the results are statistically significant. There are small overlaps observed between a H_1/H_2 ratio of 1.0 and 1.2. This suggests that the results in this region are not comprehensive as an increase or reduction may occur on the leeward footpath in these asymmetrical canyon models. In addition, an overlap is observed in the 0.5 H_1/H_2 ratio model suggesting a level of inconclusive evidence regarding the effectiveness of reduced concentrations with the implementation of a LBW on the leeward footpath for a canyon with an asymmetrical ratio of less than or equal to 0.5. Figure 5.11 illustrates the plot of the relative pollutant concentrations for different H_1/H_2 ratios on the windward footpath.

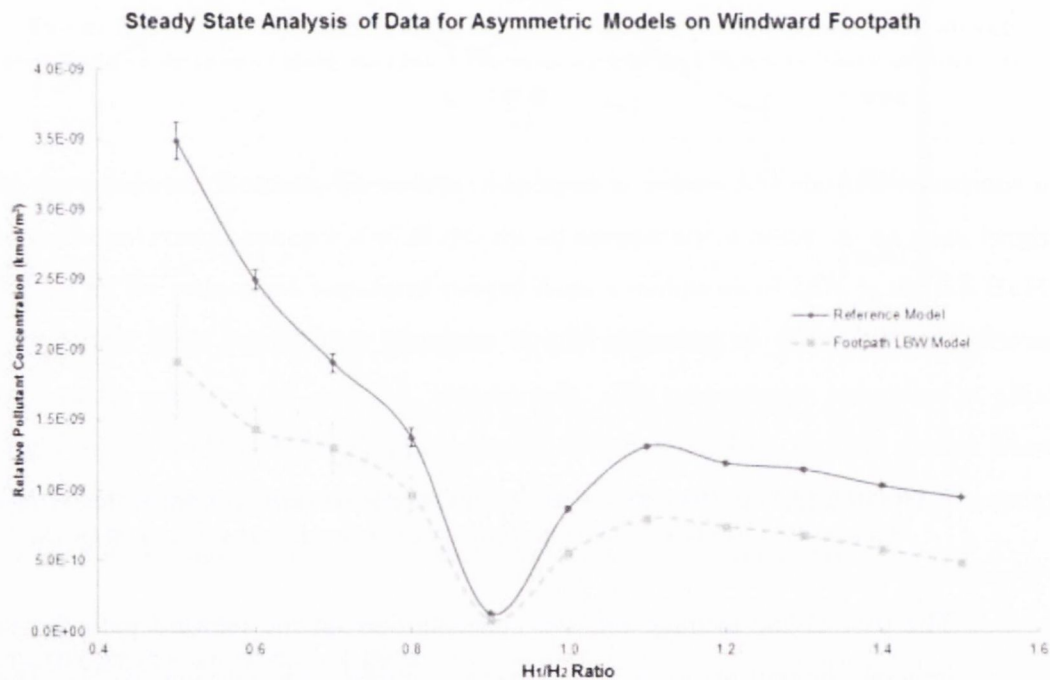


FIGURE 5.11. PLOT OF AVERAGE RELATIVE CONCENTRATION VS. ASYMMETRIC H_1/H_2 RATIO IN REFERENCE AND LBW CANYONS ON WINDWARD FOOTPATH AT 1.00 METRE HEIGHT.

An overall downward trend is evident for both sets of reference and LBW models. Linear patterns of reduction in the pollutant concentrations are evident in two zones; in the H_1/H_2 ratio model from 0.5 to 0.8 and from 1.1 to 1.5. An anomaly occurs for both the 0.9 H_1/H_2 ratio reference and LBW models, which is caused by increased

turbulence in the canyon, significantly reducing the pollutant concentration on the windward footpath. The increased turbulence in the model was due to the height of the windward building reaching a zone in which it initiated the primary vortex by channelling air downward from roof level and into the canyon.

The results displayed in Figure 5.11 clearly indicate a reduction in relative pollutant concentrations on the windward footpath with the implementation of a passive control. Due to the similar concentrations calculated for the reference and LBW models in the 0.9 H_1/H_2 model, the comparative results therefore illustrates the poorest expected performance of the LBW in this asymmetrical canyon layout.

The scale of the error bars reduces with an increase in the asymmetrical ratio on both footpaths. As illustrated by the negligible magnitude of the error bars, the concentrations calculated on the windward footpaths achieves a steady state in the 0.9 H_1/H_2 ratio models. This steady state is not as evident on the leeward footpath as the error bars are more evident for all asymmetrical canyon models. Similar results were noted for the concentrations calculated on both footpaths at an adult height of 1.76 m.

5.4.1.2 FOOTPATH VS. CENTRAL LBW MODELS

The comparative results for the footpath and central LBW configurations are shown in Table 5.3 for a high wind speed of 8 m/s and a perpendicular wind direction. The results are displayed as the percentage difference between the reference model and the corresponding LBW model for H_1/H_2 ratios of 0.5, 1.0 and 1.5.

TABLE 5.3. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW MODELS WITH A SURFACE EMISSION SOURCE IN HIGH (8 M/S) PERPENDICULAR WIND CONDITIONS.

H_1/H_2 Ratio	Footpath LBWs				Central LBWs			
	1.76m		1.00m		1.76m		1.00m	
	LW	WW	LW	WW	LW	WW	LW	WW
0.5	8%	36%	8%	45%	7%	46%	4%	44%
1.0	-14%	37%	4%	36%	12%	42%	26%	40%
1.5	3%	48%	30%	48%	29%	63%	49%	64%

Note: Negative percentages indicate an increase in the concentration between the reference and LBW model.

The results showed a reduction for almost all asymmetrical layouts with the introduction of both LBW configurations. On the leeward footpath, air quality

improved by 30% in the 1.5 H_1/H_2 ratio model, yet a deterioration of 14% was calculated in the 1.0 H_1/H_2 ratio model. The other asymmetrical canyon models displayed small improvements in air quality on the leeward footpath ranging from 3% to 8% at both monitoring heights. Consistent reductions were measured on the windward footpath ranging from 36% to 48% for the different H_1/H_2 ratios at adult and child height.

The implementation of a central LBW provided reductions in pollutant concentrations for all asymmetric ratios on the leeward footpath, with concentration reductions ranging from 12% (H_1/H_2 of 1.0 at 1.76 m height) to a maximum of 49% (H_1/H_2 of 1.5 at 1.00 m height). Reductions in pollutant concentrations were also calculated for all H_1/H_2 asymmetrical ratios in both LBW layouts on the windward footpaths. The reduction in pollutant concentrations was more prominent on the WW footpath for a central LBW as reductions ranged from 40% to 64% for different H_1/H_2 ratios. The most notable improvements in air quality on both footpaths were noted with an increase in the asymmetrical ratio from 1.0 to 1.5. The comparative results for the footpath and central LBW configurations are shown in Table 5.4 for a low wind speed of 2 m/s in perpendicular wind conditions.

TABLE 5.4. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW MODELS WITH A SURFACE EMISSIONS SOURCE IN LOW (2 M/S) PERPENDICULAR WIND CONDITIONS.

H_1/H_2 Ratio	Footpath LBWs				Central LBWs			
	1.76m		1.00m		1.76m		1.00m	
	LW	WW	LW	WW	LW	WW	LW	WW
0.5	5%	37%	13%	46%	3%	51%	3%	45%
1.0	-13%	34%	16%	38%	18%	37%	31%	32%
1.5	11%	44%	38%	44%	28%	60%	53%	61%

Note: Negative percentages indicate an increase in the concentration between the reference and LBW model.

In a similar manner to the high wind speed models, the results in Table 5.4 show a reduction in pollutant concentrations on both footpaths for most asymmetric model scenarios. A slight increase in the pollutant concentration of 13% (H_1/H_2 of 1.0 at 1.76 m height) occurred on the LW footpath with the implementation of the footpath LBWs, but more significant reductions of up to 38% were measured in the 1.5 H_1/H_2 ratio model at a height of 1.00 m. Reductions applied for all asymmetrical canyon models on the LW footpath with a central LBW ranging from a minimum of 3% for a

H_1/H_2 of 0.5 to a maximum of 53% in the 1.5 H_1/H_2 ratio model at a height of 1.00 m. On the windward footpath, reductions in the pollutant concentrations occurred for all asymmetrical ratios in both the footpath and central LBW layouts. The reduction in pollutant concentrations with footpath LBWs ranged from 34% at 1.76 m height in the symmetrical model to 46% at a height of 1.00m in the 0.5 H_1/H_2 ratio model. Reduction on the windward footpath ranged from 32% to 61% for the central LBW at a height of 1.00m for H_1/H_2 ratios of 1.0 and 1.5, respectively.

DIFFERENCES DUE TO WIND SPEED

Some differences in pollutant concentrations are evident between the low (2 m/s) and high (8 m/s) wind speeds for both LBW configurations. The differences between results for the footpath LBW models at different wind speeds ranged from -4% to 12% on the leeward footpath and between from -8% to 6% on the windward footpath. The percentage differences calculated for the different models are illustrated in Figure 5.12. This demonstrates that despite changes in wind speed influencing air flow and pollutant dispersion, it may not significantly affect the potential of passive controls in perpendicular wind conditions.

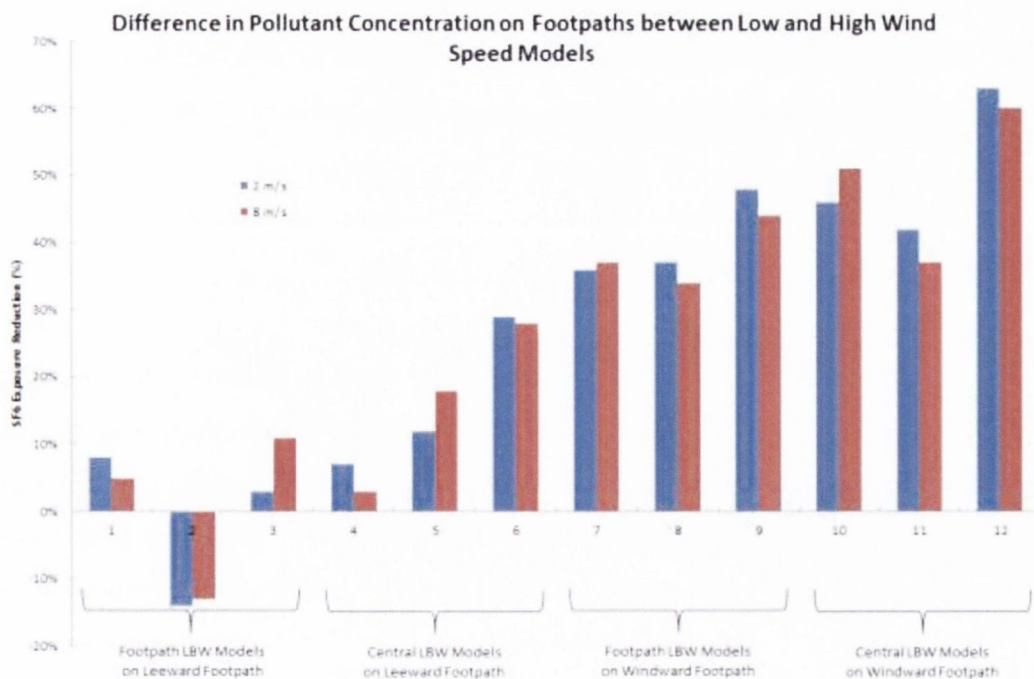


FIGURE 5.12. PLOT OF PERCENTAGE DIFFERENCES IN POLLUTANT CONCENTRATION FOR ASYMMETRIC MODELS FOR LOW AND HIGH WIND SPEED MODELS.

5.4.2 EMISSIONS SOURCE MODELS

5.4.2.1 COMPARISON OF EMISSION SOURCE TYPES

Line and surface emission sources have both been used to simulate vehicular emissions (Chang & Meroney, 2003; Baker et al., 2004; Gallagher et al., 2012). Comparing the two sets of results aims to identify any notable differences between the two methods of emissions modelling. Table 5.5 shows the results between the reference and footpath LBW models for both emission source models in low and high wind speeds at adult height of 1.76 m.

TABLE 5.5. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND FOOTPATH LBW MODELS FOR LINE AND SURFACE SOURCE EMISSIONS AT 1.76 M HEIGHT FOR DIFFERENT WIND SPEEDS.

H ₁ /H ₂ Ratio	Line Source				Surface Source			
	2 m/s		8 m/s		2 m/s		8 m/s	
	LW	WW	LW	WW	LW	WW	LW	WW
0.5	-77%	29%	28%	41%	5%	37%	8%	36%
1.0	-31%	8%	-90%	-23%	-13%	34%	-14%	37%
1.5	-115%	-41%	-39%	25%	11%	44%	3%	48%

Note: Negative percentages indicate an increase in the concentration between the reference and LBW model.

The line and surface source models displayed very large differences in concentrations between the reference and footpath LBW models at different wind speeds. The footpath LBWs caused considerable increases in concentrations on the leeward footpath for the line emissions source in the majority of the asymmetrical canyon models. In comparison, a mixture of small reductions and increases in the percentage differences of concentrations were noted using the surface emission source models.

The two sets of emission source models displayed very different patterns for an increasing H₁/H₂ emissions model on the leeward footpath. The line source model showed peak differences at a H₁/H₂ of 1.0 with reductions and increases in the percentage different of personal exposure evident with a change in the asymmetrical ratio for both low and high wind speeds, respectively. A similar peak difference was noted in the symmetrical canyon model for the surface emission models as improvements in the percentage difference of pollutant concentrations were calculated for changes in the asymmetrical ratio at both low and high wind speeds. Overall, the results from the line source models displayed lower percentage differences between

the reference and footpath LBW models on the leeward footpath for most of the asymmetrical canyon models.

The line source models also demonstrated lower percentage differences between the models on the windward footpath for most of the asymmetrical canyon models. Reductions and increases in the pollutant concentration were noted for the line source models and the results for the surface emission models demonstrated only reductions in pollutant concentrations on the windward footpath. An overall percentage increase was noted between the reference and footpath LBW models with an increase in the H_1/H_2 ratio. The two wind speed scenarios displayed very different results, as a low wind speed demonstrated a steady reduction of the percentage difference in concentrations. A deterioration in air quality conditions occurred at a H_1/H_2 of 1.0 in the high wind speed models and improvements were evident from this point for both an increase and decrease in the asymmetrical ratio. The surface emissions model displayed stable reductions on the windward footpath for both low and high wind speeds, with reductions ranging from 34% to 48%.

The results for both emission models for a child’s height of 1.00m displayed very similar differences in concentrations to the high wind model comparison. Significant differences were noted between results for both emission source type models at both adult and child height in the assessment of footpath LBWs as a passive control of air pollution in an urban canyon. Table 5.6 compares percentage difference in results between the line and surface emissions sources for the reference and central LBW models at an adult height of 1.76 m.

TABLE 5.6. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND CENTRAL LBW MODELS FOR LINE AND SURFACE SOURCE EMISSIONS AT 1.76 M HEIGHT FOR DIFFERENT WIND SPEEDS.

H_1/H_2 Ratio	Line Source				Surface Source			
	2 m/s		8 m/s		2 m/s		8 m/s	
	LW	WW	LW	WW	LW	WW	LW	WW
0.5	-120%	39%	25%	32%	3%	51%	7%	46%
1.0	-8%	20%	13%	41%	18%	37%	12%	42%
1.5	11%	44%	7%	52%	28%	60%	29%	63%

Note: Negative percentages indicate an increase in the concentration between the reference and LBW model.

The two emissions source models displayed differences in the percentage difference between the reference and central LBW models at different wind speeds. The central LBWs provided percentage reductions in concentrations on the leeward footpath for high wind conditions and increases in low wind conditions using a line emissions source model. The surface emissions model showed reductions in pollutant concentration on the leeward footpath for all asymmetrical ratios. The two emission source models displayed distinctive patterns in the calculated percentage difference in concentrations for models with an increasing H_1/H_2 ratio on the leeward footpath. The line source model showed improvements with an increasing H_1/H_2 ratio at a low (2 m/s) wind speed, yet in high wind conditions (8 m/s) the trend was reversed as a higher asymmetrical ratio reduced the effectiveness of the central LBW as a passive control. The surface emission models present a clear reduction in pollutant concentrations with an increase of the asymmetrical ratio at both low and high wind speeds. The percentage differences between the reference and central LBW models on the leeward footpath was under-predicted for the low wind speed models with mixed results for the high wind speed asymmetry models.

Reductions in the pollutant concentration were calculated for all asymmetrical ratios on the windward footpath in the line and surface source models. Both emission models displayed an overall percentage increase between the reference and footpath LBW models with an increase in the H_1/H_2 ratio. A similar pattern was found on the windward footpath with an increasing asymmetrical ratio for both emission source models. The central LBW displayed an increase and a reduction in pollutant concentrations in the symmetrical canyon model, with improvements in air quality noted on the windward footpath for the other asymmetrical canyon models. An under-prediction of the percentage differences in pollutant concentrations were found for all wind speed models using the line emission source.

DIFFERENCES DUE TO MONITORING HEIGHT

The results did not indicate a significant difference in the overall pattern of results at a monitoring height of 1.00 m. The percentage difference in concentrations maintained a similar trend to the data for adult height, with improvements in air quality evident for an increase in the H_1/H_2 ratio. The percentage differences at a height of 1.00m improved for most model scenarios on the leeward footpath, with only marginal

improvements observed on the windward footpath but for all asymmetric scenarios. Both emissions source models showed significant differences on the leeward footpath and marginal differences on the windward footpath. However, the differences generally indicated common percentage reductions in pollutant concentrations on both footpaths.

DIFFERENCES DUE TO WIND SPEED

Differences in pollutant concentrations were evident between the low (2 m/s) and high (8 m/s) wind speeds for both LBW configurations. Similar differences in concentrations were noted between the reference and LBW models (attached in Appendix A) at different wind speeds for both emission source models. The differences in concentrations between the low and high wind speeds using the surface emission source remained similar for the reference and LBW models. Average differences in the range of -9% to 10% were calculated due to differences in wind speed between the reference and footpath models. Similar differences were noted between the reference and central LBW layout, with results ranging from 14% to 9%. The concentration differences for the line emission source models at different wind speed were more substantial for the reference and LBW models. The differences between the reference and footpath models ranged from -84% to 37% with a range of -16% to 38% measured between the difference between the reference and central LBW.

From the previous section, notable differences between the results assessing the effectiveness of the LBW configurations were found using both methods of simulating vehicle emissions. The line emission source model under-predicts the percentage differences between the reference and LBW models for most asymmetric models and this section also identified that there are substantial differences due to wind speed. Therefore, the following section outlines the results of introducing static vehicles into the line emission source to add vehicular turbulence to the models.

5.4.2.2 LINE EMISSIONS SOURCE AND STATIC VEHICLES

The introduction of static vehicles into the canyon model aimed to determine whether differences between the two emissions source type models could be reduced and to

reintroduce vehicular turbulence in line source models. The static vehicles represented low levels of traffic congestion in a typical street canyon and were expected to affect the natural air flow patterns in the canyon. The dispersion of pollutants and measured concentrations on both footpaths is also expected to be affected with the introduction of static vehicles. This simplifies the need for the introduction of moving vehicles and maintains the simulation duration for the other emission source models.

The static vehicles were introduced into the reference model and both LBW models and the results at adult height of 1.76 m are presented in Table 5.7 and Table 5.8. The results displayed differences between the two model scenarios maintaining a line emissions source in both sets of models. Table 5.7 lists the results for the two sets of models as the percentage difference in concentrations on both footpaths and in low and high wind speeds at an adult height of 1.76 m.

TABLE 5.7. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN LINE EMISSIONS SOURCE REFERENCE AND FOOTPATH LBW MODELS WITH OR WITHOUT STATIC VEHICLES AT A HEIGHT OF 1.76 M.

H ₁ /H ₂ Ratio	Line Emissions				Line Emissions & Static Vehicles			
	2 m/s		8 m/s		2 m/s		8 m/s	
	LW	WW	LW	WW	LW	WW	LW	WW
0.5	-77%	29%	28%	41%	-57%	43%	16%	46%
1.0	-31%	8%	-90%	-23%	-82%	-25%	-57%	-8%
1.5	-115%	-41%	-39%	25%	-109%	-24%	-65%	16%

Note: Negative percentages indicate an increase in the concentration between the reference and LBW model.

The results displayed differences between the two sets of models. The introduction of static vehicles changed the calculated percentage reduction in pollutant concentrations on both footpaths. The static vehicles caused two distinctive patterns for the low and high wind speed between the reference and footpath LBW models.

In a low wind speed of 2 m/s, the static vehicles reduce the effectiveness of the LBWs for the symmetrical model with a H₁/H₂ of 1.0 by 51% and 33% on the leeward and windward footpath, respectively. However, the results for the asymmetrical models with H₁/H₂ ratios of 0.5 and 1.5 showed improvements in the percentage reduction on both footpaths ranging from 8% to 19%.

In comparison to the low wind speed model, the results indicated that the static vehicles model provided better air quality conditions on both footpaths for the 1.0 H_1/H_2 ratio model than in the high wind speed model. The static vehicles improved the effectiveness of the passive control by 33% and 15% on the leeward and windward footpaths, respectively. In a similar manner to the results with the low wind speed models, the results reversed for most of the asymmetrical models. A reduction in the effectiveness of the footpath LBWs of up to 27% was calculated. In addition, a small improvement of 6% was estimated on the windward footpath in the 0.5 H_1/H_2 ratio model. Table 5.8 displays the results between the reference and central LBW for the two model scenarios.

TABLE 5.8. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN LINE EMISSIONS SOURCE REFERENCE AND CENTRAL LBW MODELS WITH OR WITHOUT STATIC VEHICLES AT A HEIGHT OF 1.76 M.

H_1/H_2 Ratio	Line Emissions				Line Emissions & Static Vehicles			
	2 m/s		8 m/s		2 m/s		8 m/s	
	LW	WW	LW	WW	LW	WW	LW	WW
0.5	-120%	39%	25%	32%	-17%	52%	18%	30%
1.0	-8%	20%	13%	41%	0%	24%	16%	37%
1.5	11%	44%	7%	52%	9%	49%	-7%	45%

Note: Negative percentages indicate an increase in the concentration between the reference and LBW model.

The results displayed a less significant overall difference between the two sets of models as the introduction of static vehicles led to differences of $\pm 13\%$ for different asymmetrical ratios. An exception to this was noted in the 0.5 H_1/H_2 ratio model on the leeward footpath between the two models, with a calculated difference of 103% in a low wind speed of 2 m/s.

At this low wind speed, an increase in the H_1/H_2 ratio reduced the impact of the static vehicles on pollutant dispersion on the leeward and windward footpaths. On the leeward footpath the static vehicles models exhibited an improvement in the percentage difference of 103% in the 0.5 H_1/H_2 ratio model, yet the increase of the asymmetry to 1.5 gave a small reduction of 4%. The results measured on the windward footpath showed improvements ranging from 13% to 1% with a reduction in air quality for an increasing H_1/H_2 ratio.

The static vehicles in the model increased the average measured percentage difference on both footpaths for a high wind speed of 8 m/s. On the leeward footpath, a 3% reduction in the difference between the two models was calculated in the symmetrical canyon model, with increases between the models for both a lower and higher asymmetrical ratio. An incremental increase was noted on the windward footpath, with increases from 2% to 7% with a respective increase to the asymmetrical ratio. The findings identify distinct effects due to the introduction of static vehicles in the canyon models for both LBW models and at low and high wind speeds.

DIFFERENCES BETWEEN SURFACE & LINE EMISSIONS WITH STATIC VEHICLES

The static vehicles did lead to changes in the measured concentrations on the footpaths and thus changed the percentage differences between the reference and LBW models. From the previous section, differences of up to 14% were calculated for the surface emissions source models and up to 84% for the line source emissions model. The differences in concentrations between the wind speed models using the line emission source including static vehicles were more substantial for the reference and LBW models. The differences between the reference and LBW models ranged up to 70% for the static vehicle models.

The line emission source model with static vehicles displayed lower percentage differences between the reference and LBW models for the majority of the asymmetric models in comparison to the surface emission source models. The line source models with static vehicles displayed mixed results in comparison to the surface source models.

5.5 DISCUSSION

5.5.1 ASYMMETRICAL CANYON MODELS

The results for the asymmetrical canyon models are discussed in this section. The results identified changes in both pollutant concentrations and percentage differences of these concentrations measured on the footpaths. This section aims to identify the findings of the results section and highlight the potential of LBWs as passive controls in specific conditions.

5.5.1.1 FOOTPATH LBW MODELS

The implementation of LBWs as passive controls in street canyons can significantly increase the dispersion rate of air pollutants and potentially lead to a reduction in pollutant concentrations at street level (Buccolieri et al., 2009; McNabola et al., 2009). In this study, both reductions and increases in pollutant concentrations were found on the leeward footpath at both adult and child heights due to the addition of LBWs. The results provided similar evidence to previous investigations, which identifying the creation of different air flow patterns in different asymmetrical canyon models (Jicha et al., 2000; Crowther & Hassan, 2002). This affects pollutant dispersion in each asymmetrical street canyon model. Figure 5.13 illustrates the dispersion patterns in the footpath LBW models for a range of H_1/H_2 ratios on the leeward footpath.

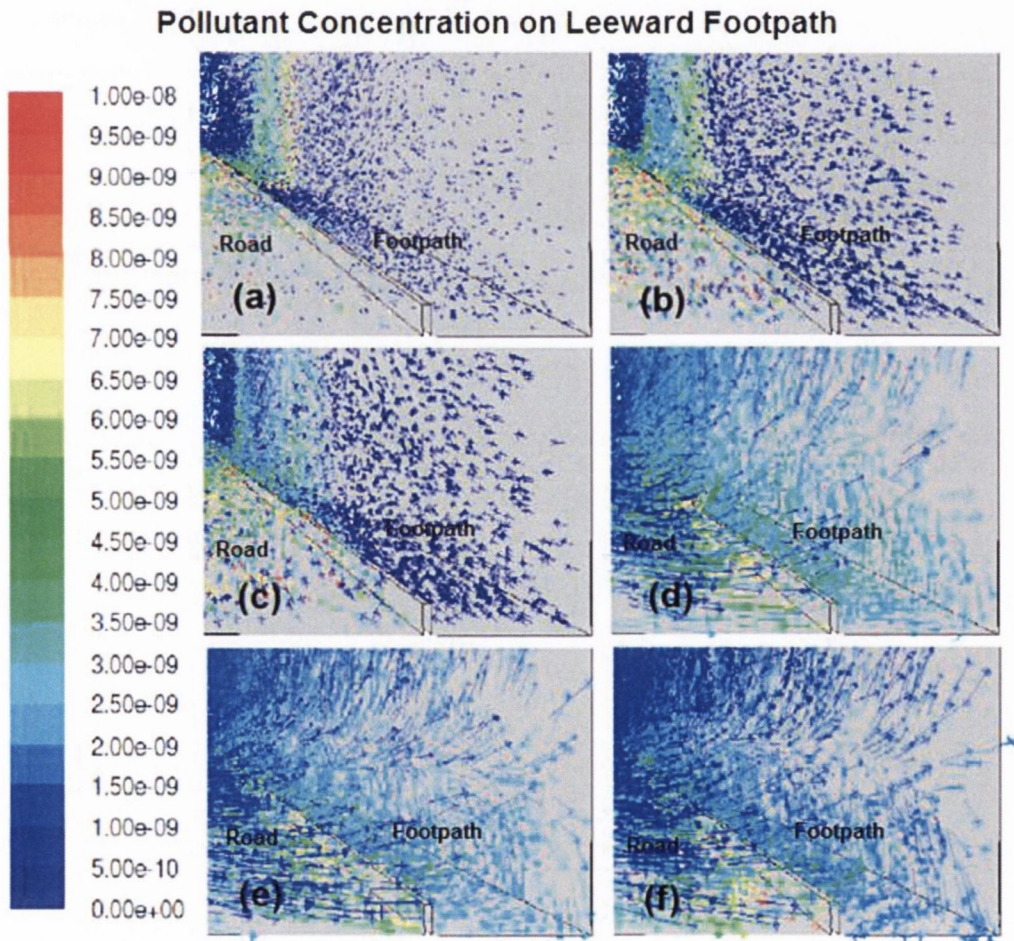


FIGURE 5.13. PLOTS OF POLLUTANT CONCENTRATIONS (kmol/m^3) AND MAGNITUDES OF VELOCITY VECTORS FOR H_1/H_2 RATIOS FROM (A) 0.5 TO (F) 1.5 IN INTERVALS OF 0.2 ON THE LEEWARD FOOTPATH OF THE LBW MODELS (GALLAGHER ET AL., 2012).

The plots display the magnitude of the resultant velocity vectors for the pollutants along the leeward footpath. The concentrations generally increased from a H_1/H_2 of 0.5 (Figure 5.13(a)) to 1.1 (Figure 5.13(d)) in the reference and footpath LBW models, with steady concentration reductions from a H_1/H_2 of 1.1 to 1.5 (Figure 5.13(f)) at adult and child heights. An increase in the pollutant concentration on the leeward footpath from a H_1/H_2 of 0.5 to 1.1 was due to an increased fraction of air entering the canyon and transporting additional pollutants to the leeward footpath. A change of the H_1/H_2 ratio from 1.1 to 1.5 increased the fraction of air (with higher magnitudes of velocity) entering the canyon and this led to the development of a more prominent primary vortex, transporting more pollutants from street to roof level.

A similar trend was identified for the percentage differences in concentration between the reference and LBW models on the leeward footpath. The minimum percentage difference occurred in the 1.1 H_1/H_2 canyon model with incremental increases occurring in both the smaller and larger asymmetric canyon models. As the H_1/H_2 ratio increased from 0.5 (Figure 5.13(a)) to 0.9 (Figure 5.13(c)), a notable change was identified between a H_1/H_2 of 0.9 and 1.1 (Figure 5.13(d)) as the lateral (+Z direction) velocity vectors became less prominent and were replaced by a counter clockwise rotational eddy (in XY plane) in the canyon. Between a H_1/H_2 ratio of 1.1 (Figure 5.13(d)) and 1.5 (Figure 5.13(f)), it was observed that the introduction of the LBW reduced the pollutant concentration on the leeward footpath and the velocity vectors became more prominent as they transported an increased fraction of pollutants out of the canyon. Figure 5.14 illustrates the dispersion patterns on the windward footpath in the LBW models for H_1/H_2 ratios from 0.5 to 1.5.

The concentrations followed the same patterns in both the reference and LBW models on the windward footpath, with air quality improved for an increasing H_1/H_2 from 0.5 (Figure 5.14(a)) to 0.9 (Figure 5.14(c)), followed by an increase in pollutant concentrations from an asymmetric ratio of 0.9 to 1.1 (Figure 5.14(d)) and a linear improvement in air quality from a H_1/H_2 ratio of 1.1 to 1.5 (Figure 5.14(f)).

A reduction in the percentage difference in concentrations occurred on the windward footpath between the 0.5 and 0.8 H_1/H_2 ratio models. This was due to the more substantial fall in gradient in the concentrations measured in the reference model than

in the LBW model as an increased fraction of pollutants are transported and subsequently trapped on the windward footpath. The development of the primary vortex in the canyon for the 0.9 H_1/H_2 ratio model reduced the fraction of pollutant concentrations on the windward footpath and this trend of improved air quality was noted for the larger asymmetrical ratio models. A small reduction in the percentage difference in concentrations between the reference and LBW model occurred between the 1.1 and 1.2 H_1/H_2 ratio models as the recirculation of pollutants in addition to pollutants transported at street level to the footpath reduced the performance of the LBW on the windward footpath. As the H_1/H_2 ratio increased further the air quality improved linearly as the vortex increased in strength, increasing dispersion and reducing the fraction of pollutants being transported against the wind to the footpath and around the windward LBW.

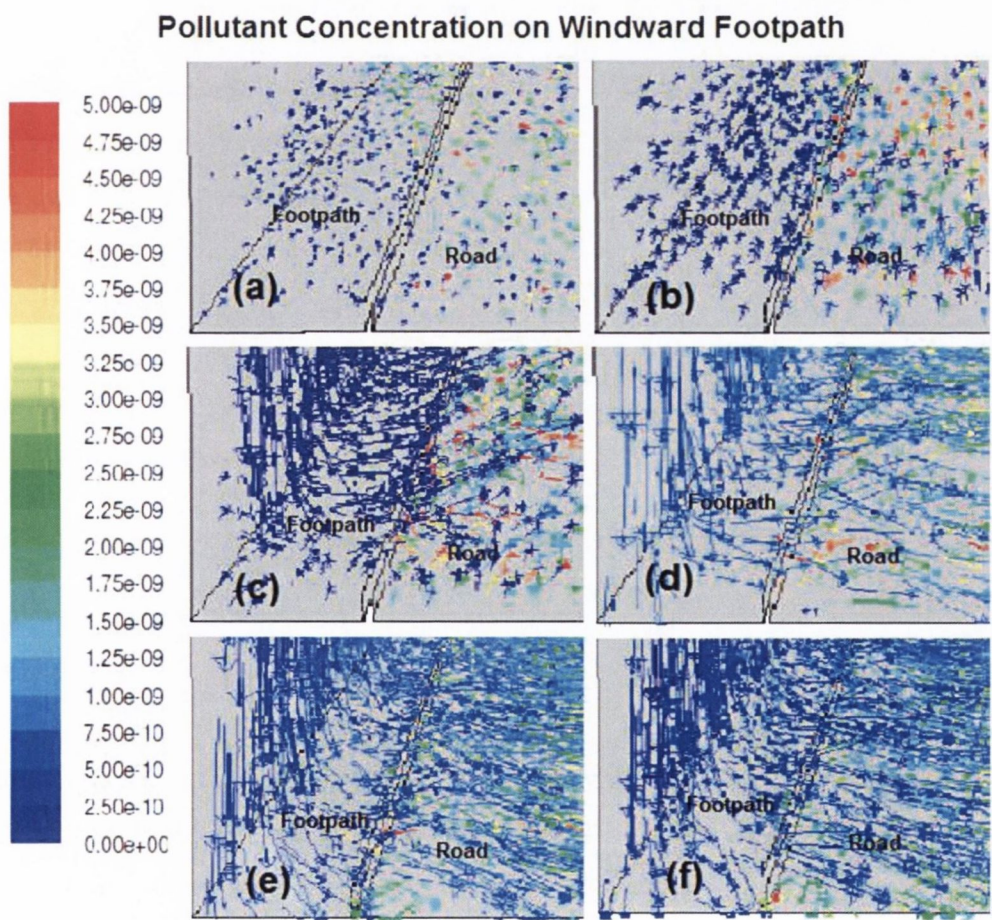


FIGURE 5.14. PLOTS OF POLLUTANT CONCENTRATIONS (kmol/m^3) AND MAGNITUDES OF VELOCITY VECTORS FOR H_1/H_2 RATIOS FROM (A) 0.5 TO (F) 1.5 IN INTERVALS OF 0.2 ON THE WINDWARD FOOTPATH OF THE LBW MODELS (GALLAGHER ET AL., 2012).

The results showed that the evaluation of pollutant concentrations from model output can be useful to gain an accurate representation of the performance of LBWs as a method of improving air quality. For example, the concentrations plotted in Figure 5.11 showed that the lowest concentrations occurred on the windward footpath in the 0.9 H_1/H_2 ratio model, yet this did not translate as the poorest performing LBW model in terms of the percentage difference between the reference and LBW model. Therefore, there is a need to specifically assess the calculated percentage difference between the model configurations as it is the best method of determining the potential of LBWs as a passive control.

5.5.1.2 FOOTPATH VS. CENTRAL LBW MODELS

The results from the comparative LBW models provided evidence that the location of the boundary wall can significantly affect the pattern of air flow in an urban street canyon. It therefore significantly affects the measured pollutant concentrations at street level. In addition, the results identified the influence of wind speed on the pollutant dispersion patterns in the street canyons. After comparing the data and the graphical plots of the asymmetrical models, it was identified that two very distinct patterns of air flow occurred in the two LBW configurations (Figure 5.15).

The central LBW model (Figure 5.15(b)) created two distinctive primary eddies as opposed to the single primary eddy created in the footpath LBWs (Figure 5.15(a)) model, and these vortices are responsible for the transport of pollutants from street level to the roof of the canyon.

The percentage reduction in pollutant concentrations differs between the two LBW configurations, but a general trend of improved air quality was evident with the implementation of the LBWs and with an increase in the H_1/H_2 ratio. Improved air quality was more evident in the central LBW models than for the counterpart footpath LBW models. This is due to the formation of two eddies (Figure 5.15(b)) in the central LBW models as the H_1/H_2 ratio increases as pollutants are transported away from both the leeward and windward footpaths before escaping the street canyon at roof level.

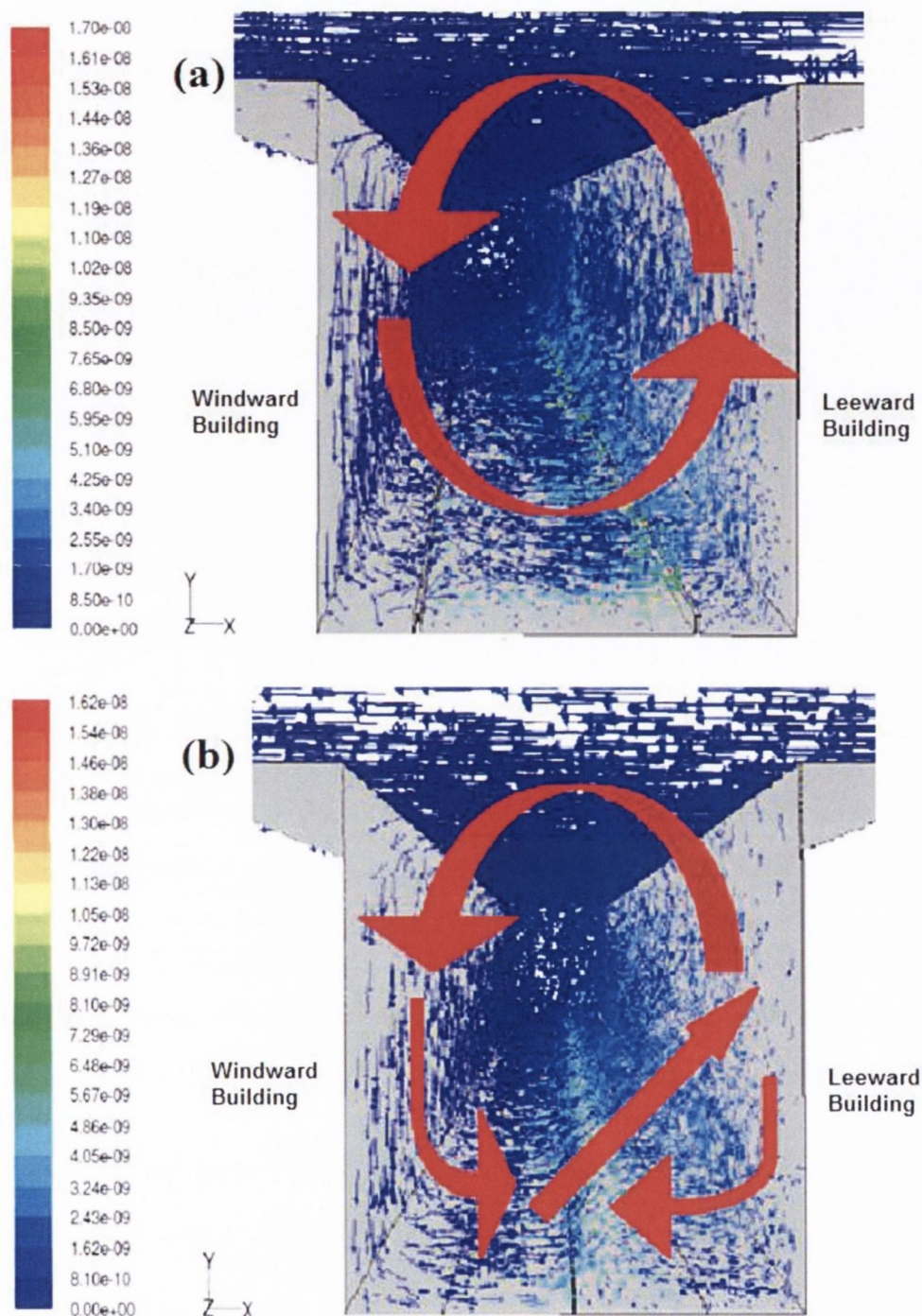


FIGURE 5.15. DISPLAYS PLOTS OF POLLUTANT DISPERSION IN THE 1.0 H_1/H_2 RATIO (A) FOOTPATH AND (B) CENTRAL LBW MODELS FOR HIGH (8 M/S) PERPENDICULAR WIND CONDITIONS (POLLUTANT CONCENTRATIONS IN KMOL/M³) (GALLAGHER ET AL., 2012).

The overall percentage reductions were noted to be more prominent for the central LBW models (up to 49%) compared to the footpath LBW models (up to 30%) on the leeward footpath. There was a large and consistent improvement in air quality on the

windward footpath for both LBW model layouts. The results showed similar evidence of enhanced reductions for the central LBW models (40% to 65%) compared to the footpath LBWs models (36% to 48%). The most substantial reductions were calculated for both LBW models for the 1.5 H_1/H_2 ratio models at both monitoring heights. This was due to an increased fraction of clean air transported into the canyon for increasing H_1/H_2 ratios, improving the magnitude and formation of the primary eddies in the canyon and transporting pollutants away from the footpaths (Figure 5.15(b)).

Examining the lower wind speed models, a similar range of percentage differences was measured between the reference models and LBW model configurations. The most notable difference were calculated between the symmetrical footpath LBW models and was due to the deflection of an increased fraction of pollutants away from the street in the low wind speed model. Reductions in the pollutant concentration become more prominent on the leeward footpath with reductions up to 53% in the 1.5 H_1/H_2 ratio models. Similar to the high wind speed models, a consistent improvement in air quality was evident in all models of the windward footpath for a wind speed of 2 m/s. Improvements in air quality on the windward footpath ranged from 34% to 46% in the footpath LBW models and 32% to 61% for the central LBW models. The results displayed no significant difference between the low and high wind speed models as no substantial percentage difference was observed between the reference and LBW models. This suggests that the pollutant dispersion patterns are similar for both set of wind condition models. Figure 5.16 illustrates the difference in the dispersion flow patterns and the pollutant concentration at street level in the 1.0 H_1/H_2 ratio central LBW models for low and high wind speeds.

Differences in concentrations were evident after comparing the results from each of the model configurations at different wind speeds. Figure 5.16 shows that the concentration is higher at street level for a low wind speed of 2 m/s than a high wind speed of 8 m/s in each of the model configurations. This highlighted the influence of wind speed on pollutant dispersion and the strength of the vortices created which transport pollutants out of the street canyon. However, the previous results identified that passive controls work in a similar manner using a surface emissions source in the asymmetric canyon models.

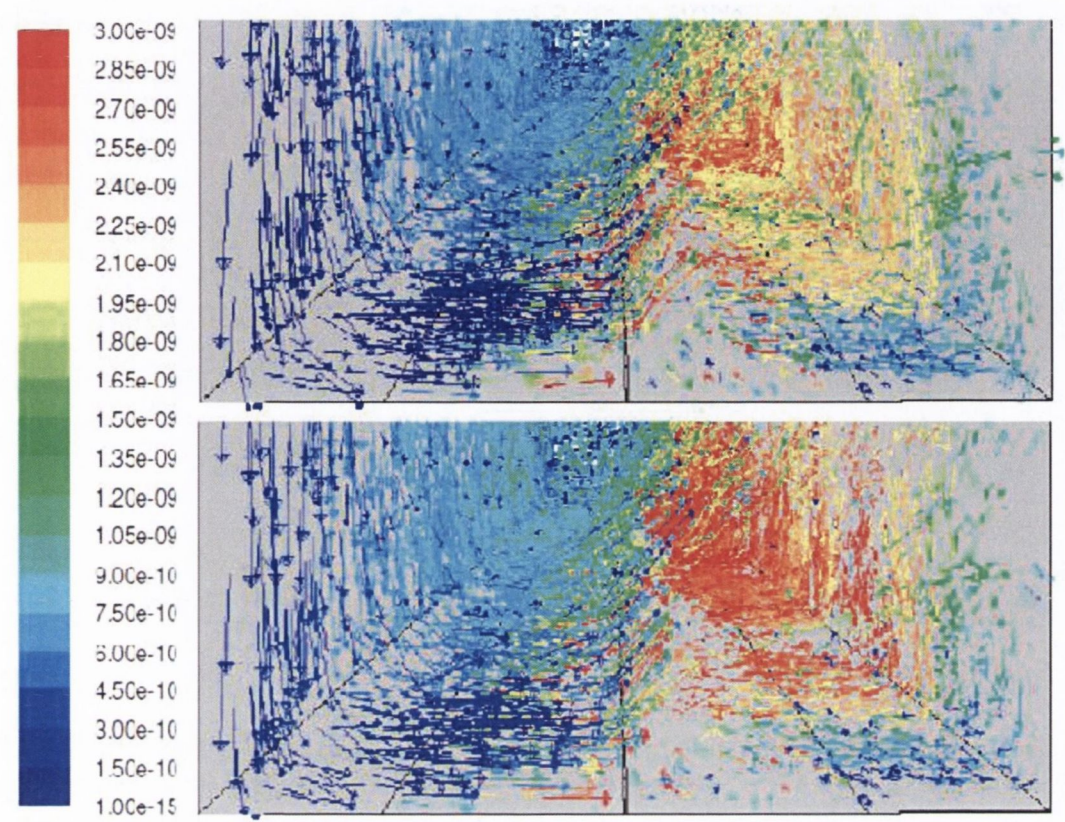


FIGURE 5.16. DISPLAYS POLLUTANT DISPERSION PLOTS OF CENTRAL LBW MODELS WITH A 1.0 H_1/H_2 RATIO FOR (A) HIGH (8 M/S) AND (B) LOW (2 M/S) WIND VELOCITIES (POLLUTANT CONCENTRATIONS IN KMOL/M^3) (GALLAGHER ET AL., 2012).

5.5.2 EMISSIONS SOURCE MODELS

5.5.2.1 COMPARISON OF EMISSION SOURCE TYPES

The results illustrated the level of confidence for passive controls based on similarities or differences in the results of the two emission source models, which both released emissions along the road surface (i.e. $Z = 0$). Table 5.9 and Table 5.10 list the percentage difference between the two types of emission source models from the results section, assessing the similarities or differences in results for the different asymmetrical street canyons. Table 5.9 summarises and compares the percentage difference between the two emission source models for low and high wind speeds.

Significant differences in results when using the two emission source models were noted on both footpaths for both wind speeds. The line emissions source demonstrated an under-prediction of the percentage difference in concentration for most asymmetrical footpath LBW models. This suggested that the line emissions source was not as suitable to determine the efficiency of LBWs as passive controls at street

level. Therefore, based on the passive control modelling investigation in Chapter 6 which develops a calibrated model using a surface source model, the line source was considered inaccurate for the purpose of assessing passive control scenarios in street canyon models. Therefore, the findings of the current study for line source emission model do not support the previous research.

TABLE 5.9. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATIONS BETWEEN REFERENCE AND FOOTPATH LBW MODELS FOR LINE AND SURFACE SOURCE EMISSION MODELS AT 1.76 M HEIGHT IN DIFFERENT WIND SPEEDS.

H_1/H_2	2 m/s		8 m/s	
Ratio	LW	WW	LW	WW
0.5	82%	8%	-20%	-5%
1.0	18%	26%	76%	60%
1.5	126%	85%	42%	23%

Note: Negative percentages indicate an increase in the difference between the emission source models.

The results in Table 5.9 present two distinct patterns with respect to the differences between the two sets of results as the asymmetrical ratio increases. The low wind speed models demonstrated a distinct pattern of results between the two models on both footpaths. The two emissions models show relatively similar patterns for the 1.0 H_1/H_2 ratio models with an 8% (18% and 26%) difference between results for both footpaths at a wind speed of 2 m/s. More significant differences were noted on the leeward footpath for the 0.5 and 1.5 H_1/H_2 ratio models. Previous investigations which have used line and surface emission source models have stated a good agreement was measured between measured and modelled results (Meroney et al., 1996; Letzel et al., 2008). These investigations have (i) focused on symmetrical investigations which do not take account of effect of asymmetry on air flow and pollutant dispersion, (ii) assessed dispersion characteristics as vertical profiles or (iii) simplified the model as a 2D problem (Meroney et al., 1996; Letzel et al., 2008; Yassin et al., 2009). The lateral dispersion effects which are not taken into account in two-dimensional models along the street floor suggests that the line emissions source model may over-simplify vehicle emissions. However, dispersion patterns at street level are very complex and the footpath zones are the most turbulent zones to measure pollutant concentrations. Therefore, it suggests that more detailed investigations are required in the future for simulating vehicular emissions at street level.

The location of the emissions sources clearly influenced the fraction of pollutants transported from the road to the leeward footpath. For the models with H_1/H_2 ratios of 0.5 and 1.5, the deterioration in air quality on the leeward footpath was due an increased fraction of pollutants transported from the source location to the footpath from the line source model. The high 1.5 asymmetric canyon model resulted in a larger difference than the 0.5 H_1/H_2 model. This was due to the increased channelling of wind which transported more pollutants to the leeward footpath. The symmetric canyon model transported the pollutants out of the canyon. The 1.5 H_1/H_2 ratio model also re-circulated a higher fraction of pollutants in the canyon.

Comparing the results in Table 5.9 at a wind speed of 2 m/s on the windward footpath, an increase in the asymmetrical ratio simultaneously caused an increase in the difference in results for both emission models. The line emissions model displayed poorer conditions on the windward footpath as more air was channelled into the canyon and the pollutants were transported to the windward footpath. At low wind speeds, the increase in wind speed transported pollutants towards the footpath, yet this wind was not strong enough to develop a substantial vortex to take pollutants from street to roof level and escape from the street canyon.

The most notable distinction between the surface and line emission source models was the consistent percentage difference with the surface emission source model in the low wind speed models. Higher concentrations were measured on the leeward footpath in the footpath LBW models using the line emission source. This was due to an increased fraction of the concentration emissions from the line source being transported to the leeward footpath compared to the other surface source models. The source concentrations and dispersion patterns of pollutants in the leeward zone of the canyon from both emission source models can be viewed in Figure 5.17.

The line emissions source model in Figure 5.17(b) clearly displays higher concentration along the canyon floor and the concentrated emissions are dispersed in a different pattern to the surface emissions source (Figure 5.17(a)). The LBW is less effective using the line source model, thus the surface emission source (which acts as a turbulence factor from moving vehicles) provides a better method of simulating emissions along the street floor for all model scenarios. The LBW acts as a more

effective passive control for the surface emissions as the wall allows for enhanced dispersion of the pollutants along the canyon floor in the region of the LBW, yet the air flow carries a higher fraction of pollutants over the wall from the line source prior to additional dispersion.

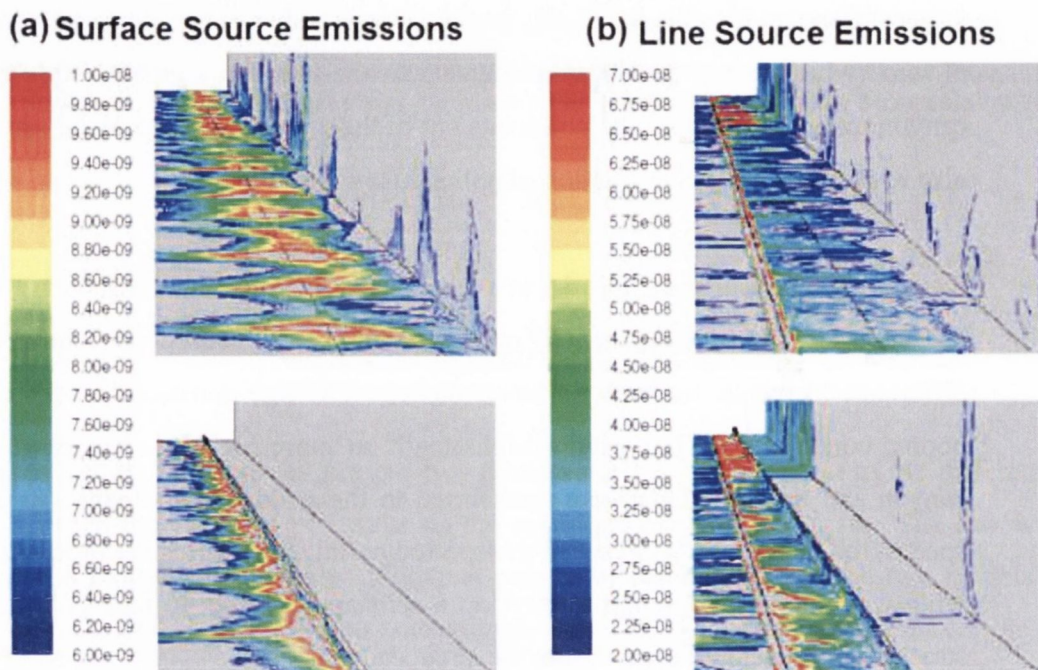


FIGURE 5.17. DISPLAYS POLLUTANT DISPERSION PLOTS OF REFERENCE (TOP) AND FOOTPATH (BOTTOM) LBWs IN THE 1.5 H_1/H_2 RATIO MODELS FOR (A) SURFACE AND (B) LINE EMISSION SOURCE MODELS IN LOW (2 M/S) WIND VELOCITIES (POLLUTANT CONCENTRATIONS IN KMOL/M^3).

The percentage difference in concentrations between the emission models displayed a similar pattern of change as the primary eddy was more evident in the high wind speed asymmetric models. The line source model showed evidence of improved conditions for the 0.5 H_1/H_2 ratio models which differed from all other comparisons of model results. The line source model for this asymmetrical ratio at a high wind speed allowed for the transport of a more significant fraction of pollutants away from the footpaths. Differences between the emission models for the other asymmetrical canyons ranged from 23% to 76%. The most significant difference was noted for the symmetrical canyon (1.0 H_1/H_2 model) as the surface source model increased initial dispersion across the whole canyon floor. The vortex was found to be more effective in transporting pollutants out of the canyon for this layout. The surface emissions model also provided better results than the line source in the 1.5 H_1/H_2 ratio models, but the difference was less prominent than the symmetrical canyon due to increased

recirculation of pollutants in the canyon for the surface emissions model. Table 5.10 displays the summarised results that compare the percentage difference between the two emissions source models upon implementing the central LBW for different winds speeds. The comparative results show an over-prediction of percentage differences between the two models for the 0.5 H_1/H_2 ratio model and under-predictions for all other asymmetric model scenarios.

TABLE 5.10. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATIONS BETWEEN REFERENCE AND CENTRAL LBW MODELS FOR LINE AND SURFACE SOURCE EMISSION MODELS AT 1.76 M HEIGHT IN DIFFERENT WIND SPEEDS.

H_1/H_2	2 m/s		8 m/s	
Ratio	LW	WW	LW	WW
0.5	123%	12%	-18%	14%
1.0	26%	17%	-1%	0%
1.5	16%	13%	22%	11%

Note: Negative percentages indicate an increase in the difference between the line emission source models.

An initial inspection of the comparative results from Table 5.10 displayed a less substantial difference between the two sets of emission source models for most asymmetrical scenarios. The central LBW evidently alters air flow and pollutant dispersion for both emission source models. It is also notable that wind speed does not play as significant a role in providing considerably different results as for the footpath LBW models. In both wind speed models, the difference between the results for both emission source models is quite similar in most cases. A substantial difference of 123% was calculated between the two source models on the leeward footpath in the 0.5 H_1/H_2 ratio model. Visually comparing the modelling results for both emission source models, the central LBW did not create the primary vortices in the low 0.5 H_1/H_2 ratio models. Emissions in the line source model are more concentrated and a larger fraction of pollutants are directed towards the leeward footpath. This is similar for the other asymmetrical ratios on the leeward footpath as pollutants are more concentrated in the centre of the lane and higher concentrations are transported to the footpath. The increase in the H_1/H_2 ratio strengthened the primary vortices as the difference between the source models became less substantial. The increasing H_1/H_2 ratio in the models caused an increased fraction of pollutants being transported to the windward footpath.

The comparative results for the central LBW models seems to display results that show the line emissions source under-predicts the percentage differences for the majority of the asymmetric models. This is evident from the positive percentage differences for the majority of scenarios between the datasets of the two models in Table 5.9. However, the differences are not as substantial for the central LBW case and therefore the results from both methods of simulating vehicle emissions can give an indication of the effects of introducing a central LBW.

For the symmetrical canyon models with a 1.0 H_1/H_2 ratio, very similar results were observed in both emission source models in high wind speeds. Overall, an increasing trend was noted on the leeward footpath as the asymmetrical ratio increased. An increased fraction of the concentrated emissions from the line source model was transported to the leeward footpath. This was due the strengthening of the vortices in the canyon as the asymmetrical ratio increased and led to the recirculation of pollutants in the vortex to the leeward region of the canyon. The percentage difference in concentrations on the windward footpath was noted for two reasons; a weak vortex in the 0.5 H_1/H_2 ratio model allowed the transportation of concentrated line emissions to the footpath and the increased 1.5 H_1/H_2 ratio model allowed for the recirculation of the concentrated line emissions towards the windward footpath.

Similar results were found after comparing the results for the data measured at a 1.00m height to the data in Table 5.9 and Table 5.10 for almost all asymmetrical canyon models. This suggests that the monitoring height on both footpaths does not affect the overall results comparing the two emission source models.

The results for both emission source models displayed very distinct behaviours in the different asymmetrical canyons. As previously stated, the use of line source emissions omits any element of vehicular turbulence unlike the surface emissions source. Therefore, this justifies the latter method as a more suitable method of emissions simulation. However, further analysis is required to determine the effects of vehicular turbulence at street level.

DIFFERENCES DUE TO WIND SPEED

Differences were observed between the two sets of results for low and high wind speeds for both LBW configurations. The footpath LBW models displayed differences of up to 115% on the leeward footpath and 66% on the windward footpath. Figure 5.18 displays a plot of the two footpath LBW models for both low and high wind speeds in the 0.5 H_1/H_2 ratio model. The plot illustrates examples of the differences in concentrations measured on both footpaths due to different wind speeds.

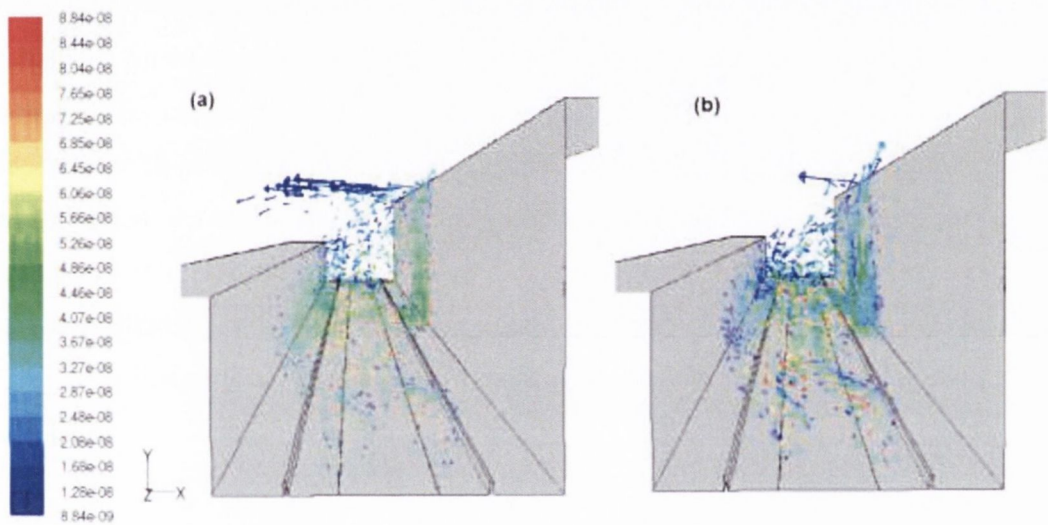


FIGURE 5.18. PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M³) AND MAGNITUDES OF VELOCITY VECTORS FOR THE 1.5 H_1/H_2 RATIO FOOTPATH LBW MODELS AT A (A) LOW AND (B) HIGH WIND SPEED FROM MAXIMUM CONCENTRATION TO 1E-01 OF MAXIMUM CONCENTRATION.

The footpath LBW models presented significant differences between the results for the low and wind speed models. An increase in wind speed led to a deterioration of up to 59% on the footpaths in the asymmetrical canyon model. The higher wind speed models displayed improved air quality on the footpaths in the asymmetrical reference models as the wind increased dispersion in the canyon. The pollutant concentrations increased on both footpaths for the footpath LBW models in high wind speed conditions. This was as a result of the wind transporting an increased fraction of pollutants to the footpaths and the LBWs trapped concentration on the footpaths.

Both reductions and increases in the asymmetrical ratio demonstrated improvements in air quality on both footpaths with the introduction of the LBWs. The greatest reduction of 115% in the pollutant concentration on the leeward footpath was

measured between the low (Figure 5.18(a)) and high (Figure 5.18(b)) wind speed models for the 0.5 H_1/H_2 ratio model. This was related to improved dispersion and transportation of additional pollutants out of the canyon. An analysis of the average steady state concentrations determined that the percentage difference between the reference and footpath LBW models showed improvements of up 87% for the H_1/H_2 asymmetric canyon models. The 0.5 H_1/H_2 reference models showed an increase in pollutant concentrations on the leeward footpath and an inverse reduction on the windward footpath with an increase in wind speed. Similar behaviour was noted for the footpath LBW models, yet the increase in wind speed decreased the difference on the leeward footpath and enhanced the difference on the windward footpath. For the 1.5 H_1/H_2 ratio model, the increase in wind speed displayed a reduction in concentration for both footpaths. This is due to a larger fraction of air channelled into the canyon strengthening the primary vortex, which extracted pollutants from the canyon floor to roof level and escape the canyon. Figure 5.19 illustrates two central LBW canyon models with H_1/H_2 ratios of 1.5 including the velocity magnitude and concentration profiles in the canyons at low and high wind speeds.

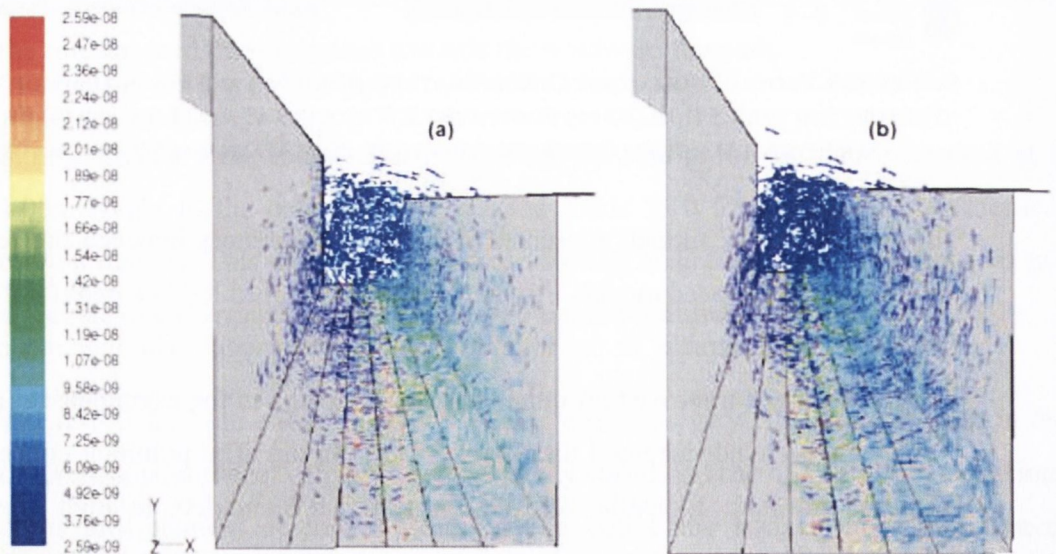


FIGURE 5.19. PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M^3) AND MAGNITUDES OF VELOCITY VECTORS FOR THE 1.5 H_1/H_2 RATIO CENTRAL LBW MODELS AT A (A) LOW AND (B) HIGH WIND SPEED FROM MAXIMUM CONCENTRATION TO $1\text{E}-01$ OF MAXIMUM CONCENTRATION.

Differences in results in the central LBW models for a low and high wind speed were calculated as up to 183%. The most significant differences were noted in the central

LBW models (0.5 H_1/H_2 ratio models) on the leeward footpath, yet only minor differences (maximum of 21%) measured on the footpaths in the other asymmetrical canyon models. The difference in concentration measured between the low and high wind speed models varied for each asymmetrical ratio.

The low 0.5 H_1/H_2 ratio model illustrated a similar pattern as the reference model, albeit to a lesser degree, as an increase in wind speed reduced air quality on the leeward footpath and improved conditions on the windward footpath. The central LBW reduced the wind speed on the canyon floor which diminished the transport of pollutants to both footpaths. Consistent reductions of 46% to 49% were measured in the central LBW canyon models with a H_1/H_2 of 1.0 as the two primary vortices effectively transported pollutants out of the canyon as the wind speed increased. The central LBW showed only a small difference (up to 19%) between the two wind speed models on the footpaths in the 1.5 H_1/H_2 ratio model. The high wind speed increased the strength of the vortices to transport pollutants out of the canyon. The differences between the 1.0 and 1.5 H_1/H_2 ratio models were considered to be due to the increased asymmetrical ratio, which enhanced the rate of pollutant recirculation into the canyon.

The scale of over/under-prediction of results for both LBW layouts is significant for the majority of asymmetrical canyon ratios. Therefore, the results would suggest that there is no direct correlation between the percentage differences of results and wind speed. In a similar manner to the surface emission models, wind speed influences the effectiveness of passive controls when using a line source model to replicate vehicular emissions. This highlights the need for the further evaluation of the line source model to allow for the simulation of vehicular turbulence in street canyon models as different results were clearly identified using both these methods. Therefore, the static vehicle model takes an initial step in this process to identify the effects of idle vehicles on air flow and pollutant dispersion at street level.

5.5.2.2 LINE EMISSION SOURCE AND STATIC VEHICLE

The introduction of static vehicles at street level in the line source emission models demonstrated variations in the percentage difference between the reference and LBW models. Therefore, introducing static vehicles alters local dispersion patterns at street

level to replicate more real-time traffic conditions. Figure 5.20 displays the pollutant dispersion and velocity vectors in the symmetrical canyon models with the line source emission model without and including static vehicles. The static vehicles distorted the previous dispersion patterns and the concentration measured on both footpaths in the reference and LBW models.

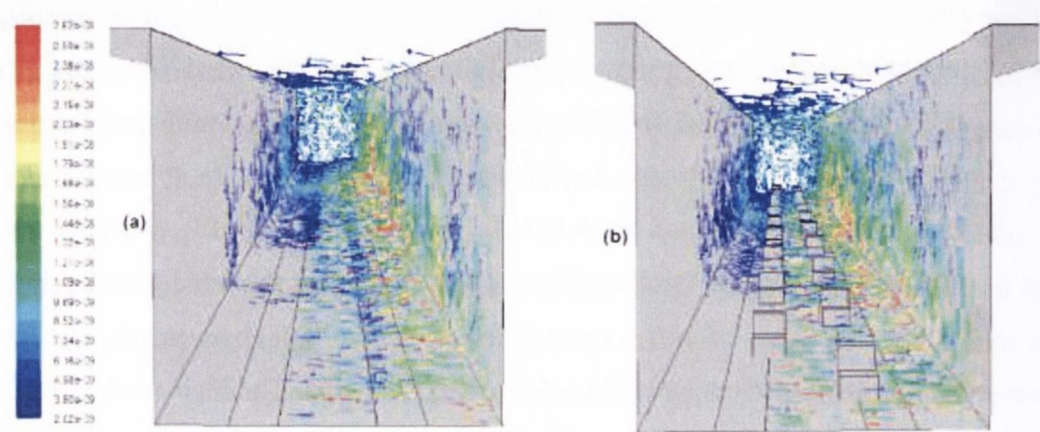


FIGURE 5.20. PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M³) AND MAGNITUDES OF VELOCITY VECTORS AT STREET LEVEL FOR THE 1.0 H₁/H₂ RATIO REFERENCE MODELS WITH (A) LINE SOURCE AND (B) LINE SOURCE & STATIC VEHICLES.

In a similar manner to the previous section, summary tables were created to allow for a clear comparison of the results. Table 5.11 and Table 5.12 presents the difference between the line emission source models before and after introducing the static vehicles. Table 5.11 compared the results between the reference and footpath LBW models for both scenarios in the different asymmetrical canyon layouts.

TABLE 5.11. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATIONS BETWEEN RIFERENCE AND FOOTPATH LBW MODELS WITH AND WITHOUT STATIC VEHICLES FOR LINE SOURCE EMISSIONS AT 1.76 M HEIGHT IN DIFFERENT WIND SPEEDS.

H ₁ /H ₂	2 m/s		8 m/s	
	LW	WW	LW	WW
0.5	20%	14%	-11%	6%
1.0	-51%	-33%	32%	15%
1.5	6%	-65%	-27%	-10%

Note: Negative percentages indicate an increase in the difference between the static vehicles emission models.

The results in Table 5.11 displayed positive and negative differences between the two sets of models. The mixed results were associated with a change in the dspersion

patterns at street level, which translated as an improvement or deterioration in air quality on the footpaths.

In the low wind speed models, the comparative results between the two line emission models illustrated distinct differences on both footpaths for an increasing asymmetrical ratio. The static vehicles improved conditions by up to 20% and reduced the pollutant concentration in the canyons with H_1/H_2 ratios of 0.5 and 1.5 on the leeward footpath. The static vehicles increased dispersion for these asymmetrical ratio models as the pollutants were transported along the canyon floor. The symmetrical canyon models (Figure 5.21) exhibited an increase of 51% on the leeward footpath due to the disruption of the primary eddy in the low wind speed models.

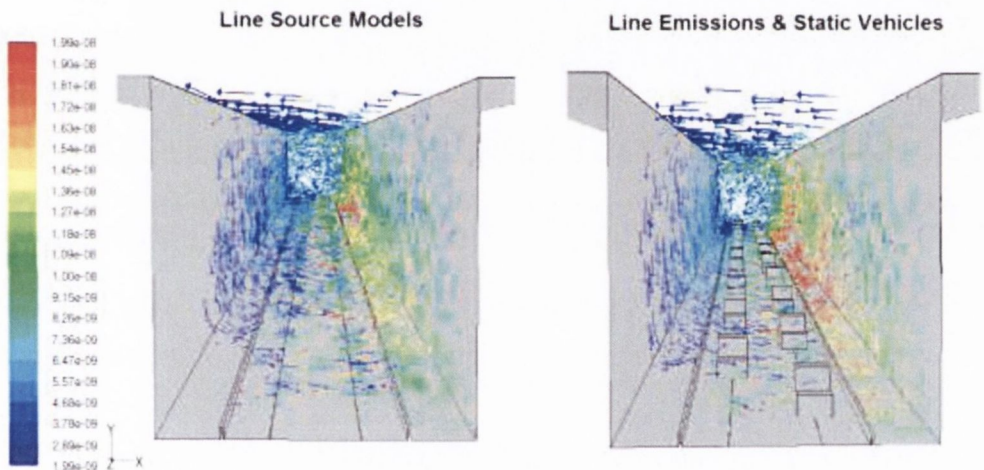


FIGURE 5.21. PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M³) AND MAGNITUDES OF VELOCITY VECTORS OF LINE SOURCE MODELS WITH FOOTPATH LBWs IN SYMMETRICAL CANYONS (H_1/H_2 OF 1.0) IN LOW WIND SPEEDS.

A similar increase was measured on the windward footpath in the symmetrical canyon models and is evident in Figure 5.21. A 14% decrease in the effectiveness of the passive control was calculated in the asymmetrical canyon model with a H_1/H_2 of 0.5. The opposite effect was noted with the higher H_1/H_2 ratio models of 1.5 as a decrease of 65% was noted on the windward footpath between the line emission models. An increased fraction of clean air was channelled into the canyon and transported towards the windward footpath. Improvements in the fraction of clean air in this region were proportional to an increase in the asymmetrical ratio of the line source models. Therefore, the overall trend on the windward footpath in the low wind speed models

showed that the introduction of the static vehicles increased dispersion in the street and a higher fraction of clean air was maintained on the windward footpath.

The static vehicles displayed a very different set of results comparing the line source models at a high wind speed as shown in Table 5.11. An inverse pattern between the models was noted on the leeward footpath compared to the low wind speed models. The high wind speed caused a deterioration of air quality on the footpath in the static vehicle models by 11% and 27% at H_1/H_2 ratios of 0.5 and 1.5, respectively. The deterioration in air quality on the leeward footpath for the 0.5 H_1/H_2 model was due to the static vehicles reducing the wind velocity and the fraction of pollutants transported out of the canyon. The asymmetrical canyon with a H_1/H_2 ratio of 1.5 showed a deterioration of pollutant concentrations on the leeward footpath as the static vehicles reduced the dispersion along the canyon floor and transported increased pollutants to the footpath. The symmetrical static vehicle model reduced the concentration by 32% on the leeward footpath as shown in Figure 5.22. This was due to increased dispersion in the centre of the canyon and the development of a stronger primary vortex above the rooftops of the static vehicles to transport the pollutants out of the canyon. The footpath LBW became more effective in the static vehicle model for the symmetrical canyon layout as it deflected pollutants upwards and out of the canyon in the primary vortex.

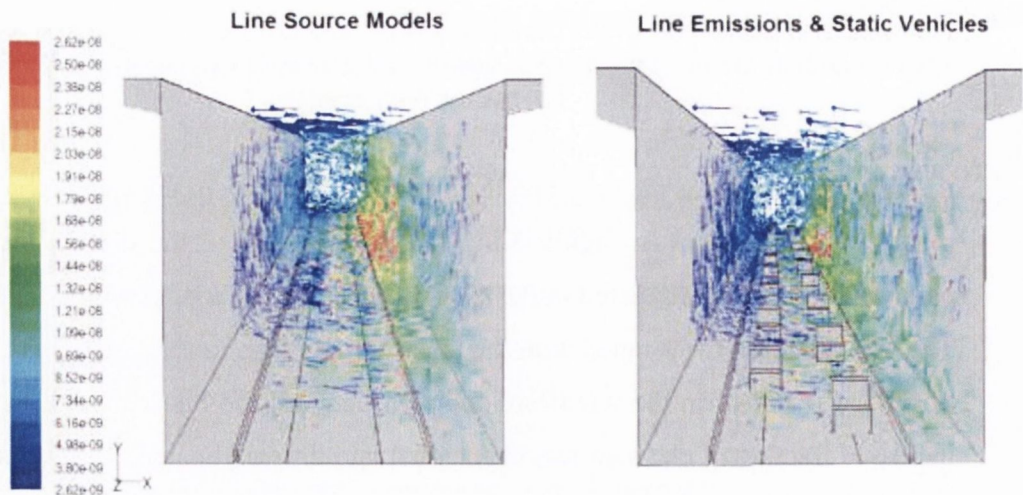


FIGURE 5.22. PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M³) AND MAGNITUDES OF VELOCITY VECTORS OF LINE SOURCE MODELS WITH FOOTPATH LBWS IN SYMMETRICAL CANYONS (H_1/H_2 OF 1.0) IN HIGH WIND SPEEDS.

The smallest differences in the result were measured on the windward footpath for the high wind speed models. This was noted to be due to the larger fraction of clean air entering the canyon from rooftop level (associated with high wind speed models) and a reduced impact of static vehicles on pollutant concentrations on the windward footpath. The static vehicle models displayed improvements in air quality on the windward footpath of 6% and 15% for the asymmetrical ratios of 0.5 and 1.0, respectively. The static vehicles increased dispersion in the street and reduced the fraction of pollutant transported towards the windward footpath. A deterioration in air quality on the windward footpath occurred in 1.5 H_1/H_2 ratio model, which was due to an increase in the recirculation of pollutants in the canyon.

The central LBW models showed a very different set of results to its counterpart LBW layout and the percentage differences between the two line source emission models is shown in Table 5.12. The results from Table 5.12 displayed minor differences ($\pm 13\%$) between the two sets of line emission models for most asymmetric model scenarios. An exception was noted between the 0.5 H_1/H_2 ratio models in the low wind speed models of 103%.

TABLE 5.12. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATIONS BETWEEN REFERENCE AND CENTRAL LBW MODELS WITH AND WITHOUT STATIC VEHICLES FOR LINE SOURCE EMISSIONS AT 1.76 M HEIGHT IN LOW AND HIGH WIND SPEEDS.

H_1/H_2 Ratio	2 m/s		8 m/s	
	LW	WW	LW	WW
0.5	103%	13%	-8%	-2%
1.0	8%	4%	3%	-4%
1.5	-4%	1%	-13%	-7%

Note: Negative percentages indicate an increase in the difference between the static vehicles emission models.

The plot of the pollutant concentrations in both these models are shown in Figure 5.23. The plots display significant differences between concentrations on the leeward footpath in the models. The central LBW and static vehicles significantly increased dispersion and improved air quality on the footpath. The introduction of static vehicles for other asymmetric canyon models did not display notable differences on the footpaths at both low and high wind speeds. Therefore, static vehicles in the street did not influence the findings of the modelling results significantly for most of the two line emissions source models with the central LBW layout.

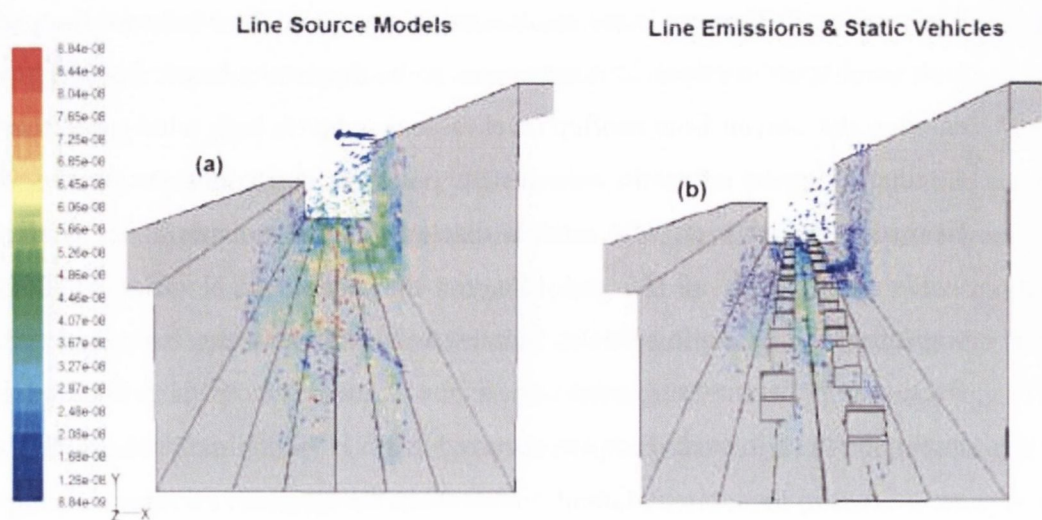


FIGURE 5.23. PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M³) AND MAGNITUDES OF VELOCITY VECTORS FOR LOW WIND SPEED MODELS WITH (A) LINE SOURCE MODEL OR (B) LINE SOURCE MODEL AND STATIC VEHICLES FOR THE 0.5 H₁/H₂ RATIO CENTRAL LBW MODELS.

DIFFERENCES BETWEEN SURFACE & LINE EMISSIONS WITH STATIC VEHICLES

The introduction of static vehicles altered the percentage difference between the two emission source models for the asymmetrical canyon models. Similar to the line emission source model, the static vehicle models also under-predicted the results from the surface emission source models. This suggests that the line emission source models are not as suitable to represent vehicle emissions compared to the surface emission source in both LBW configurations. Despite the line emission source being an established method of simulating vehicle emissions, there is considerable doubt that it can be used to effectively assess passive controls due to the significant differences in results compared to the surface emission model.

The introduction of static vehicles presented a potential solution to including vehicular turbulence in the line emissions source models. However, the results displayed a continued over-prediction of the results for the majority of the asymmetric canyon models. The line emission source with or without static vehicles does not provide a suitable alternative to simplifying vehicle emissions in CFD models.

5.6 CONCLUSIONS

The results from this study identify the effects of LBWs as passive controls in asymmetric street canyons. The findings from the different investigations carried out

as part of the asymmetry study displayed distinctive sets of results. The following conclusions summarise the findings of the results and discussion sections.

Firstly, similarities were observed across all the modelling investigations regarding air flow and pollutant dispersion patterns in the asymmetric street canyons. The low H_1/H_2 ratio models demonstrated predominant lateral dispersion as the asymmetric ratio hindered the development of a primary vortex in the canyon. The symmetric canyon model displayed evidence of the creation of the primary vortices in each model. In the high H_1/H_2 ratio models, the fraction of air channelled into the canyon increased and strengthened the vortices.

The implementation of footpath LBWs displayed increases and reductions in the percentage difference for measured concentrations along the footpaths in the surface source models. The results of the surface emission source models displayed an increase of 19% to a reduction of 30% for different H_1/H_2 asymmetrical ratios on the leeward footpath. Reductions in the pollutant concentration were calculated between 26% and 50% on the windward footpath.

A set of central LBW models were also investigated and the results were compared to the findings of the footpath LBW models. The results identified distinctive air flow patterns; one primary vortex was created in the footpath LBW models, while two distinctive primary vortices developed in the central LBW models. The results showed that the central LBW performs better for all H_1/H_2 ratio models with reductions of between 4% and 64% on the footpaths for a high wind speed of 8 m/s.

The model investigation was extended for a series of low (2 m/s) wind speed models where results for both LBW configurations identified the reduction in strength of the vortices in the low wind speed conditions. A similar trend of results was noted for the low wind speed models between the reference and LBW models.

A comparison of line and surface emission source models was carried out to determine if these methods of simulating vehicle emissions would provide similar results. The line emission source models displayed a lower percentage difference in concentrations on both footpaths for the majority of different asymmetrical layouts.

The line emissions source models provided a more concentrated output and neglected lateral dispersion in comparison to the surface source models.

The introduction of static vehicles to represent vehicular turbulence was introduced into the line emissions source models and compared to the previous results. The static vehicles influenced air flow and pollutant dispersion in the street which affected measured concentrations on the footpaths. However, the majority of models still under-predicted the percentage differences in concentrations compared to the surface emission source models. A comparison of the three sets of models identified that the introduction of static vehicles had mixed results in closing the gap between the calculated percentage differences between the emission source models.

As the subsequent Pearse Street study adopts the surface emissions source model and successfully calibrates the model using this emission modelling method, it was considered as the most suitable method of simulating vehicle emissions. The study therefore highlights the variances between results for the surface and line emissions source model with or without static vehicles, which suggests further research is required in the area of emissions source modelling.

The study highlights the potential of passive controls in asymmetric street canyons and extends the research to date carried out for the implementation of LBWs in real asymmetric canyons.

6. PASSIVE CONTROL OF AIR POLLUTION EXPOSURE IN PEARSE STREET, DUBLIN: A COMBINED MEASUREMENT AND MODELLING STUDY.

6.1 INTRODUCTION

This study focused on determining the effectiveness of different forms of passive controls to reduce personal exposure to vehicular pollutants in a real street canyon. A model was constructed to replicate a section of Pearse Street in Dublin (Figure 6.1), a busy urban street canyon with four lanes of traffic. The model was calibrated using measurements of local meteorological conditions, in-street pollutant concentrations and traffic count data. The potential reduction in personal exposure to a specific air pollutant primarily source from vehicle emissions, Nitrogen Oxide (NO), and was calculated between the current street layout without passive controls and a subsequent scenario including different forms of passive controls in the canyon. NO is a reactive pollutant in a street canyon environment. Therefore, the measurement study for model calibration was carried out in winter conditions to minimise reactive conditions in the street canyon (Huang et al., 2008; Parra et al., 2010). Lower temperatures in the street can increase thermal stability and reduce dispersion (Oke, 1988; Jicha et al., 2000; Santese et al., 2007; Huang et al., 2008). The study assessed the influence of LBWs placed along the edge of both footpaths and parked cars in Pearse Street.



FIGURE 6.1. PEARSE STREET IN DUBLIN CITY CENTRE (GOOGLE EARTH, 2012).

Manual traffic counts were taken to establish an understanding of the different traffic flows in each of the traffic lanes during peak and off-peak times of the day. In addition, the traffic counts identified the fleet composition travelling in each lane. Air

quality monitoring was carried out in the street, as NO_x concentrations were measured at the. The data were used in the calibration of the model after a detailed analysis of the relationship of the pollutant concentration to traffic emissions and meteorological conditions. A thorough analysis of real-time data was carried out initially to identify trends and correlations between varying traffic volumes and compositions, pollutant concentrations and meteorological conditions. The study assessed the effect of wind speed and direction on pollutant dispersion and the development of vortices within the canyon, which previous researchers have found to significantly influence air flow patterns (DePaul & Sheih, 1986; Hoydysh & Dabberdt, 1988; Crowther & Hassan, 2002).

The objective of this study was to construct a calibrated model of Pearse Street. Generic modelling studies are useful for the comparison of multiple scenarios for the implementations of passive controls, yet it is important to establish their potential within a real world scenario, such as the Pearse Street model. From the earlier chapters, an understanding has been established of the potential benefits of passive controls in the form of on-street parked cars and how LBWs may affect pollutant dispersion in asymmetrical canyons. The Pearse Street model deals with the effects of air flow and pollutant dispersion in an asymmetric street canyon and for different forms of passive controls. Therefore, this study provides a calibrated model of a real world street and further evidence for the potential of passive controls, in addition to the previous two generic modelling studies.

6.2 DATA COLLECTION

6.2.1 PEARSE STREET MODEL

This study developed a calibrated three-dimensional model of Pearse Street, an urban street canyon in Dublin, and takes account of real-time traffic data, meteorological conditions and pollutant concentrations in the street canyon. The model was constructed from shapefiles of the buildings on Pearse Street sourced from Dublin City Council (DCC) using geographical information system (GIS) data. The shapefiles were imported from ArcGIS to Gambit via AutoCAD in ACIS format (Figure 6.2). The model was then constructed in Gambit and geometric complexities were included of the street canyon, such as the rail bridge over Pearse Street.

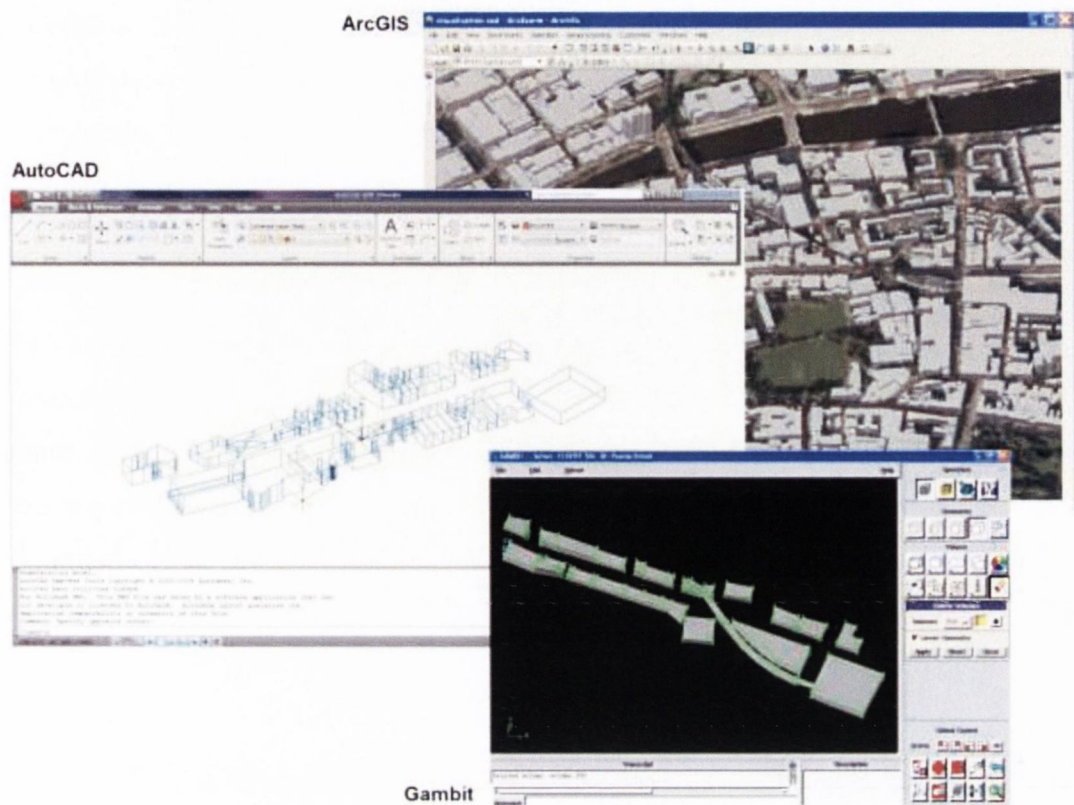


FIGURE 6.2. TRANSFER OF SHAPEFILES FROM ARCGIS 9 TO GAMBIT v2.3 VIA AUTOCAD 2009.

The initial reference model was constructed based on the current Pearse Street layout. After this model was calibrated, the subsequent passive control models containing combinations of LBWs and parked cars were developed. The reference model was calibrated using the combined data collected for traffic volumes, NO_x concentrations in the street canyon and local wind parameters. The conditions were replicated in the passive control models and results were compared to the reference model. The models were solved using the LES turbulence model for different traffic flows, wind conditions and passive control configurations. The LES model has been previously used to successfully simulate air flow and pollutant dispersion in a real street canyon environment (Liu et al., 2011).

The initial step of the calibration process for the Pearse Street model was the optimisation of the mesh scheme. Several different mesh schemes were investigated during the mesh discretization process to (i) encourage convergence within the model and (ii) reduce simulation running time, and this is discussed in detail in section 6.4.1 of this chapter.

The models were run using Fluent 6.3.26, adopting a similar set-up approach to the previous investigations. Any differences in the procedure of the modelling process are discussed in this section. Due to the simulation of pollutant emissions from the individual lanes, multiple scenarios for each canyon model had to be run. The method of analysis and calibration is discussed in section 6.4 of this chapter.

Air pollutant concentrations were assessed in the footpath regions of the CFD models (as defined in the methodology chapter), with improvements or deteriorations in air quality calculated between the reference and passive control models. Similarly, the concentrations were compared to yield the percentage difference between each model. Convergence was considered to be sufficient based on the same criteria outlined in Chapter 3.

The airflow in the modelling study was simulated from the flow of air over the top of the buildings, through the side street intersections and from either end of the street section by the velocity inlets. Velocity inlet properties were attached to different faces of the model depending on the direction of the prevailing wind. The relationship between the inlet velocity parameters and the measured wind speed and direction measured around Pearse Street was determined as part of the calibration process. The dispersion of NO_x in the turbulent air stream from traffic was simulated by releasing concentrations of the gas at street level. The emissions were represented as a surface source across each of the traffic lanes and were released after the initial development of vortices in the canyon.

The model was constructed as defined in Chapter 3. Figure 6.3 displays the reference model layout and displays the boundary surfaces in the model and their associated characteristics. As numerous models were simulated for different wind directions, the north, south, east and west faces alternated between velocity inlets and pressure outlets, depending on the wind direction simulated. The values for wind velocity and direction were specified as components in the X and Y directions, to simulate real-time wind conditions. The top of the model was considered as a pressure outlet in each of the models. The associated dimensions of the Pearse Street model are discussed later, in the calibration section of this chapter.

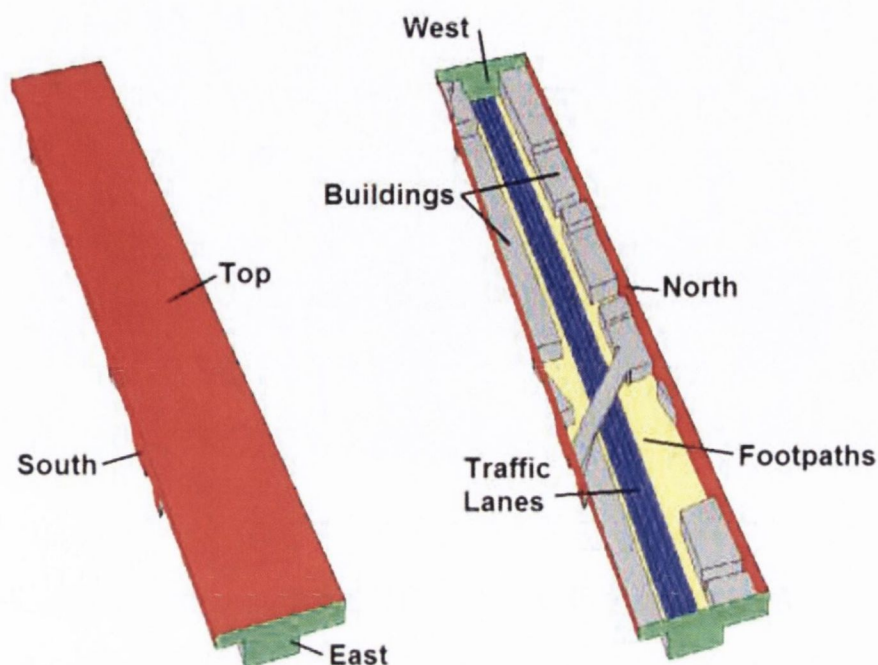


FIGURE 6.3. DISPLAY OF (A) CLOSED VOLUME AND (B) OPEN VOLUME FLUENT MODELS.

Figure 6.3(b) displays the layout of the Pearse Street model and clear differences in the associated asymmetry layouts are noted between the west and east sides of the canyon i.e. the east side of the street has more open spaces than the west side of the street. Therefore, the pollutant concentration in the models was recorded as path lines along the centre of both footpaths. These monitoring lines started in the centre of the canyon, either on the east or west side of the street canyon model.

6.2.2 NO_x MEASUREMENT

NO_x concentrations were measured from the 2nd to the 19th of December 2011 at a selected location (Figure 6.4) in Pearse Street to allow for the calibration of the model. Total NO_x and NO were measured using a calibrated Chemiluminescent NO/NO₂/NO_x Analyser (Model 200EU) and NO₂ was calculated as the difference between the two concentrations under ISO 7996: 1985 standards (CEC, 1999). The NO_x analyser was located on the north side of the street from the 3rd floor of a building (Figure 6.4). This was considered a suitable location to monitor the pollutant concentration in the air flow of the canyon, as the zone was of a less turbulent nature than at street level. Therefore, it was considered that the data collected would be more stable and could allow the calibration of the model to be more accurate.



FIGURE 6.4. WIND (BLUE) AND NO_x (RED) MONITOR LOCATIONS ON PEARSE STREET (GOOGLE EARTH, 2012).

Typically, vehicular pollutants such as benzene (C₆H₆) and carbon monoxide (CO) are considered as conventional tracer pollutants for vehicle emissions (Loh et al., 2009; Taseiko et al., 2009) due to their inert characteristics. However, NO was used in this investigation as it is a suitable tracer for vehicle emissions (Huang et al., 2008) in conditions which suppressed photochemical reactions of the pollutant. It is considered as a highly reactive gas as oxidation of NO leads to the formation of secondary pollutants, namely nitrogen dioxide (NO₂) and ozone (O₃) by means of photochemical reactions between the pollutant and sunlight. Measurements of NO_x concentration are generally an overestimation of pollutant emissions during the summer months (Jensen et al., 2009). Therefore, the measurement of NO_x in winter conditions with low levels of solar radiation and temperatures can allow an accurate representative measurement of NO_x sourced from vehicle emissions (Gualiteri & Tartaglia, 1997; Huang et al., 2008). This removed the complexity of modelling pollutant reactions in this study.

6.2.2.1 NO_x ANALYSER DATA COLLECTION & CALIBRATION

The monitor acted on the principle of Chemiluminescence, simply meaning that light is emitted due to a chemical reaction, in this case when NO is exposed to O₃ and creates NO₂ and O₂. The linear relationship of light to stabilised NO₂ (stabilised between 600 and 3000 nm) allowed for the measurement of the pollutant. The non-light emitting NO₂ reacts using molybdenum heated to 31°C and is transformed to NO and then is measured by the analyser alongside NO_x and NO₂. The 200EU Model analyser was calibrated prior to the monitoring period using a zero air scrubber and a

gas cylinder with a known concentration. Prior to gas calibration, the 5 μm filter (which has a 2-3 week lifespan) was changed. The analyser was calibrated in a span i.e. a two-phase process: (i) calibrated to zero and (ii) calibrated to a known NO concentration, allowing for the gas concentrations to stabilise for several minutes before deciding if calibration was required. Calibration was deemed necessary if a difference greater than ± 0.2 ppb was noted between the known and measured concentrations. The NO_x data were measured as average concentrations over 15 minute and 1 hour intervals.

6.2.3 WIND DATA

Local wind speed and direction was measured using a Model 05103L wind anemometer and CR200 series data logger at an elevation of 19.3 m above street level, located on the roof of a building on Pearse street, as shown previously in Figure 6.4. Measurements of wind speed and direction over the street recorded at the instrument location (Figure 6.5), as the location was chosen as it was one of the highest points along the street canyon.



FIGURE 6.5. WIND ANEMOMETER (BLUE) ON PEARSE STREET ROOFTOP (GOOGLE EARTH, 2012).

The anemometer was set-up above the urban canopy layer (UCL) i.e. above the mean building height in the area (Oke, 1988). The data collected at the selected location was therefore considered to be in the inertial sub-layer (ISL), which suggests a reduced influence on wind data incurred by roughness from building rooftops (Oke, 2006). This was to endeavour to capture accurate wind data over the street canyon which conforms to guidelines in the report by the World Meteorological Organization (WMO) WMO/TD-No. 1250 (Oke, 2006). Wind measurements were collected at 5 minute intervals for the duration of the pollutant monitoring period. This data was then averaged to 15 minute intervals to correspond with the NO_x measurements and traffic data for calibration purposes.

Wind data was additionally sourced from Met Éireann weather stations (Met Éireann, 2012) and from several Wunderground stations (Alexander et al., 2011) to assess the quality of data collected from the Pearse Street station. Figure 6.6 displays the locations of each of the potential sources where weather data could be sourced.



FIGURE 6.6. LOCATIONS OF WEATHER STATIONS ACROSS DUBLIN.

Met Éireann has two stations as indicated in Figure 6.6 in the Dublin city region: Dublin Airport and Phoenix Park, of which only the Dublin Airport site measured wind speed and direction (Met Éireann, 2012). Seven Wunderground sites (Figure 6.6) were also chosen to enhance the existing data set from the two sites (Pearse Street and Dublin Airport). Only four of the seven sites were found to be actively measuring

meteorological conditions during the monitoring period in December 2011. The four sites which had active data collection taking place during the monitoring period were Blanchardstown, North Strand road, Templeogue and Tallaght. These sites were all situated in the UCL, nevertheless, the data from these sites allowed for a comparison to the Pearse Street and Dublin Airport data.

The use of multiple stations for the comparison of wind data allowed for the observation of any air flow patterns to be identified around Dublin during the monitoring period. The importance of understanding local wind conditions and measuring local wind parameters is crucial to calibrate the Pearse street model, as highlighted by several previous investigations (De Paul & Sheih, 1986; Hoydysh & Dabberdt, 1988; Karim & Matsui, 1998; Crowther & Hassan, 2002; So et al., 2005; Hu et al., 2009).

The Met Éireann and Wunderground data also included additional weather measurements for rainfall, atmospheric pressure and stability class, temperature, humidity and solar radiation. This information would add huge complexities to the calibration of the Pearse Street model, therefore it was omitted from this investigation as geometric (Santiago & Martin, 2005; Xie et al., 2005), traffic (Qin & Kot, 1993; Tsai & Chen, 2004) and wind (Hoydysh & Dabberdt, 1988; Ghenu et al., 2008; Parra et al., 2010) parameters took precedence over these additional factors.

6.2.4 TRAFFIC COUNTS

Traffic data were acquired from two sources: (i) manual data collection of traffic volumes on Pearse Street for individual lane traffic counts and (ii) Dublin City Council's (DCC) intelligent transport system which is known as Sydney Coordinated Adaptive Traffic System (SCATS) and which continuously monitors traffic flows in Dublin (NRA, 2010). SCATS adapts traffic light 'green time' based on traffic movements using data collected from road surface sensors (inductive loop detectors) at street intersections throughout the city. Using both methods of traffic data collection improved the input data available of fleet composition and distribution for model calibration. The data aimed to improve the estimation process for the average

emissions rate (ER) for each lane based on identifying the different fractions of vehicle categories, similar to a previous investigation by Huang et al. (2008).

The vehicles were categorised as (i) light vehicles i.e. cars and motorcycles, (ii) medium and large vehicles, (iii) buses and (iv) cyclists. The manual traffic data were collected at random peak and off-peak times during the pollutant monitoring period to record data in different weather conditions. A summary of the data collected from the manual traffic counts and the corresponding weather data (Met Éireann, 2011) is displayed in Table 6.1.

TABLE 6.1. TRAFFIC SURVEY DATA FOR PEARSE STREET DUBLIN (DECEMBER, 2011).

Run No.	Survey Information	Peak Traffic Times		Off-Peak Traffic Times	
		Morning	Evening	Morning	Evening
		08:00 – 09:00	17:00 – 18:00	11:00 – 12:00	19:00 – 20:00
A	Date	Tues 6/12/11	Tues 6/12/11	Mon 5/12/11	Tues 6/12/11
	Total Traffic	1898	2467	1516	1862
	Weather	Overcast	Recent Shower	Sunny, No Clouds	Recent Shower
	W. Direction	E	SW	E	SW
	W. Speed	25 km/h	24 km/h	26 km/h	24 km/h
	Temperature	4 °C	6 °C	2 °C	4 °C
B	Date	Wed 7/12/11	Wed 7/12/11	Tues 6/12/11	Mon 12/12/11
	Total Traffic	1942	2728	1695	1661
	Weather	Sun	Fair	Sun & Cloud	Raining
	W. Direction	W	W	SW	SW
	W. Speed	33 km/h	33 km/h	24 km/h	20 km/h
	Temperature	3 °C	5 °C	4 °C	9 °C
C	Date	Thur 8/12/11	Tues 13/12/11	Wed 7/12/11	Tues 13/12/11
	Total Traffic	2012	2636	1720	2115
	Weather	Light Rain	Fair	Sun	Fair
	W. Direction	SW	SW	W	SW
	W. Speed	41 km/h	39 km/h	33 km/h	39 km/h
	Temperature	9 °C	2 °C	5 °C	9 °C
D	Date	Thur 8/12/11			
	Total Traffic	1895			
	Weather	Recent Rain			
	W. Direction	SW			
	W. Speed	41 km/h			
	Temperature	8 °C			

A total of fourteen individual traffic counts took place during the monitoring period. The traffic dataset was collected by carrying out simultaneous manual counts for each of the four traffic lanes, distinguishing the fleet composition and the fractions of the total traffic that are in each of the lanes. A significant variance for each of the weather parameters can be observed from throughout the monitoring period. This underlines the complexity of the data collected with respect to the development of a calibrated model for Pearse Street.

6.3 DATA ANALYSIS

A detailed analysis of the data collected for each of the parameters was carried out individually prior to the calibration of the Pearse Street model. This was to individually assess the data sets and to investigate unusual events, which were not considered to fit within the standard cyclic patterns of hourly, daily or weekly routine. The correlation of traffic emissions to measured pollutant concentrations was initially considered to be relatively straightforward prior to the analysis carried out in this section. However, as Figure 6.7 displays, the correlation between these two parameters in parallel and perpendicular wind conditions can be more complex than expected.

The poor correlation noted between the traffic volumes and pollutant concentrations is due to a number of factors. The pathways between the pollutant source and receptor is very much dependent on the fleet composition, the distribution of vehicles between the lanes and the vehicle type and speed which influences mechanical turbulence in the street. In addition, the wind speed in the canyon also affects the amount of pollutant dispersion and the fraction of pollutants released from the canyon, but it also affects the rate of influence of the traffic related parameters.

Therefore, during the calibration process, a number of different parameters that vary over time will need to be considered and taken into account. The introduction of a turbulent canyon environment with continuously changing wind direction and speed reduces the strength (displayed as R^2 values) of the assumed direct relationship between vehicular emissions and measured NO_x concentrations. This section will therefore primarily examine the measured pollutant concentrations and traffic data,

and subsequently assess the effect of these parameters and endeavour to calibrate the mode and correlate emissions with measured concentrations. Comparing the different sources of data also allows for the development of a better understanding of each of the data sets prior to the calibration process of the Pearse Street model.

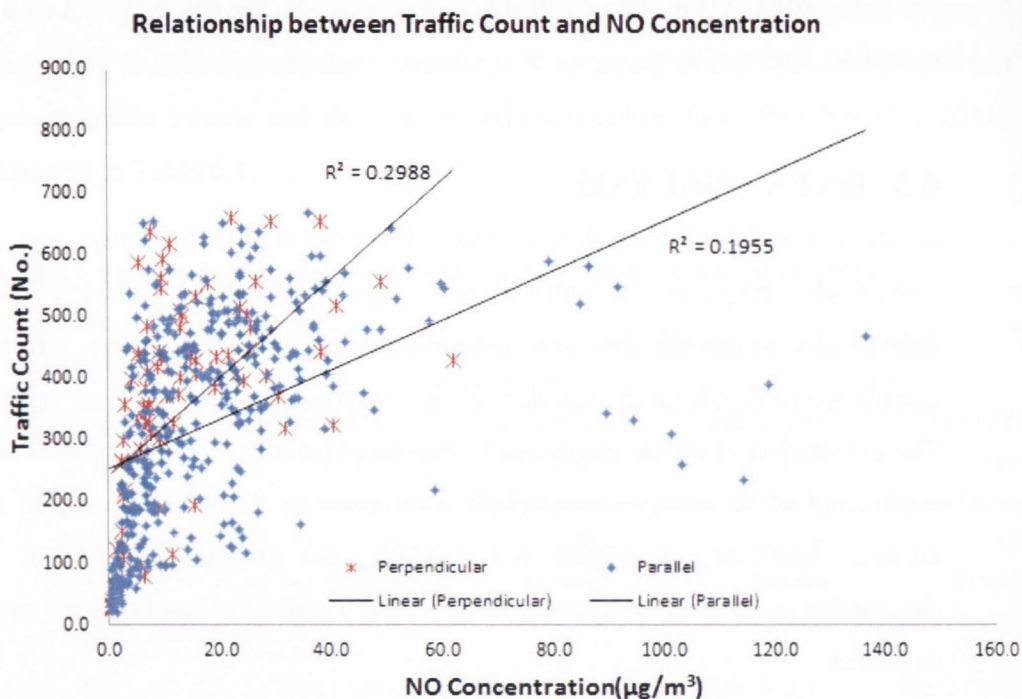


FIGURE 6.7. PLOT OF NO CONCENTRATION AGAINST TRAFFIC DATA ON PEARSE STREET (GALLAGHER ET AL., 2013).

6.3.1 NO_x CONCENTRATION

The data collected for the collective NO_x pollutants were initially examined as a whole for the full monitoring duration from the 2nd to the 19th of December 2011. The monitoring duration set the initial extremities of the duration for potential calibration of the Pearse Street model. Figure 6.8 displays the pollutant concentrations measured during the monitoring period from the location marked in Figure 6.4 at a height of 7.8 m above street level. The monitoring location was set up in accordance with Annex III of the CAFÉ directive (2008/50/EC) which defines the controlling parameters for pollutant monitoring (EP & CEU, 2008). As previously stated, the monitoring tubing was extended outwards by approximately 300 mm from the face of the building to measure pollutant concentrations in the direct air flow of the canyon. Due to restrictions of the apparatus and to minimise any attention drawn to the

instrumentation, the distance the tubing could extend from the building face could not exceed 300 mm.

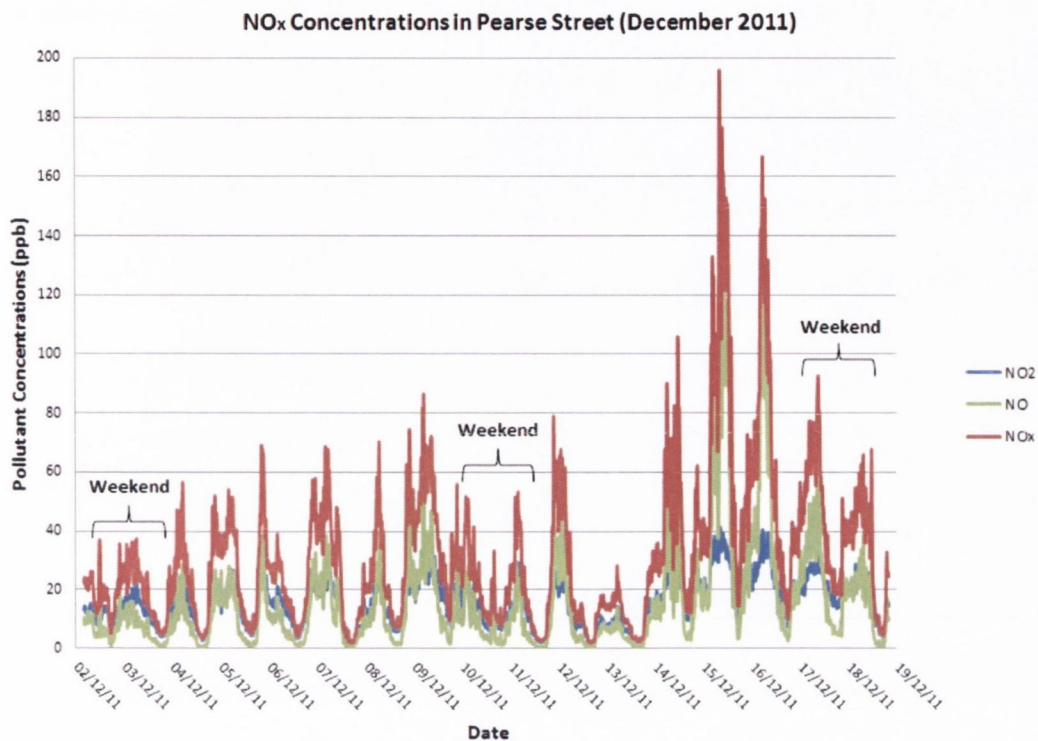


FIGURE 6.8. PLOT OF NO₂, NO & NO_x CONCENTRATION ON PEARSE STREET.

The plot of NO_x concentrations in Figure 6.8 displays a cyclic pattern with daily peaks occurring during the morning through to evening and lows occurring at night time. As the pollutant concentrations were measured over both weekdays and weekends during the monitoring period, it can be observed that weekday peaks exceed weekend peaks (as indicated in Figure 6.8). In addition, the steady increase in pollutant concentrations during the day was considered to be due to an increase in traffic rather than a build-up of pollutants, as the retention time in the street was considered to be relatively short. This was due to the expected reduction in vehicles numbers on Saturdays and Sundays. It should be noted that the monitoring period was during December and the high concentrations increased towards the end of the monitoring period (both weekdays and weekend). This is assumed to be due to additional traffic in the city centre due to Christmas shoppers and will be discussed in more detail in the subsequent sections of this chapter, when a comparison of the measured NO_x data to traffic data and local weather conditions is carried out.

In addition to the examination of the cumulative measured NO_x concentrations during the monitoring period, a refined study was carried out solely for NO . This was due to the function of this pollutant for the calibration of the Pearse Street model. A diurnal plot of the data is presented in Figure 6.9, which shows the average daily, weekday and weekend concentrations during the monitoring period.

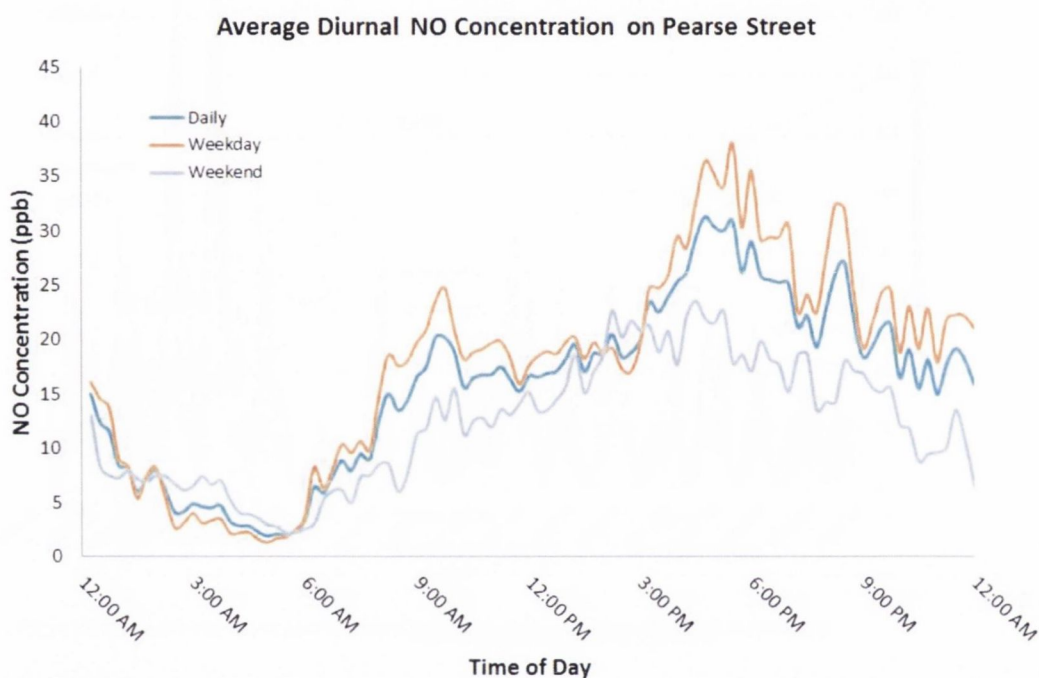


FIGURE 6.9. PLOT OF DAILY NO CONCENTRATIONS IN PEARSE STREET THROUGHOUT THE MONITORING PERIOD OF THE PEARSE STREET STUDY.

An analysis of Figure 6.9 identifies the common trend for the daily NO concentrations in Pearse Street. A gradual reduction of NO is observed from midnight (00:00 am) to the early hours of the morning (5:00 - 6:00 am). This is followed by a sharp increase during the morning period (6:00 - 10:00 am), with a gradual levelling out of NO concentrations in the later morning through to mid-afternoon (10:00 am - 3:00 pm). A steady increase can be viewed (3:00 - 5:00 pm) until peak evening traffic (5:00 - 7:00 pm) followed by an ultimate steady reduction in the NO concentration towards midnight (7:00 pm - 12:00 am).

The diurnal cycle observed for NO on Pearse Street differs from previous pollutant investigations (Carslaw & Beevers, 2005; Ghenu et al., 2008; Morawska et al., 2008; Zhou & Levy, 2008; Han et al., 2009) as the morning peak is not as significant as the

evening peak. Barry (2010) stated that differences in concentrations shown in a diurnal cycle plot can be associated with a combination of invariable emission patterns (Morawska et al., 2008), urban morphology and meteorological conditions (Schnelle & Brown, 2001). In this case, Pearse Street contains of four lanes of one-directional traffic. Typical traffic volumes use the same route (a two-directional street) in the morning and evening to travel to and from a place of work, residence or other activity. If the NO concentrations were considered to be associated with Pearse Street traffic volumes (this will be discussed in more detail at a later stage), then the majority of road vehicles use Pearse Street solely during the evening. The retention time for NO in the canyon was considered quite low, and therefore was not an influential factor in the correlation process for the calibration of the model.

The additional plots in Figure 6.9 for NO show the clear difference between the average weekday and weekend concentrations. This is considered to be due to an increase in traffic volumes during weekdays compared to weekend or Sunday traffic, which was also noted in investigations by Ghenu et al. (2008), Broderick et al. (2006) and Wehner et al. (2002).

The NO data collected during the monitoring period and which corresponds to the times of the manual traffic counts are summarised in Table 6.2. Table 6.2 shows the average NO concentrations measured for the total monitoring duration and the average concentrations for Week 1 and Week 2. From the previous observation of Figure 6.8, it was noted that a significant peak in NO concentration occurred in Week 2 (15th and 16th of December). Upon analysing the figures, it is apparent that the large increases in NO lie outside the standard range of concentrations on these dates. This results in the maximum values in Table 6.2 for the total monitoring duration to exceed the upper confidence interval set at the 95th percentile threshold (i.e. average concentration plus twice the calculated standard deviation).

The results of the study were also compared to assess any exceedences of CAFÉ directive (2008/50/EC) thresholds during the monitoring period (EP & CEU, 2008). The NO₂ hourly upper threshold value was 140 µg/m³ and no exceedences of this value was noted during the two-week monitoring period, with the maximum measured hourly NO₂ concentration being 37 µg/m³.

TABLE 6.2. SUMMARY OF NO MONITORING DATA ON PEARSE STREET (µG/M³).

Duration	(µg/m ³)	Peak Traffic Times		Off-Peak Traffic Times	
		Morning	Evening	Morning	Evening
		08:00 – 09:00	17:00 – 18:00	11:00 – 12:00	19:00 – 20:00
Total	Min.	1.3	6.7	6.0	3.8
	Avg.	14.9	30.3	16.5	22.2
	Max.	38.9 ^a	111.4 ^a	37.0 ^a	76.2 ^a
Week 1	Min.	1.3	8.7	6.4	6.1
	Avg.	16.5	22.0	13.9	15.4
	Max.	38.9	37.0	24.2	35.5
Week 2	Min.	1.8	6.8	6.5	3.8
	Avg.	14.0	38.2	17.3	26.0
	Max.	18.3	111.4 ^b	37.0	76.2 ^b

^a Denotes concentrations which lie outside the 95th percentile (average ± two standard deviations) of the respective data sets.
^b Evening concentrations during week 2 which are significantly higher from equivalent week 1 concentrations.

The analysis and the breakdown of the data as two separate weeks underlined the notable differences between the upper ranges of concentrations measured during the two weeks. This was partially due to the smaller data set for each individual week which increased the calculated standard deviation for each week. However, a substantial difference can be noted in Table 6.2 between the maximum average concentrations between the data for both weeks. As weekday and weekend traffic behaviour were relatively different and this is reflected in Figure 6.9, the weekday data was more suitable for calibration, rather than a mixed average over seven days.

6.3.2 TRAFFIC DATA

This section examines the relatively small data set collected manually by carrying out traffic counts of Pearse Street and compares it to the SCATS data over the entire monitoring period. A strong correlation between the manual and automated traffic count systems would provide a basis to use the larger SCATS data set in assessing the relationship between traffic volumes and NO_x concentrations (Vardoulakis et al., 2003). The traffic counts taken during the sampling period from the two traffic data sources for each lane are presented in Table 6.3, with Table 6.4 showing the percentage relationship between the two data sets for each individual lane (L1 to L4) and grouped lanes.

TABLE 6.3. COMPARISON OF MANUAL AND SCATS TRAFFIC DATA FOR PEARSE STREET.

	Manual Data				SCATS Data*			
	L1 ^a	L2	L3	L4	L1 ^a	L2	L3	L4
Min.	29	177	141	0	1	127	151	8
Avg.	75	215	199	56	38	200	204	66
Max	102	270	247	143	442	248	248	175

* The Shaw Street traffic was equally divided evenly over the four lanes (L1 to L4) to simplify this comparison.
^a Bus Lane.

Table 6.3 lists the average and limits for traffic counts over 15 minute intervals on Pearse Street for each lane. From initial observations of the data, a close relationship between the average manual and traffic counts are evident. In particular, the traffic numbers in the two central lanes accounts for almost 80% of the total traffic in Pearse Street and predominantly consisted of light duty vehicles. The strongest correlation of the two data sets for the central two lanes of traffic is further enhanced by the information shown in Table 6.4.

TABLE 6.4. CORRELATION COEFFICIENTS BETWEEN MANUAL AND SCATS DATA.

	Individual Lanes				Combined Lanes	
	L1 ^a	L2	L3	L4	L2-L4	L2-L3
Min.	0	0.63	0.67	0.31	0.75	0.73
Avg.	3.57	0.89	1.04	1.76	1.04	1.01
Max	12.44	1.16	1.35	18.00	1.35	1.29

^a Bus Lane.

The data exhibits considerable variances between the two traffic data sources, with the most significant differences observed in L1 and L4. The number of axles measured by automated system SCATS is calculated based on the number of axles passing a sensor location and this can lead to errors, as the numbers of axles are transformed to vehicle counts in the street (Fehon & Peters, 2010). Therefore, an error of 10% was deemed acceptable between the manual and automated systems. The most significant average difference of the correlation coefficient was calculated for L1 (3.57), and upon some correspondence with Dublin City Council (DCC) it was identified that this was due to an issue with the SCATS censor for L1 (Carrig, 2012). The most significant difference for the Lane 4 data was primarily due to the low traffic numbers in the lane during off-peak traffic times, which led to a large difference in the calculated coefficients between the two data sets.

Despite a poor correlation between the traffic counts in the outer lanes, a strong relationship was observed for the combined results of L2 and L3 with average differences of 0.89 and 1.04, respectively. The combination of three lanes of traffic (L2-L4) improved the average correlation coefficient to 1.04, but combining the two central lanes (L2 and L3) improved the correlation to 1.01. This would suggest that that there is very little difference between traffic numbers measured by both the manual and SCATS systems for three of the four lanes.

Despite the strong correlation between the data sets for three of the four lanes of traffic, there was some concern for the use of SCATS data to predict a relationship between NO_x concentrations and traffic emissions. During the model calibration process, the manual traffic information was used as much as possible as it provided more accurate information for both the traffic lane distribution and the vehicle composition. In scenarios where the SCATS data was used (to ensure the data sets were large enough to identify trends), the traffic data for the bus lane i.e. L1, was estimated only when corresponding manual data had been collected i.e. during the four 1-hour periods during the weekdays. This was considered essential for the accurate allocation of specific ERs rates along each of the traffic lanes in Pearse Street.

6.3.2.1 FLEET COMPOSITION IN IRELAND

The composition of the traffic fleet in Dublin has changed significantly in recent years (CSO, 2012a). This section summarises the fraction and type of different vehicles in the Irish fleet from the 2012 *Road Freight Transport Survey* and *Transport Omnibus* reports compiled by the Central Statistics Office (CSO, 2012a; b). They provide details of the average vehicle age and engine type of the fleet and the variability of the data sets in estimating the average fleet emission rates. The following details in Table 6.5 were noted with regards to the makeup of the Irish fleet.

The data in Table 6.5 demonstrate the variability in the Irish fleet composition for both private and goods vehicles over the past number, both nationally and in individual counties (e.g. between 30% and 37% of all vehicles were registered in Dublin between 2000 and 2010). This presents a challenge in estimating the likely

emissions associated with vehicles in Pearse Street. Changes have occurred in the composition of engine types and emission bands for newly registered private vehicles, with a shift from a majority of petrol vehicles (77%) in 2005 to a majority of diesel vehicles (67%) in 2010.

TABLE 6.5. STATISTICAL DATA FOR IRISH VEHICLE FLEET (CSO, 2012A; B).

CSO Report	Information
Road Freight Transport Survey	• 81,178 new registered goods vehicles n 2011
	• Continued downward trend of registered vehicles since 2007
	• Lowest tonne- and vehicle- kilometers since before ‘01
	• 65% of vehicles in 2-5 tonne category, but only 4% activity
	• 12% of vehicles in > 12 tonne category and 54% of activity
	• 36% of fleet over 10 years old and responsible for 26% activity
Transport Omnibus	• 1.87m private vehicles on Irish roads in 2010 (0.33m goods)
	• 0.49m private vehicles on Dublin roads in 2010 (0.06m goods)
	• Petrol/Diesel vehicles – 77/23% in 2005 to 33/67% in 2010
	• 129,000 private vehicles registered in 2010 (89k new, 40k imported)
	• 80% of new private vehicles in A & B CO ₂ emission bands in 2010
	• Vehicles registered in Dublin - 30.1% (2010) to 36.8% (2001)

6.3.2.2 CORRELATION OF NO/NO_x CONCENTRATIONS TO FLEET COMPOSITION

An evaluation of the composition of the traffic fleet was also carried out in Pearse Street. This composition of the vehicle fleet was based on those outlined from section 6.2.4 of this chapter and is presented in Table 6.6 and Figure 6.10. Examining the results from Table 6.6 shows some trends with regards to changes in the vehicle composition on Pearse Street during peak and off-peak times.

The highest fraction of light vehicles occurred during off-peak periods in the day. Large vehicles were primarily using Pearse Street during the morning (both at off-peak and peak times), with approximately 3-4 times the number of large vehicles on the road in the morning period. The fraction of buses remained relatively constant (average of 2.0%) as a fraction of the total traffic, but a small increase was observed in the morning period, at the peak morning traffic time (2.4%) in particular. The percentage of cyclists varied throughout the day (from 2.6% to 7.9%) with the most significant fraction of cyclist numbers (7.9%) accounted for during the evening peak traffic time. This coincided with peak traffic volumes and directly identified the time which cyclists are exposed to the highest pollutant concentrations from vehicles.

TABLE 6.6. PERCENTAGES OF FLEET COMPOSITION DURING PEAK AND OFF-PEAK TIMES.

Vehicle Category	Average	Peak Traffic Times		Off-Peak Traffic Times	
		Morning	Evening	Morning	Evening
		08:00 – 09:00	17:00 – 18:00	11:00 – 12:00	19:00 – 20:00
Light	91.3%	90.3%	89.8%	93.3%	91.8%
Med/Large	1.2%	1.7%	0.6%	1.9%	0.5%
Bus	2.0%	2.4%	1.7%	2.1%	1.9%
Cyclist	5.5%	5.6%	7.9%	2.6%	5.9%

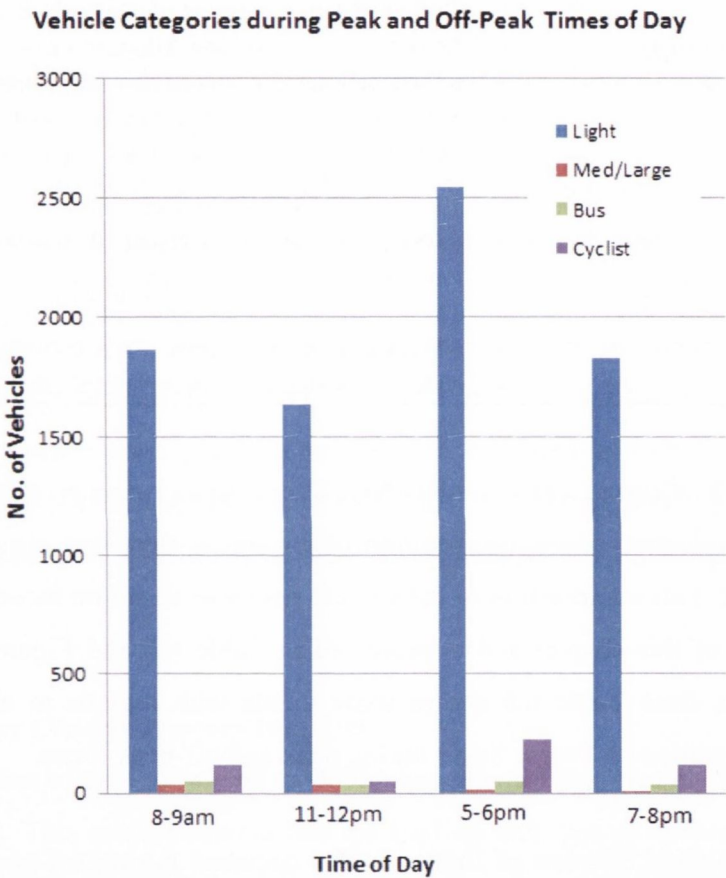


FIGURE 6.10. VARIATIONS IN THE FLEET COMPOSITION DURING PEAK AND OFF-PEAK TIMES.

It can be clearly observed that the vast majority of vehicles (> 91%) in Pearse Street fall into the category of light vehicles and motorcycles. Cyclists (5.5%) are considered the second highest category of vehicles in Pearse Street during all peak and off-peak times. Buses (2.0%) are the third largest vehicle group and the remaining medium and large vehicles (1.2%) making up the smallest fraction of the total traffic on Pearse Street.

As each vehicle category is responsible for different emission rates, the number of vehicles in each category was multiplied by a coefficient for the respective vehicle type. A number of sources were reviewed for NO_x emissions factors (EFs) as differences in these EFs were observed between the literature sources. These document sources included the National Atmospheric Emission Inventory database (NAEI, 2009), Bureau of Environment of Tokyo (Huang et al., 2008), Department of Environment, Food and Rural Affairs (Defra, 2001b), Dzung & Thang (2008), Wang et al. (2008) and (Ho & Clappier, 2011).

Several previous investigations have estimated the emissions intensity of NO_x from vehicles as g/km (Dzung & Thang, 2008; Wang et al., 2008; NAEI, 2009; Ho & Clappier, 2011; Leinert et al., 2011; Zhang et al., 2011a). The emission factors for this study were taken as 0.3 g NO_x /km for light vehicles and 8.0 g NO_x /km for buses (NAEI, 2009). As the fraction of medium and large vehicles accounted for only 1.2% of the fleet composition, a similar emissions factor of 8.0 g NO_x /km was used for this vehicle category. A plot of the total NO_x emissions for each vehicle category is shown in Figure 6.11(a).

As this study models the dispersion of NO, additional literature was reviewed to determine the ratio of NO to total NO_x . Studies identified the concentration of NO_2 and NO_x and therefore NO was calculated as the difference between NO_x and NO_2 (Carslaw, 2005; Carslaw & Beevers, 2005; Department for Environment Food and Rural Affairs, 2007). To summarise the findings by Carslaw (2005), NO_x concentrations have reduced in the past number of years, yet the NO_2 concentrations have remained constant. Therefore the $\text{NO}_2:\text{NO}_x$ ratio has recently seen an increase due to the increase of some types of filters fitted to diesel buses (Carslaw, 2005). This means that a small adjustment was required to the total NO_x emission factors for estimating NO.

Data specific to the emission rates for the Irish fleet was unavailable, therefore the figures derived by Carslaw (2005) was used for this study. The availability of this data could allow for small adjustments of the model, but would not considerably affect the assessment of the passive controls in the street canyon. Despite the European Emission Standards being more up-to-date, they were not considered accurate for

estimating NO_x emissions from vehicles as Fu et al. (2013) demonstrated that significant variability existed for ERs between different Euro classes. The percentage of NO_2 to NO_x for light vehicles is approximately 4% and a more significant 20% on average for buses and medium/large vehicles (Kelly et al., 2011). Therefore, an ER of 0.3 g NO/km for light vehicles and 6.4 g NO/km for buses or medium/large vehicles was projected after calculating the NO fraction of total NO_x . Figure 6.11(b) illustrates these NO emissions.

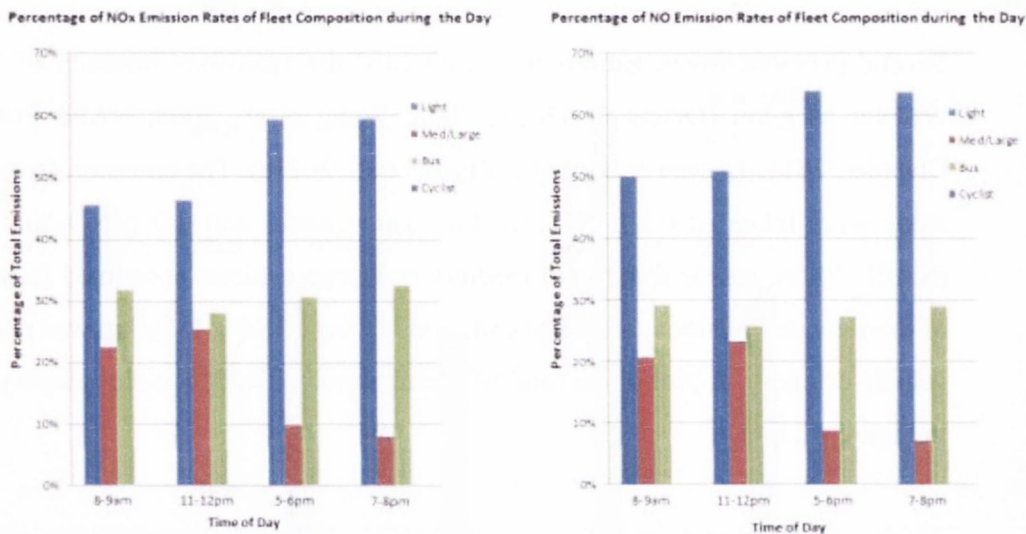


FIGURE 6.11. PLOTS OF (A) NO_x AND (B) NO EMISSIONS ASSOCIATED WITH FLEET COMPOSITION.

The plot of the percentage emissions in Pearse Street which is created by the different vehicle categories in Figure 6.11 is very different compared to the previous plot of the fleet composition in Figure 6.10. This highlights the importance of accurately assessing the fleet composition as the assumption of an average emission factor for each vehicle generates a substantial error of the Pearse Street model calibration process. As cyclists have no associated ER, this category is not depicted in Figure 6.11. The fraction of light vehicles equated to an average of 53% and 57% of the total NO_x and NO traffic emissions, respectively. However, a distinct difference of approximately 13% was observed between the average emissions for both NO_x and NO during the morning (46% and 59%) and evening (50% and 63%) periods. This was due to increases of traffic volumes in Pearse Street in the evening period, of which it is primarily light class vehicles. In a similar manner to Figure 6.10, a clear difference in NO_x and NO emissions sourced from medium and large vehicles was

observed between the morning (24% and 22%) and evening (9% and 8%) periods due to the majority of the vehicles delivering goods in the morning. A similar pattern was visible from the emissions sourced from buses with only a small difference of approximately 2% observed for NO_x (28 to 32%) and NO (26 to 30%) during the day.

Based on the analysis of the traffic data, the calculation of NO emissions from vehicles has a significant amount of variability based on the vehicle type, size, average speed and fuel type. Zhang et al. (2011a) stated that measured concentration in a street canyon can be dependent on driving behaviour, vehicle dispersion and traffic flow and that these factors can lead to almost double the pollutant concentration in relatively similar dispersion conditions. The calibration of this model required significant analysis to establish that the input parameters met real world conditions.

The estimated ER for the vehicle categories in g-NO/km allows for the calculation of a set ratio between a car and bus or medium/large vehicle emissions. This ratio is useful to reverse calculate the ER of the vehicle emissions in the Pearse Street model from the monitored NO concentration in $\mu\text{g}/\text{m}^3$. This will be discussed in further detail in Section 6.4.3.1.

6.3.3 WIND DATA

An initial analysis of the data from the wind anemometer on Pearse Street was carried out to identify patterns or trends with respect to wind direction and speed. This was considered important to understand the local wind conditions in Pearse Street and to assess if local data is necessary for the calibration process or whether external data can be used for the calibration process. Therefore, the Pearse Street data were compared to several other stations identified from the previous illustration of Figure 6.6 in Section 6.2.3. A plot of the Pearse Street wind parameters can be observed in Figure 6.12 for the monitoring period in December 2011.

It can be easily identified from Figure 6.12 that there is a common range for local wind speed and direction. The predominant wind parameters measured in Pearse Street shown a range in wind speed of 2 to 3 m/s and WNW wind direction range of between 290° and 310°.

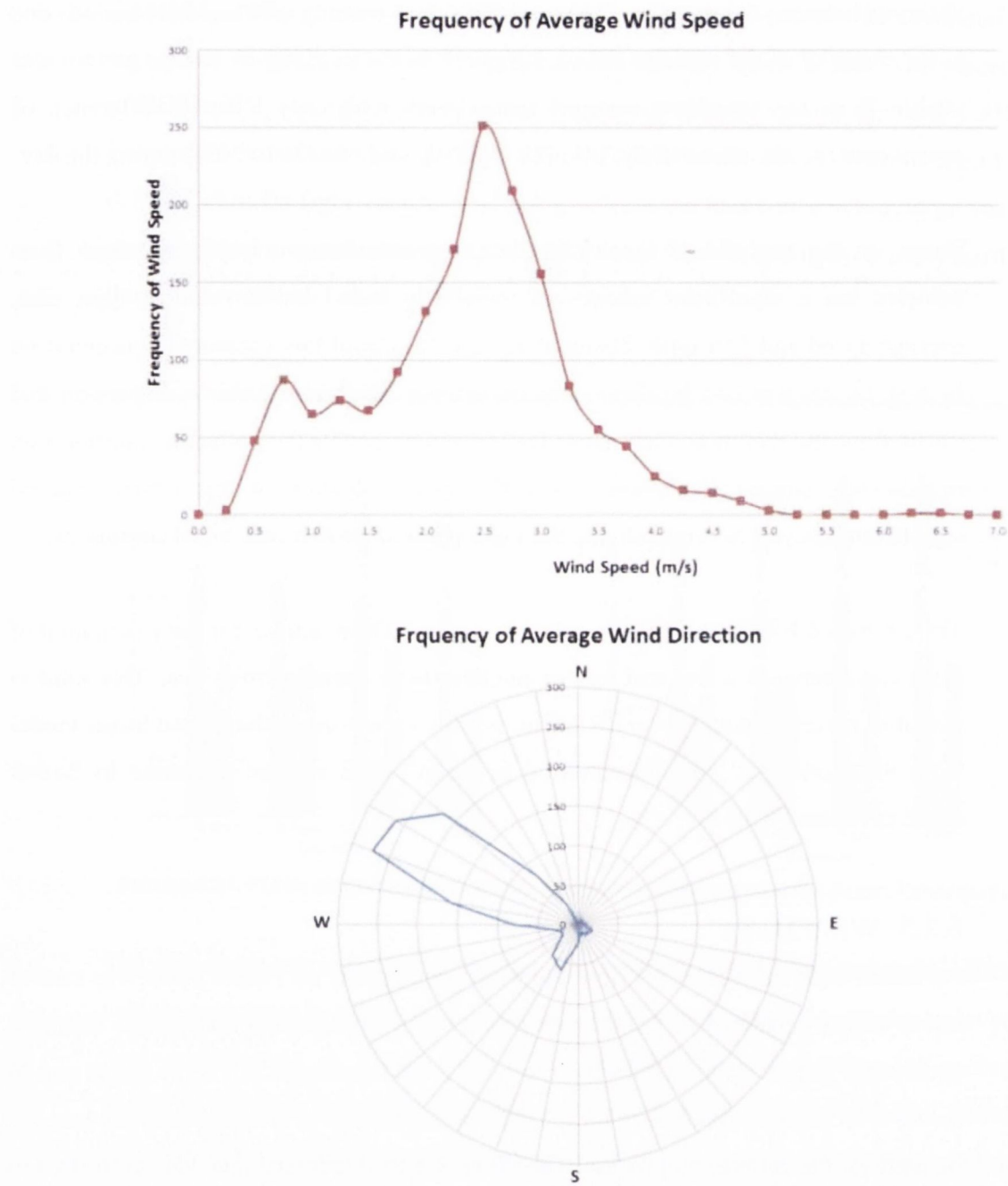


FIGURE 6.12. FREQUENCY PLOT OF AVERAGE WIND SPEED AND DIRECTION IN PEARSE STREET (GALLAGHER ET AL., 2013).

The predominant wind direction displayed in the wind rose in Figure 6.12 averaged at around 300° and the orientation of Pearse Street is approximately 286°. Therefore, it was noted that the alignment of the street likely influenced the air flow direction at the monitoring location, as the street channelled the air relatively parallel to the alignment of the street.

6.3.3.1 COMPARISON OF LOCAL AND REGIONAL WIND DATA SOURCES

Prior to the model calibration process, a comparison of the Pearse Street wind data against both the Met Éireann and Wunderground sites was carried out for both wind direction (Figure 6.14) and speed (Figure 6.13). The data from most of the stations was collected in 15 minute intervals, with the exception of Dublin Airport which only measured the average hourly wind speed and direction. To maintain a similar scale across all of the data sets, the Dublin Airport data was multiplied by a factor of four. Figure 6.13 displays the frequency and magnitude of wind direction for each of the stations.

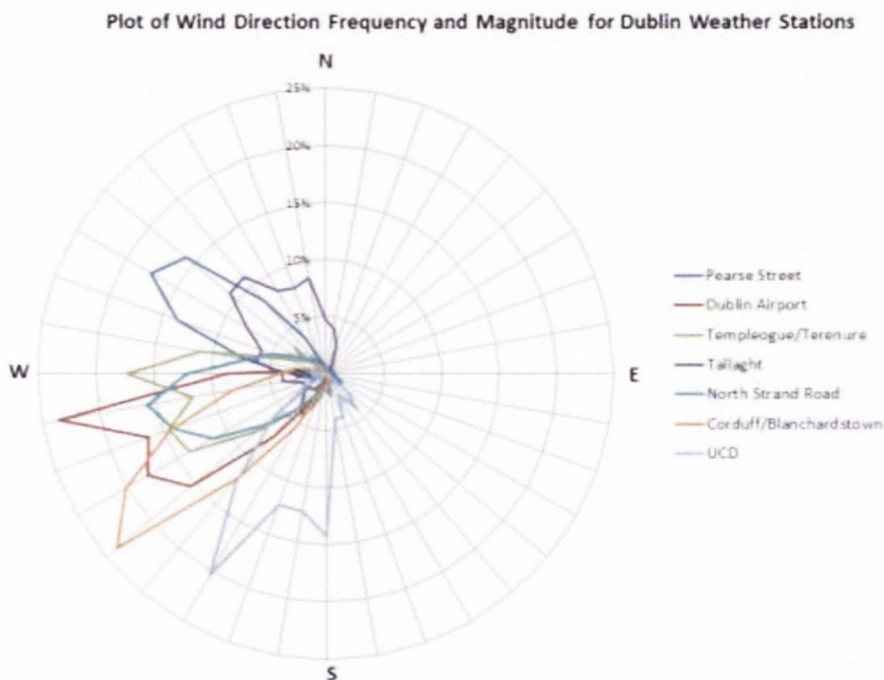


FIGURE 6.13. WIND ROSE OF DATA FROM WEATHER STATIONS IN DUBLIN CITY (DISPLAYING THE PERCENTAGE OF TIME WIND BLOWING IN A SPECIFIC DIRECTION).

The wind rose in Figure 6.13 can illustrate the seven stations; however two of the stations datasets (Templeogue/Terenure and UCD stations) were relatively small for the monitoring period and were not considered as statistically significant as the other sites. Therefore, only five sites were considered for comparison of wind direction. The Pearse Street data shows a common predominant direction with the Tallaght station of WNW to NW. The other three stations (Dublin Airport, Corduff/Blanchardstown and North Strand Road) which are all situated to the north of Pearse Street, demonstrated similar patterns to one another of a predominant W to SW

direction. This suggests that there are some similarities between data sets for some of the sites. However, variances between wind directions are clearly evident from an analysis of a sub-set of the data comparing the average wind direction at different 15 minute intervals. A stronger correlation is observed between the Pearse Street and Tallaght sites compared to the other three sites, however differences of between 30° and 40° are found after comparing the two groups of sites. This suggests that local data is the most suitable for the calibration process and the use of external site data would enhance inaccuracies in the model. The frequency and range for wind speed and altitudes of the five sites is presented in Figure 6.14.

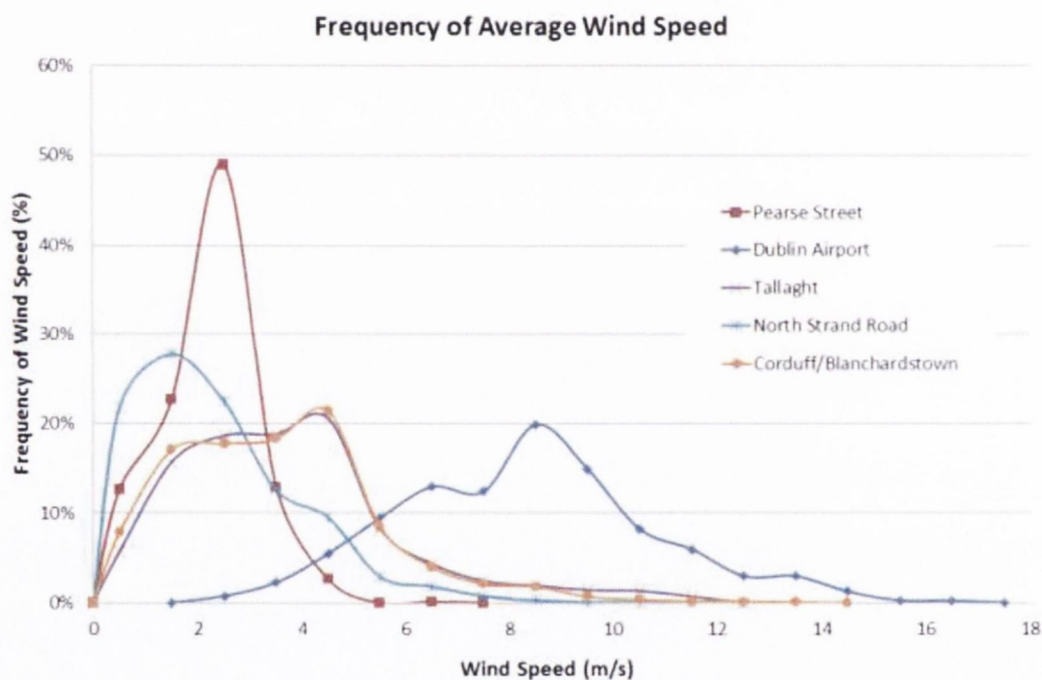


FIGURE 6.14. COMPARISON OF WIND SPEED DATA FROM DUBLIN WEATHER STATIONS (NOTE: MONITORING HEIGHTS NOT AVAILABLE FOR SITES).

The background site at Dublin Airport clearly displayed the lowest frequency and highest average wind speed (8.3 m/s) compared to the other urban sites. The Pearse Street site measured the highest frequency for a low average wind speed of 2.2 m/s. This suggests that the wind speed in the Pearse Street site is dominated by the local environment as background wind speeds are significantly reduced by the urban morphology. The three remaining Wunderground sites (all situated in the UCL) displayed broadly similar patterns for frequency and average wind speeds, with the Tallaght and Corduff/Blanchardstown sites having near identical patterns of frequency

and average wind speeds of 3.7 m/s and 3.5 m/s, respectively. In a similar manner to the investigation of wind direction patterns, it was determined that local wind speed data was the most accurate for calibrating the Pearse Street model. The predominant wind direction highlights the possible influence of urban geometry on air flow as the orientation of Pearse Street was relatively similar to the predominant wind direction. The variability between each of the sites shows how influential the urban morphology is with respect to its influence on wind speed and direction.

Based on a detailed understanding and evaluation of the datasets collected for NO_x concentrations, traffic information and wind parameters, the data can now be considered for the calibration process of the Pearse Street model.

6.4 MODEL CALIBRATION

A series of distinctive steps were identified prior to the calibration process of the Pearse Street model. This allowed for a detailed analysis to be carried out for each of the steps, as they all affected model accuracy. It was considered important for the development of the Pearse Street model to identify the individual elements that influenced dispersion as previous research studies have highlighted both the individual and collective effects of street geometry, emissions source and meteorology on pollutant dispersion. The following sub-sections discuss these individual elements and how they were incorporated into the model during each of the steps in the calibration process.

6.4.1 CANYON GEOMETRY

As previously outlined in section 6.2.1, the Pearse Street model was constructed from GIS shapefiles and transferred to Gambit via AutoCAD. The model was run in Fluent v.6.3 using the LES turbulence model, in a similar manner to the previous chapters (Gallagher et al., 2011; 2012). Numerous studies have highlighted the importance of model geometry to endeavour for an accurate investigation of pollutant dispersion in a street canyon (Oke, 1988; Santiago & Martin, 2005; Xie et al., 2005; Yassin, 2011). This has been reviewed in detail in section 2.3.2.1 of the literature review.

As the street canyon dimensions are predefined as shapefiles, this allowed the canyon geometry to accurately represent the geometry buildings in Pearse Street. This section assesses the optimisation of the Pearse Street model with regards to the accuracy of the model output against the computational running time. This optimisation takes into account the importance of building shapes and the density of the 3D mesh used for the finite volume analysis of the model.

6.4.1.1 MESH DISCRETIZATION

A detailed mesh discretization analysis was carried out in Fluent in a similar manner to the previous investigations, to determine suitable mesh parameters for the Pearse Street model in accordance with modelling guidelines by COST (2005). The street canyon model was designated with a series of grid mesh schemes (shown in Table 6.7) combining different surface meshes at canyon floor and/or building surfaces with a proportionate volume mesh. To put the mesh dimensions in context of the size of the canyon model, the street floor was an average of 22m wide, 380m long with an average building height of approximately 10m. This excludes a significant extended height above the buildings and the width over the rooftops.

OPTIMISATION OF MESH SCHEME

Three meshing schemes were constructed (in line with methodology guidelines) and reviewed to determine the most suitable mesh to optimise accuracy and running time, the results of which are shown in Table 6.7 and Figure 6.15. Table 6.7 shows details of the three mesh schemes, the number of cells in each model (which is inversely proportional to the model running time) and the average concentration measured on the footpath at times of 150 and 300 seconds. Figure 6.15 illustrates the plots of the pollutant concentrations for each of the mesh schemes.

TABLE 6.7. DETAILS OF REFINED MESH GRID SCHEMES AND NO DISPERSION RESULTS.

Mesh	Mesh Scheme Dimensions ¹			Cells ²	Comparison ³	
	Floor	Buildings	Volume		150It	300It
Fine	0.4	-	1.6	1.33	1.25	1.24
Medium	0.5	-	1.5	0.97	1.60	1.53
Coarse	0.5	-	2.0	0.74	1.87	1.95

¹ All mesh dimensions in metres
² Cell count in millions
³ 1e-04 of pollutant concentrations measured on footpath

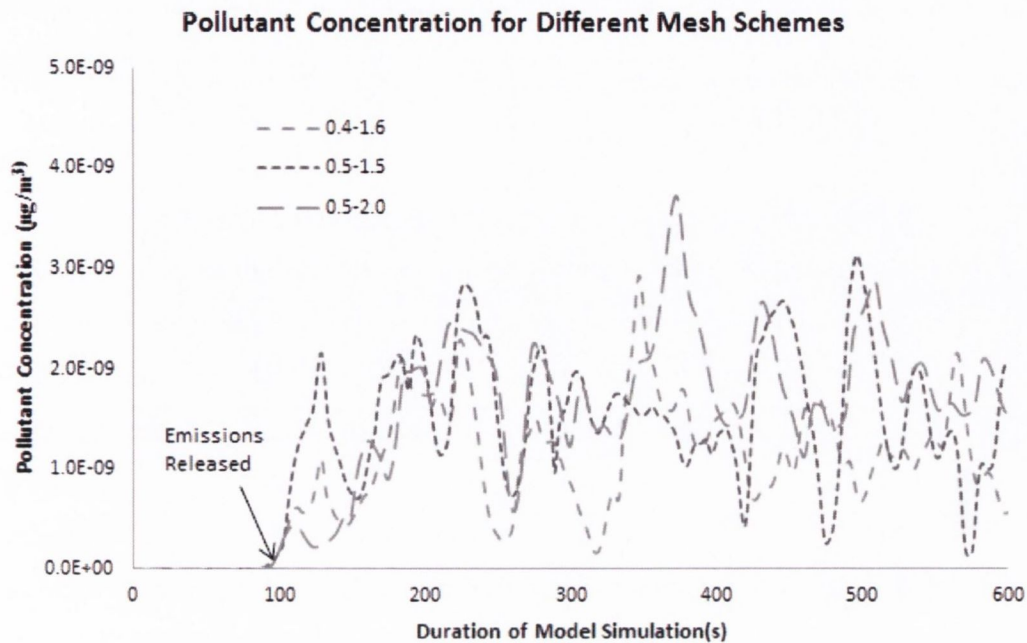


FIGURE 6.15. CONCENTRATION AT MONITORING LOCATION FOR DIFFERENT MESH SCHEMES.

Based on these results and the refined meshing techniques developed from the previous studies in this thesis (Gallagher et al., 2011; 2012), the coarse grid mesh (i.e. 0.5 to 2.0 m) was selected for the canyon model. Differences were observed in the results between the mesh schemes from Table 6.7, however the turbulent behaviour displayed in Figure 6.15 existed in all models and suggests that the difference in pollutant concentration was not significant. The mesh schemes meet guideline requirements as the footpath areas were of specific interest and therefore the chosen mesh layout is deemed adequate for this study. The model was meshed with triangular mesh elements of 0.5 m on both footpaths and the road surface with the overall volume meshed with a 2.0 m tetrahedral mesh.

OPTIMISATION OF STEADY STATE SIMULATION

Prior to the release of the pollutant concentration, the model was initially run for 60 seconds to allow the development of the vortices in the canyon in a similar manner to Baker et al. (2004). This allowed a steady state for air flow to be achieved in the Pearse Street model. The NO concentrations were then released from the individual traffic lanes at ground level (i.e. $Z = 0$) in the Pearse Street model. The pollutants were emitted as a species mass fraction with different ER for each traffic lane based on the associated traffic composition of the respective lanes. The same ER was used in the

reference and passive control models. This allowed for a clear comparison of the effectiveness of the passive control layouts in a real street canyon in different traffic and meteorological conditions.

OPTIMISATION OF ATMOSPHERIC EXTENSION ABOVE CANYON

The model was extended above the rooftop of the buildings by a height of H_r (H_r equals 4 multiplied by the tallest building height in the canyon) to allow for air flow entering or exiting the canyon above the buildings. The previous studies of passive controls (Gallagher et al., 2011; 2012) used a significantly smaller H_r value (0.25 and 0.5 previously) as the models simulated an environment where buildings were all the same height and turbulence at rooftop level was not an issue. In this investigation of Pearse Street, a complex building geometry exists and elements such as a railway bridge increase the complexity of the model and turbulence at roof level. An extended rooftop height of $4H_r$ was therefore selected for the modelling study as it minimised the volume of the models and further optimised the computational timeframe requirements.

OPTIMISATION OF ITERATIONS PER TIME STEP

An evaluation of the requirements to minimise the computational running time from the CFD models was carried out. Two sets of models were compared for different simulation criteria, primarily assessing the difference in model accuracy with respect to a reduction in the number of iterations per time step during the model simulation. From a previous investigation of passive controls, Gallagher et al. (2012) found that after the initial development of the air flow in the canyon to reach a steady state, significant reductions in the number of iterations per time step could be made. This section compares the measured concentrations at the monitoring location and on the northwest and southwest footpaths of both models with 10 and 50 iterations per time step. The findings are displayed in Figure 6.16.

As Figure 6.16 displays convergence of results for both sets of models for the different iteration criteria, 10 iterations per time step is considered suitable for the Pearse Street model after the initial step of modelling the wind flow in the canyon for the initial 60 seconds. The steady state average value from 250 seconds onward display similar results between the two iterative models and therefore the faster model

(10 iterations per time step) can be chosen. This finding allowed the simulation time to be reduced by 80% for each model.

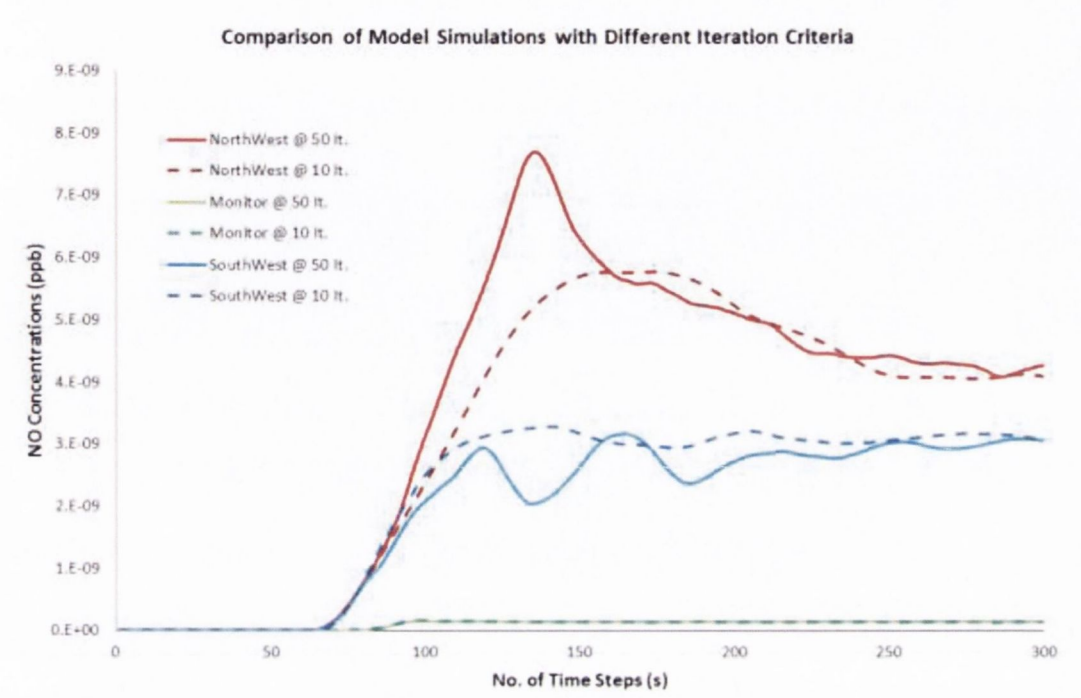


FIGURE 6.16. DATA COMPARISON OF CFD MODELS WITH 10 & 50 ITERATIONS PER TIME STEP.

6.4.1.2 BUILDING ROOF SHAPES

Upon constructing the Pearse Street model, it was noted that the GIS shapefiles for each of the buildings consisted of all flat roofed buildings. Therefore, a model was constructed with sloped roofs on some of the buildings, based on a visual inspection of the street in conjunction with consulting several aerial photographs of the street rooftops. The sloped roofs added significant complexities to the model and a highly complex grid meshing was required to successfully mesh the Pearse Street model. This significantly increased the running time of the model by tenfold and only small differences were noted between the measured concentrations on the footpaths. In addition, the influence of the sloped roofs on air flow at street level was not considered as significant compared to previous investigations (Hoydysh & Dabberdt, 1988; Yassin, 2011). It was noted by Yassin (2011) that a small overestimation of pollutant concentrations occurred at street level with the use of flat roofs, however this overestimations was not considered to be significant in the context of the Pearse Street study. The geometry of some of the roof shapes of buildings in Pearse Street is shown in Figure 6.17.

The examples of the roof shapes in Figure 6.17 were found to be relatively common in Pearse Street. The extended height of the facade of the building above the eaves location significantly reduced the influence of the sloped roof and therefore the use of a flat roof would be considered adequate for the Pearse Street model. The mean height for each building was therefore considered suitable for the Pearse Street model.



FIGURE 6.17. IMAGES OF BUILDING CROSS-SECTIONS AND ROOF DETAILS.

6.4.2 WIND SPEED & DIRECTION

A number of model scenarios were run for different wind speeds and directions. The objective of this phase of the calibration process for the Pearse Street model was to identify the correlation between the input wind parameters and the output at the wind anemometer location in the model. The monitoring site was located on a staggered flat roof and the geometry on the rooftop of this building accurately replicated the existing structure to ensure the wind characteristics behaved similarly in the CFD model. The initial wind speed and direction characteristics were input into the model by attaching boundary conditions to surface(s) categorised as a velocity inlet in the model.

6.4.2.1 MODEL CALIBRATION FOR WIND DIRECTION

As previous studies have shown, wind direction around a street canyon is very much influenced by the urban morphology (Hoydysh & Dabberdt, 1988; Oke, 1988; Chan et al., 2001; Santiago & Martin, 2005). Some of these studies particularly highlighted canyon asymmetry as an influencing factor on pollutant dispersion (Hoydysh & Dabberdt, 1988; Santiago & Martin, 2005). This is due to the turbulent behaviour of air around and through urban street canyons and thus increased complexity with respect to gauging the air quality at street level. This highlighted the importance of gaining a comprehensive understanding of dispersion patterns in street canyons under real meteorological conditions (Zhang et al., 2011b).

The calibration of wind direction and speed was carried out separately. This was to distinguish between the elements that can influence these parameters individually as well as in unison in an urban canyon environment. Prior to modelling emissions transport and dispersion, a series of models were run for different wind directions (primarily in 45° segments) at the average wind speed measured from the wind anemometer of 2.5 m/s. The results of this investigation are plotted in Figure 6.18.

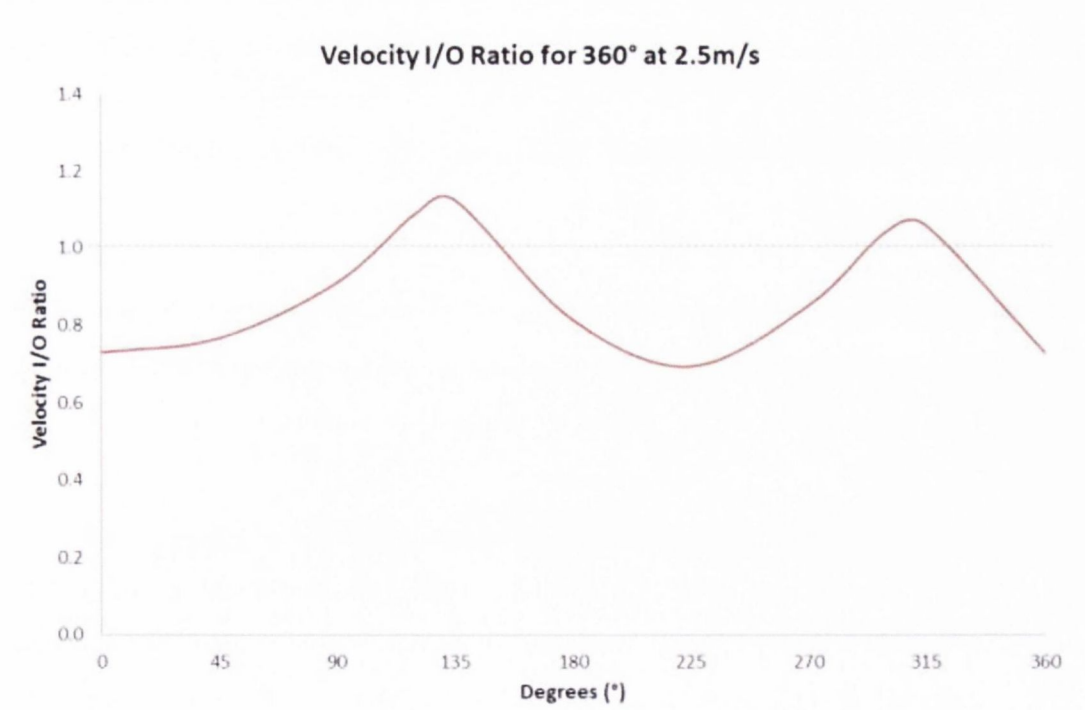


FIGURE 6.18. PLOT OF VELOCITY INLET VS. MEASURED VELOCITY FOR 360°.

Figure 6.18 illustrates the relationship between the inlet velocity, I , and the measured output velocity, O , at the wind anemometer location in each model. A 1.0 I/O ratio equated to an inlet velocity equalling the measured outlet velocity. The plot displays the varying relationship between input and output with respect to the different wind directions. This allows for a back calculation of the input parameters to correspond to a required measured output value, and the calibration of the wind direction in the Pearse Street model. The deviations in the I/O ratio were due to the surrounding geometry of the buildings in the canyon, which influenced the wind direction in some cases.

A comparison of the input wind direction to the output wind direction was assessed. An average variability of $\pm 7.5^\circ$ was found at a wind 1.0 m/s, with average differences of $\pm 4.1^\circ$ and $\pm 3.9^\circ$ for higher wind speeds of 2.5 m/s and 5.0 m/s, respectively. The findings suggest an increase in the confidence level of wind direction with an increase in wind speed.

The values of the individual X and Y components of the input velocity and the measured wind anemometer velocity were also compared. This found that differences existed between the percentage differences for the individual X and Y components of the wind velocity. Therefore the wind direction calibration process requires a case by case assessment to endeavour for accuracy of the wind direction in the model.

A series of canyon simulations were run to establish a confidence level in the calibration process of wind conditions. The results identified a high level of accuracy in wind direction based on input values for wind component values, with a maximum error of $\pm 5^\circ$ deemed acceptable for the calibration process.

6.4.2.2 MODEL CALIBRATION FOR WIND SPEED

In addition to the calibration of wind direction, two additional sets of models were run for different wind speeds (as a uniform velocity profile along the full height of the model) to correspond to the lower (1.0 m/s) and higher (5.0 m/s) range of measured wind speeds in Pearse Street. The models were run for different wind directions in a similar manner to the previous section. The plot layout for each of the wind speeds

resembles the previous figure, but shows a mix of similar and contrasting results for different wind directions (Figure 6.19).

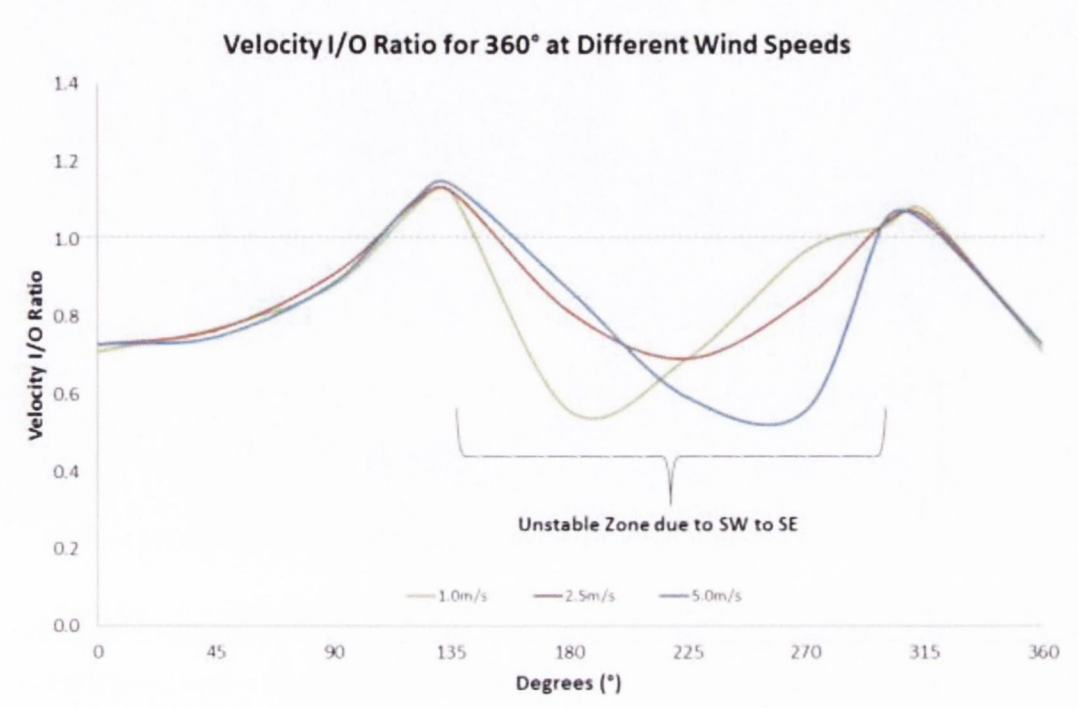


FIGURE 6.19. VELOCITY INLET VS. MEASURED VELOCITY AT DIFFERENT WIND SPEEDS.

There is a notable variance in the I/O ratio for different wind speeds between 135° and 300°. This is considered to be due to the building extension which had been added to the building and was situated to the south of the wind anemometer, causing a level of recirculation and turbulence of air.

The zone highlighted in Figure 6.20 is located to the south of the wind anemometer and therefore wind is clearly influenced by the building behind the anemometer and thus affects the I/O relationship identified in Figure 6.19.

As the I/O ratio is less than 1.0, the input velocities will be higher than the measured output velocities to calibrate the model. This is due to losses in wind velocity caused by the asymmetry and shapes of the buildings. This reduction in velocity can explain the significant difference of wind measurements between the Pearse Street monitoring station and the background Dublin Airport site. Therefore, an increased inlet velocity was included for calibrating the Pearse Street model for most scenarios.

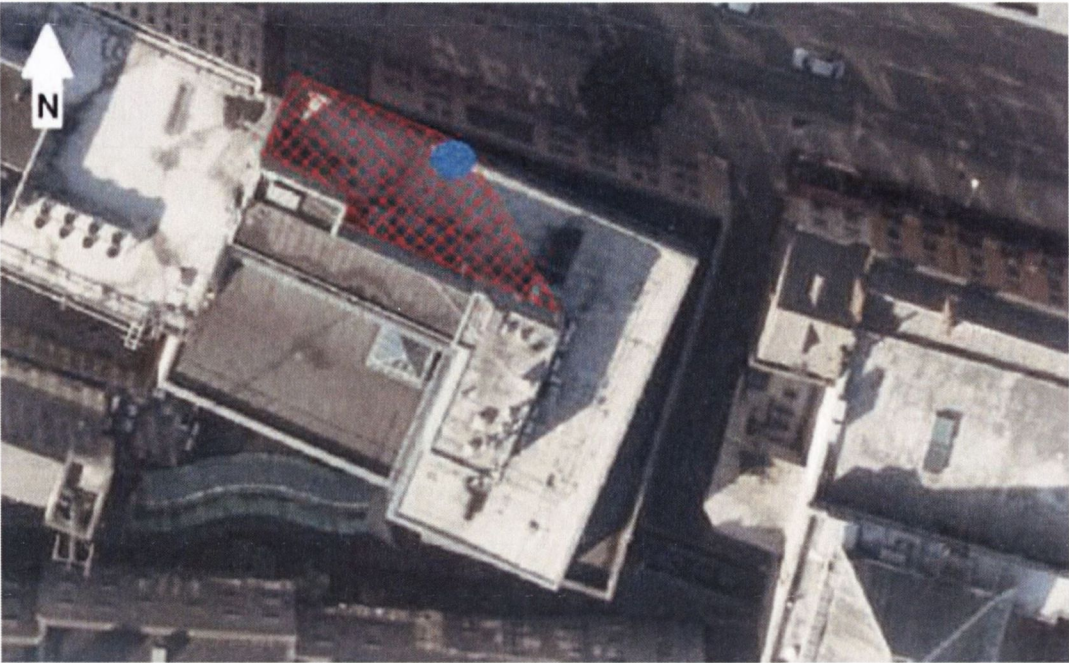


FIGURE 6.20. TURBULENCE ZONE BETWEEN 135° AND 315°.

This analysis allows for the accurate input of I, to endeavour that O was correlated to the wind velocity required in the Pearse Street model. After analysing the individual X and Y components of the measured wind velocity against the input velocity, the results suggest a very turbulent zone specifically between 135° and 315°. Table 6.8 identified differences of up to 41% (for both 180° and 270°) were calculated for the X and Y components in this turbulent zone. This does highlight the possible requirement for a case-by-case calibration of any street canyon model.

TABLE 6.8. INPUT & OUTPUT WIND SPEED COMPONENTS FOR DIFFERENT WIND DIRECTIONS.

Wind Direction	Model Input (m/s)			Model Output (m/s)			% Differences		
	1.0	2.5	5.0	1.0	2.5	5.0	1.0	2.5	5.0
45°	1.0	2.5	5.0	0.77	1.92	3.75	77%	77%	75%
90°	1.0	2.5	5.0	0.88	2.28	4.45	88%	91%	89%
135°	1.0	2.5	5.0	1.12	2.81	5.71	112%	113%	114%
180°	1.0	2.5	5.0	0.54	2.03	4.35	54%	81%	87%
225°	1.0	2.5	5.0	0.69	1.73	2.95	69%	69%	59%
270°	1.0	2.5	5.0	0.97	2.12	2.79	97%	85%	56%
315°	1.0	2.5	5.0	1.07	2.65	5.23	107%	106%	105%
360°	1.0	2.5	5.0	0.71	1.82	3.65	71%	73%	73%

From this assessment, the correlation of I/O in the coefficient plot (Figure 6.19) identified differences between the input values of wind speed and direction and the

measured values by the wind anemometer. This endeavoured to provide an accurate estimation of the input velocity component values to calibrate the model to real world conditions. The turbulent zone from Figure 6.20 is also highlighted in data in Table 6.8 from the Pearse Street model, whereby wind speed and direction is influenced in one particular zone (180° to 270°). Once the model was calibrated for these conditions, the NO emissions were simulated to calibrate the pollutant concentration to the monitoring point (displayed previously in Figure 6.4) in Pearse Street.

A series of simulations were run taking into account the findings from Table 6.8, using the data for the percentage difference for wind speed to input the adjusted value to endeavour for a correlation between the model output and measured wind speeds from the monitoring period. Figure 6.21 displays a plot of confidence (R^2 of 0.96) for output wind speed from some of the models versus measurements of wind speed by wind anemometer in parallel wind conditions i.e. east to west. Similar confidence levels were estimated for both the X and Y components with calculated coefficients of determination (R^2) of 0.96 and 0.94, respectively.

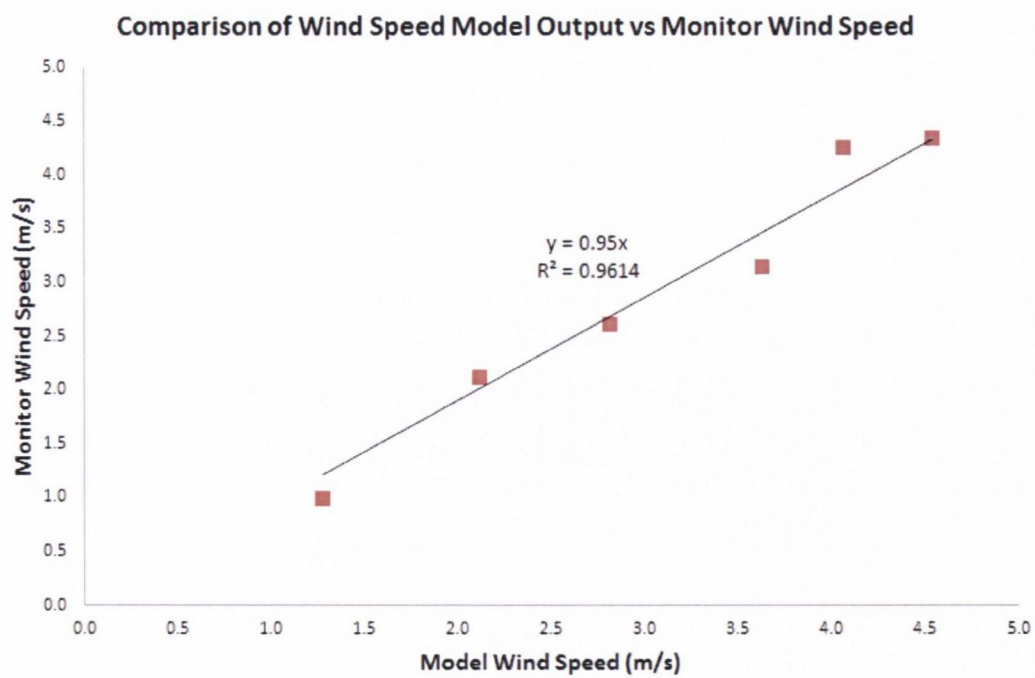


FIGURE 6.21. CONFIDENCE IN MODEL OUTPUT VS. REAL-TIME WIND SPEED MEASUREMENTS.

6.4.3 NO EMISSIONS

A breakdown of the different traffic fleet compositions was required for the NO calibration process to estimate the emissions entered into the Pearse Street model. Due to the regular variances in wind direction, the calibration of the model focused on wind data corresponding to the parallel wind direction to the direction of the street. As the data varied significantly for each 15 minute duration, a $\pm 10^\circ$ variance to the given wind direction was considered acceptable as it behaved in a similar manner as defined by Hoydysh & Dabberdt (1988). To ensure that the most accurate NO data set was selected, the 5 minute wind direction averages were also reviewed and compared to the 15 minute values. The NO concentrations were only included if the variation in the 5 minute averages were within a $\pm 20^\circ$ deviation from each selected wind direction. This reduced the total size of each dataset, but the selected NO concentrations were considered more suitable for the model calibration process.

For the perpendicular wind direction, a different approach was required as no perpendicular wind data met the criteria set out by the previous section. The wind rose in Figure 6.13 displayed a low fraction of perpendicular wind conditions, therefore a selection of 5 minute average values were chosen to calibrate the Pearse Street model. Traffic data was then adjusted for the 5 minute averages for each of the lanes and the average measured pollutant concentration over the 15 minute period which the 5 minute wind direction fell within was used.

6.4.3.1 NO EMISSIONS VS. LANE DISTRIBUTION

As Figure 6.1 showed no direct correlation between the traffic data and measured pollutant concentrations, the distribution of traffic across the four lanes was considered. The data sets shown in Table 6.9 and Table 6.10 contain a mix of peak or off-peak traffic times, high or low wind speeds and different traffic compositions for the perpendicular and parallel wind directions, respectively. These data sets meet the criteria detailed in the previous section for the suitable selection of data for the calibration of the Pearse Street model.

TABLE 6.9. NO CONCENTRATIONS AND TRAFFIC DATA FOR PERPENDICULAR WIND CONDITIONS AT 5 MINUTE INTERVALS.

No.	Date	Time	Wind		Traffic*				
			Direction (°)	Speed (m/s)	L1 ^a	L2	L3	L4	Total
1	04/12/2011	8:15 AM	200.72	1.83	9	38	48	5	100
2	19/12/2011	8:30 AM	204.72	1.50	43	160	173	86	462
3	06/12/2011	11:35 AM	204.91	1.86	13	50	66	3	132
4	11/12/2011	11:55 AM	199.45	0.54	42	108	159	12	321
5	13/12/2011	5:55 PM	200.77	1.97	22	87	76	55	240
6	14/12/2011	7:15 PM	186.07	0.41	97	244	256	61	658
7	14/12/2011	7:20 PM	205.94	0.54	90	205	254	60	609

* Lanes 1 to 4 defines as L1 to L4.
^a Bus Lane.

TABLE 6.10. NO CONCENTRATIONS AND TRAFFIC DATA FOR PARALLEL WIND CONDITIONS AT 15 MINUTE INTERVALS.

No.	Date	Time	Wind		Traffic*				
			Direction (°)	Speed (m/s)	L1 ^a	L2	L3	L4	Total
1	07/12/2011	8:15 AM	280.13	2.43	30	192	160	52	434
2	05/12/2011	8:15 AM	295.28	2.98	38	149	179	75	442
3	05/12/2011	8:45 AM	290.40	3.04	45	160	222	98	524
4	05/12/2011	11:15 AM	291.25	2.59	54	182	147	0	383
5	09/12/2011	11:15 AM	286.77	2.64	39	190	204	17	450
6	13/12/2011	11:15 AM	289.63	2.83	38	179	202	20	437
7	07/12/2011	11:30 AM	288.91	4.60	50	189	169	10	418
8	15/12/2011	11:45 AM	292.75	3.22	38	186	193	30	447
9	07/12/2011	11:45 AM	284.05	4.52	44	202	158	7	411
10	05/12/2011	12:00 PM	284.01	3.19	53	177	152	6	388
11	05/12/2011	5:15 PM	285.62	2.71	56	229	223	138	646
12	06/12/2011	5:45 PM	282.94	1.92	49	216	246	129	640
13	08/12/2011	5:45 PM	283.58	4.22	43	142	141	172	497
14	15/12/2011	7:15 PM	296.19	0.88	46	216	217	59	537
15	06/12/2011	7:30 PM	291.88	2.09	67	194	182	13	456
16	15/12/2011	7:45 PM	287.50	0.78	46	223	228	42	539
17	08/12/2011	8:00 PM	284.56	3.63	43	226	210	24	504

* Lanes 1 to 4 defines as L1 to L4.
^a Bus Lane.

Where manual traffic data were not available, the automated SCATS traffic counts were used. As significant errors were evident for L1, estimations were made for the lane based on trends. These were based on the trends identified during the analysis of the manual traffic data for peak and off-peak traffic and the relationship between the manual and automated traffic counts for the other three lanes.

Traffic distribution, fleet composition and vehicular dispersion are simplified in the FLUENT models and therefore a semi-empirical equation was developed to take into account these factors in addition to the results from the model in a similar manner to Gualiteri & Tartaglia (1997). Eqn. 6.1 shows the derived equation which accounts for factors which are not included in the CFD model. The equation defines that the monitored NO concentration is a function of vehicle speed, fleet composition, lane distribution, emission rates and vehicular turbulence.

$$NO_M = \left(\sum_{L=1}^4 \frac{E_C}{S_A} \cdot V_C \cdot D_L + 22 \sum_{L=1}^4 \frac{E_O}{S_A} \cdot V_O \cdot D_L \right) \cdot T_C \quad \text{EQN. 6.1}$$

Where;

NO_M	NO measured by monitor in Pearse Street (10^{-9} g/m ³)
E_C	ER rate for cars (based on average vehicle speed in different traffic conditions) (10^{-3} g/m)
E_O	ER rate for other vehicles (10^{-3} g/m)
S_A	Surface area of each traffic lane (m ²)
V_C	Number of cars in the respective lane
V_O	Number of other large vehicles (Buses & HGVs) in the lane
D_L	Coefficient for distribution of emissions between individual lane and monitor
T_C	Coefficient of vehicular turbulence in the canyon calculated using Eqn. 6.7

The ERs from Section 6.3.2.1 for cars (E_C) and other vehicles (E_O) equalled 0.3 and 6.4 g NO/m, respectively. As NO monitoring data (NO_M in g/m³) was collected as volumetric data, the calculated ERs (E_C and E_O in g/m) were divided by a factor representing the road surface area (S_A in m²) for each lane as defined in Eqn. 6.2. The pollutant emissions were released as a surface source along the floor of the traffic lanes (i.e. $Z = 0$). This ensured the semi-empirical equation produced values with the same units as the monitoring data i.e. g/m³.

$$E_R = \frac{E_C}{S_A} \text{ or } \frac{E_O}{S_A} \quad \text{EQN. 6.2}$$

FLEET DISTRIBUTION

Eqn. 6.3 was initially developed based on the diffusion equation defined by Johnson et al. (1973), which calculated the pollutant concentration at the receptor location as a function of distance from the pollutant source. The NO concentration transported from the emissions source to the human receptor on the footpath for different vehicle types,

namely cars (V_c) and other (V_o), was based on the traffic counts and fleet composition from each individual lane.

$$NO_M = \sum_{L=1}^4 V_C \cdot \frac{E_C}{S_A} + \sum_{L=1}^4 V_O \cdot \frac{E_O}{S_A} \quad \text{EQN. 6.3}$$

This equation takes fleet composition into consideration, and the introduction of the $E_c:E_o$ ER ratio for cars to large vehicles which was calculated as 1:22 (from section 6.3.2.1) was then introduced into Eqn. 6.. This updated version of the equation is shown in Eqn. 6.4.

$$NO_M = \sum_{L=1}^4 V_C \cdot \frac{E_C}{S_A} + 22 \sum_{L=1}^4 V_O \cdot \frac{E_C}{S_A} \quad \text{EQN. 6.4}$$

TRAFFIC LANE EMISSIONS

The previous section dealt with simplifying the effect of wind direction in the calibration process, however, a number of elements were still not included in this equation and needed to be addressed, namely the effect of wind speeds and vehicular turbulence. The simulation of traffic emissions from each individual lane determined the distribution of emissions (D_L) from the source to receptor which varied in parallel and perpendicular wind conditions and was dependent on wind speed. To endeavour for optimum accuracy in the calibration process, the equations shown in Figure 6.22 and Figure 6.23 (based on 1.0 g/m^3 emitted from lane) captured the behaviour of pollutant dispersion from each traffic lane at different wind speeds in the Pearse Street model. These were used to establish the dispersion coefficients from each lane of interest to the monitoring location along the footpath based on the respective wind speed and direction. This was then used to relate the pollutant concentration on the footpath to the emissions rate associated with each traffic lane.

In parallel wind conditions, the increase in wind speed had only a small influence on the fraction of emissions transported from each lane to the monitoring location. The curvilinear profile of NO concentrations against wind speed, displayed in Figure 6.22, suggests that an increase in wind speed clearly reduces the concentration measured at the monitoring location. In addition, the most notable differences in NO

concentrations occurred with an increase in wind speed at the lower end of the wind speed profile.

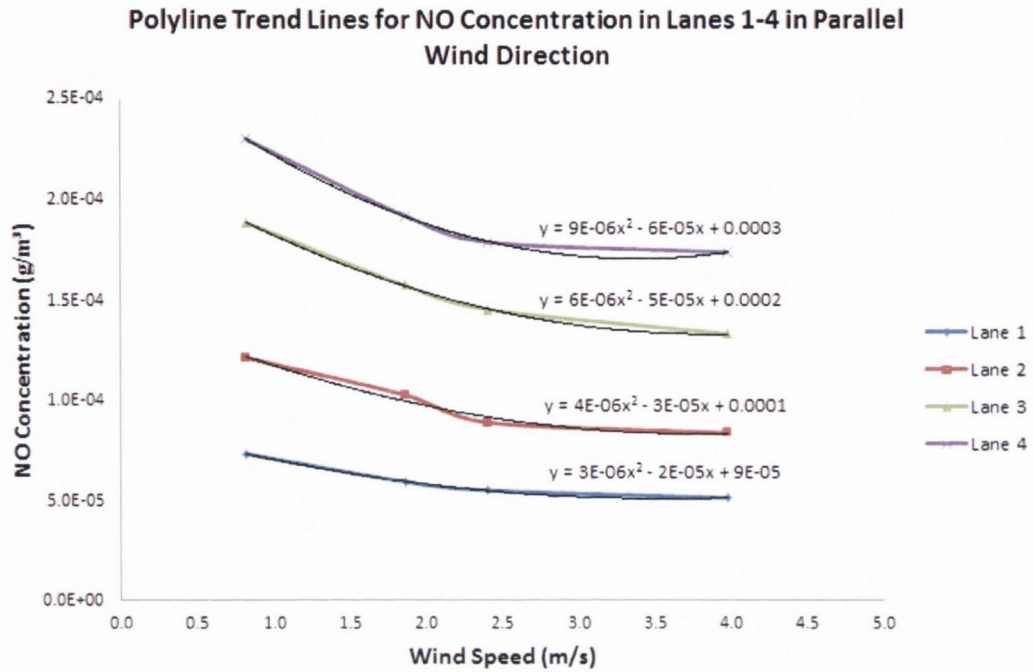


FIGURE 6.22. ESTIMATION OF VEHICLE EMISSIONS TRANSPORTED FROM TRAFFIC LANE TO MONITOR IN PARALLEL (286°) WIND CONDITIONS USING POLYLINE TREND LINES.

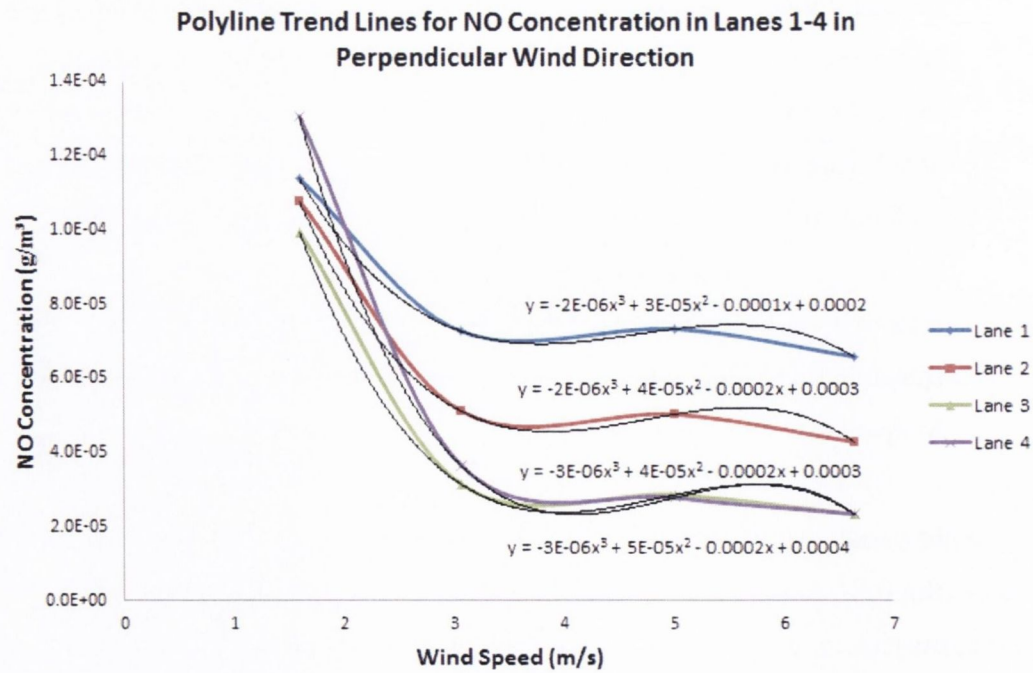


FIGURE 6.23. ESTIMATION OF VEHICLE EMISSIONS TRANSPORTED FROM TRAFFIC LANE TO MONITOR IN PERPENDICULAR (196°) WIND CONDITIONS USING POLYLINE TREND LINES.

In perpendicular wind conditions, the results of the simulations suggest that the emissions were transported by the primary eddy away from the monitoring location and then recirculated in the eddy towards the monitor in higher wind conditions. In low wind conditions, the highest concentration measured at the monitoring point were sourced from Lane 4, which was the lane nearest the monitor. This was due to the weakness of the eddy in low wind speeds, thus dispersion was reduced and the emissions were transported directly from the traffic lane to the monitor. The results suggest that the bus lane (which is location the largest distance away from the monitor) constitutes the greatest fraction of NO at the monitoring location in higher wind speeds, assuming vehicular turbulence is not included in the simulations. Figure 6.22 and Figure 6.23 allow for the introduction of emissions distribution into Eqn. 6.5 for the respective lanes to calculate the ER or measured NO concentration. The concentrations were calculated with respect to the measured wind speed. A simplified version of the equation is shown in Eqn. 6.6.

$$NO_M = \sum_{L=1}^4 V_C \cdot D_L \cdot \frac{E_C}{S_A} + 22 \sum_{L=1}^4 V_O \cdot D_L \cdot \frac{E_C}{S_A} \quad \text{EQN. 6.5}$$

$$NO_M = \frac{E_C}{S_A} \cdot \left(\sum_{L=1}^4 V_C \cdot D_L + 22 \sum_{L=1}^4 V_O \cdot D_L \right) \quad \text{EQN. 6.6}$$

As the emissions rate (E_C) and surface area (S_A) are the same in both vehicle categories due to the inclusion of the correction factor of 22, these factors can be taken out of the overall equation. The equation term for estimating the emission transport from the source to receptor ($[x^2+z^2]^{1/2}$ based on Pythagoras's theorem to calculate hypotenuse length) by Johnson et al. (1973) was omitted here and replaced by the term representing the distance between the source and receptor for each lane with the D_L coefficient.

6.4.3.2 VEHICULAR TURBULENCE

The introduction of vehicular turbulence (T_C) was the most challenging element of the model calibration process. A turbulence coefficient was required in the equation to compensate for the omission of vehicular turbulence in the model simulations due to the simplification of the surface emissions source, commonly used to significantly

reduce the computational running time of each model (Baker et al., 2004; Murena et al., 2009; Gallagher et al., 2011; 2012). As the turbulence and emission rates are affected by the speed and nature of flow of traffic, some statistical analysis was required to determine a series of different turbulence coefficients for different traffic flows (Jicha et al., 2000; Solazzo et al., 2008; 2009). The turbulence coefficient included factors such the rate of turbulence, average vehicle speed and wind speed. The vehicular turbulence formula is displayed in Eqn. 6.7.

$$T_C = S_F \left(V_S / W_S \right)^2$$

EQN. 6.7

Where;

- S_F

Vehicle shape factor based on vehicle counts and fleet composition in street
- V_S

Average vehicle speed (m/s) based on Table 6.11
- W_S

Average wind speed at corresponding time of day (m/s)

A statistical analysis of the data sets in Table 6.9 and Table 6.10 was carried out to estimate a set of turbulence coefficients related to vehicular turbulence. This took into account the measured wind speed (W_S) and estimated average traffic speeds (V_S) at different times of the day and which were considered to be proportional to the traffic count in the street canyon. Table 6.11 lists the estimated average vehicle speeds in each lane for each of the traffic count periods, based on approximations from average city driving speeds and a visual interpretation of the traffic flows in each respective lane at different times of the day. The traffic speed and traffic volume are both linked to the rate of congestion in the canyon, therefore each parameter was interconnected in the analysis process so that a change of one value alters the result of the entire equation.

TABLE 6.11. AVERAGE VEHICLE SPEED IN EACH LANE IN DIFFERENT TRAFFIC CONDITIONS.

Time	Average Speed (m/s)				
	L1	L2	L3	L4	Average
8:00 – 9:00AM	5.56	4.17	4.17	6.94	5.2
11:00 – 12:00PM	6.94	4.17	5.56	6.94	5.9
5:00 – 6:00PM	5.56	2.78	2.78	6.94	4.5
7:00 – 8:00PM	6.94	4.17	5.56	6.94	5.9

Note: Average Speed limits adjusted to correspond to different traffic counts

The level of congestion in the street is directly linked to the average vehicle speed as the increase in vehicle numbers leads to increased congestion at peak traffic times, which can reduce the effect of vehicular turbulence and increase emission rates from vehicles. The calibration of pollutant concentration is highly influenced by all these factors and the subsequent paragraphs deal with the calibration of the model to take vehicular turbulence into account in the equation.

TURBULENCE SHAPE FACTOR

Section 6.3.2.1 established the correlation of NO for different vehicle types, so a vehicle shape factor (S_F) related to turbulence traffic rate was calculated and used instead of the actual traffic count. This rate was calculated using Eqn. 6.8.

$$S_F = \frac{(V_{tc} + V_{to})}{(V_{tc} + t_o \cdot V_{to})} \qquad \text{EQN. 6.8}$$

Where;

- V_{tc} Total number of cars in street
- V_{to} Total number of other large vehicles in street
- t_o Turbulence coefficient for larger vehicle (in this case 5)

The fraction of large vehicles varies during the day and therefore influences pollutant dispersion in the model. The distribution of the average percentage of large vehicles in each lane is plotted in Figure 6.24. It displays the differences in fleet composition in the four traffic lanes at different times of the day.

Two scenarios were compared using the final calibration equation, to determine the effect of the turbulence shape factor in the final equation. As manual traffic data was required to include this factor, it was considered important to understand the scale of influence of the shape factor. The findings determined that the exclusion of the shape factor did not significantly influence the results and therefore the automated traffic data could be used as it provided a larger data set for calibration purposes.

The relationship between the average vehicle speed (V_s) and average wind speed (W_s) in Eqn. 6.7 accounts for the effect of vehicle speed upon wind speed as values constantly change for both parameters. Eqn. 6.9 displays the simplified version of Eqn. 6..

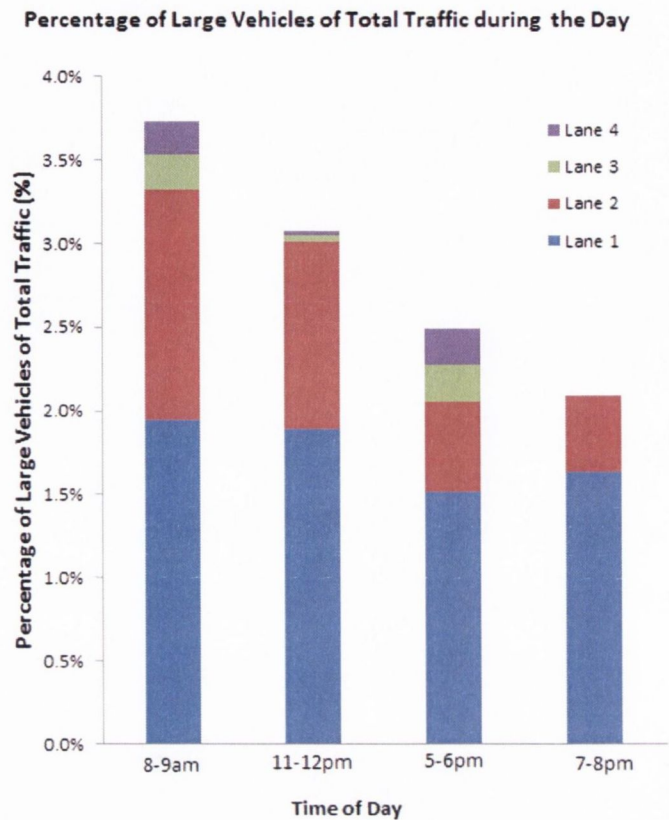


FIGURE 6.24. PERCENTAGE OF LARGE VEHICLES OF TOTAL TRAFFIC AT PEAK AND OFF-PEAK TRAFFIC TIMES.

$$NO_M = \frac{E_C}{S_A} \cdot \left(\sum_{L=1}^4 V_C \cdot D_L + 22 \sum_{L=1}^4 V_O \cdot D_L \right) \cdot T_C \tag{EQN. 6.9}$$

EMISSIONS ADJUSTMENT COEFFICIENT

The fit between the monitoring data and the output from Eqn. 6.9 required a further coefficient to further improve the accuracy of the equation. The ratio between the NO monitoring data and the calculated NO concentration was plotted against wind speed for the parallel and perpendicular data sets. These plots are displayed in Figure 6.25 and Figure 6.26.

The data in both figures represent the most stable wind conditions and therefore a high level of confidence (R^2 of 0.87 and 0.95) can be taken for the fit equations to estimate the pollutant concentration at the monitoring location. Therefore, the equations for the trend lines (C_R) in Eqn. 6.10 can be used to approximate the pollutant concentration. In addition, the I/O coefficient is included so that the calculated concentration equalled the measured concentration for each data point.

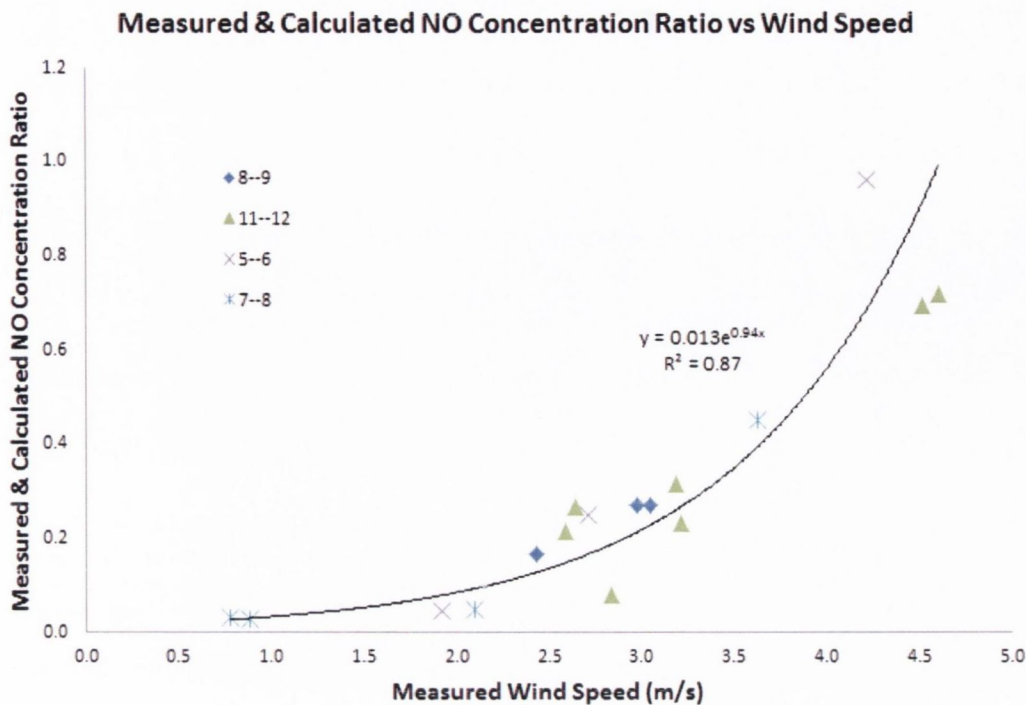


FIGURE 6.25. CORRELATION OF MEASURED WIND SPEED AND RATIO OF MEASURED AND CALCULATED NO CONCENTRATIONS IN PARALLEL WIND CONDITIONS.

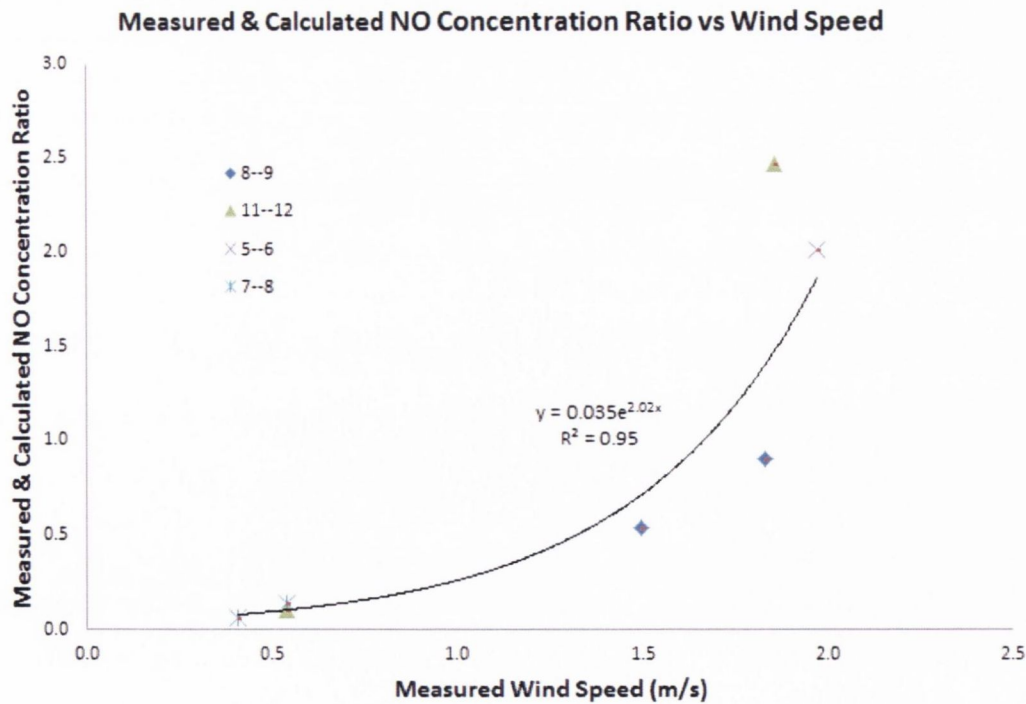


FIGURE 6.26. CORRELATION OF MEASURED WIND SPEED AND RATIO OF MEASURED AND CALCULATED NO CONCENTRATIONS IN PERPENDICULAR WIND CONDITIONS.

$$NO_M = \frac{E_C}{S_A} \cdot \left(\sum_{L=1}^4 V_C \cdot D_L + 22 \sum_{L=1}^4 V_O \cdot D_L \right) \cdot T_C \cdot C_R \cdot C_{IO}$$

EQN. 6.10

Where;

- C_R

Adjustment coefficient based on measured to calculated concentration ratio against wind speed
- C_{IO}

I/O coefficient of calculated (y) to measured (x) concentrations

The I/O coefficients vary for different wind directions and values of 1.37 and 1.13 were calculated for parallel and perpendicular wind directions, respectively.

6.4.4 PREDOMINANT WIND DIRECTION

Based on the findings of the parallel and perpendicular calibration process, the same procedure was adopted for the predominant wind direction data. Despite a similar sized data set being used to the perpendicular model calibration process (shown in Table 6.12), the accuracy of the calibrated model was not as good as the parallel and perpendicular models.

TABLE 6.12. NO CONCENTRATIONS AND TRAFFIC DATA FOR PREDOMINANT WIND CONDITIONS AT 15 MINUTE INTERVALS.

No.	Date	Time	Wind		Traffic*				
			Direction (°)	Speed (m/s)	L1 ^a	L2	L3	L4	Total
1	07/12/2011	8:30 AM	302.55	3.02	29	194	158	52	433
2	17/12/2011	8:45 AM	299.57	2.38	20	73	109	14	216
3	07/12/2011	11:15 AM	304.40	4.51	56	182	174	11	423
4	17/12/2011	11:15 AM	304.50	2.37	44	131	146	18	339
5	17/12/2011	11:30 AM	299.06	3.00	46	136	159	12	353
6	18/12/2011	11:45 AM	299.75	2.17	35	97	135	1	268
7	11/12/2011	5:45 PM	301.82	2.16	43	181	171	9	404
8	08/12/2011	6:00 PM	300.40	3.86	51	150	134	149	484

* Lanes 1 to 4 defines as L1 to L4.
^a Bus Lane.

The data in Table 6.12 represented the best fit results for the predominant wind direction for 5 and 15 minute intervals. Figure 6.27 displays the fit of the model to the measured and calculated NO concentrations against measured wind speed.

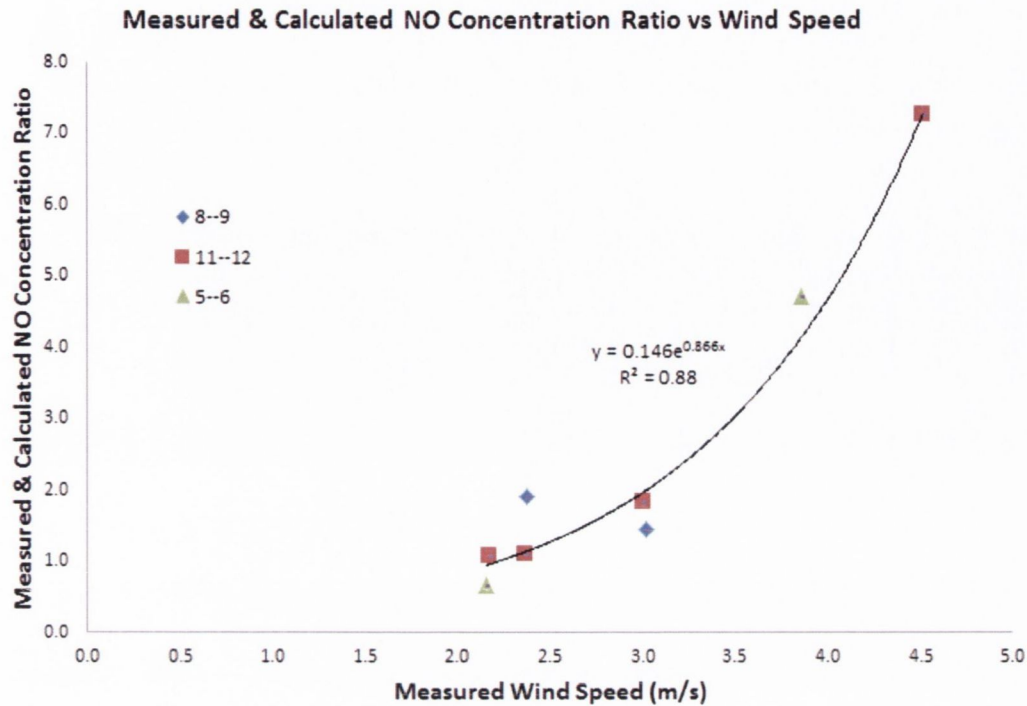


FIGURE 6.27. CORRELATION OF MEASURED WIND SPEED AND RATIO OF MEASURED AND CALCULATED NO CONCENTRATIONS IN PERPENDICULAR WIND CONDITIONS.

A good fit is represented with an R^2 of 0.88 in the plot in Figure 6.27. Unlike the parallel and perpendicular data sets, two outliers were removed from the plot prior to defining the best fit trend line. The outliers were due to the variability of the channelling effect of the canyon in different wind conditions. Therefore, in the predominant wind direction, which is offset by 15° to the parallel wind, air flow and pollutant dispersion is influenced by the shape and orientation of Pearse Street. An I/O coefficient (C_{IO}) of 12.1 was calculated for the predominant wind direction equation.

6.4.4.1 NO MEASUREMENT VS. MODEL OUTPUT

Measurements of NO were compared to the calibrated model for each wind direction and the findings are shown in Figure 6.28. An R^2 of 0.76 demonstrated a good fit for the calibrated model (Eqn. 6.10) to the measured NO concentrations in Pearse Street. Based on the findings of the calibrated Pearse Street models for three different wind directions, the assessment of introducing passive controls in the models was subsequently carried out.

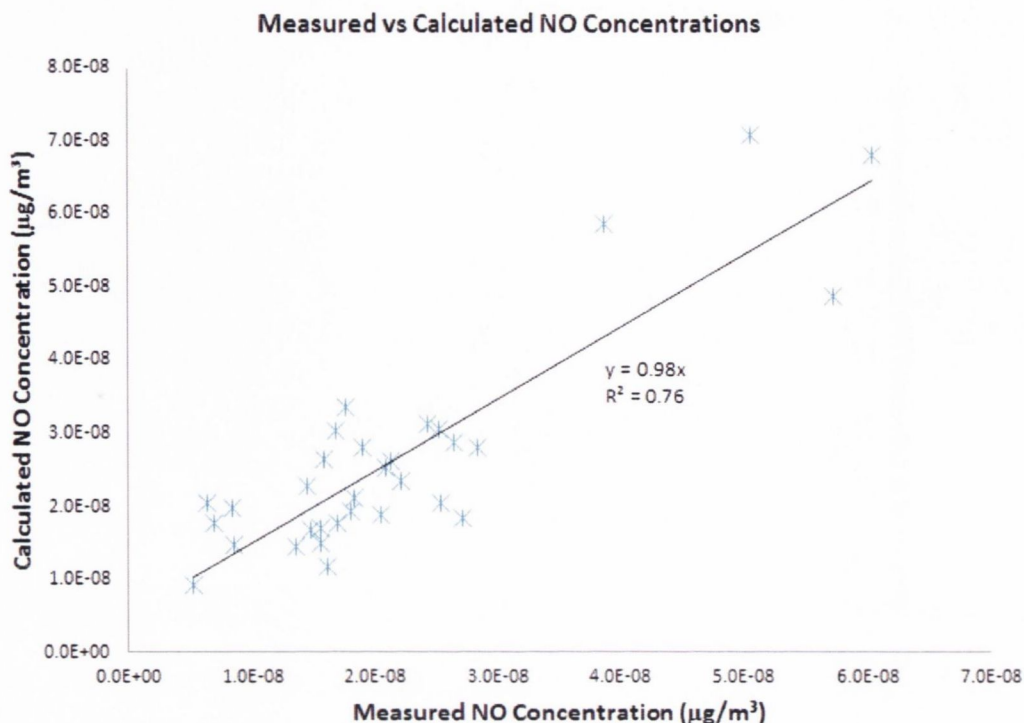


FIGURE 6.28. CORRELATION OF MEASURED NO CONCENTRATIONS VS. MODEL OUTPUT.

6.5 MODELLING RESULTS

This section outlines the results of the modelling Pearse Street modelling investigation to determine the effect of implementing different passive control scenarios including; (i) parked cars, (ii) footpath LBWs and (iii) a combination of parked cars and LBWs. Each of the investigations assessed the passive controls in parallel ($\sim 286^\circ$) and perpendicular ($\sim 196^\circ$) wind direction to traffic flow in the canyon. The predominant wind speed of 2.5 m/s which was measured at the monitoring location was also used in the modelling process to investigate all passive control models. Figure 6.29 displays the locations of the monitoring point in the Pearse Street plan view of the street canyon.

An additional section details the quantification of the reductions or increases in pollutant concentrations on the footpaths after the introduction of the passive control in the Pearse Street model.

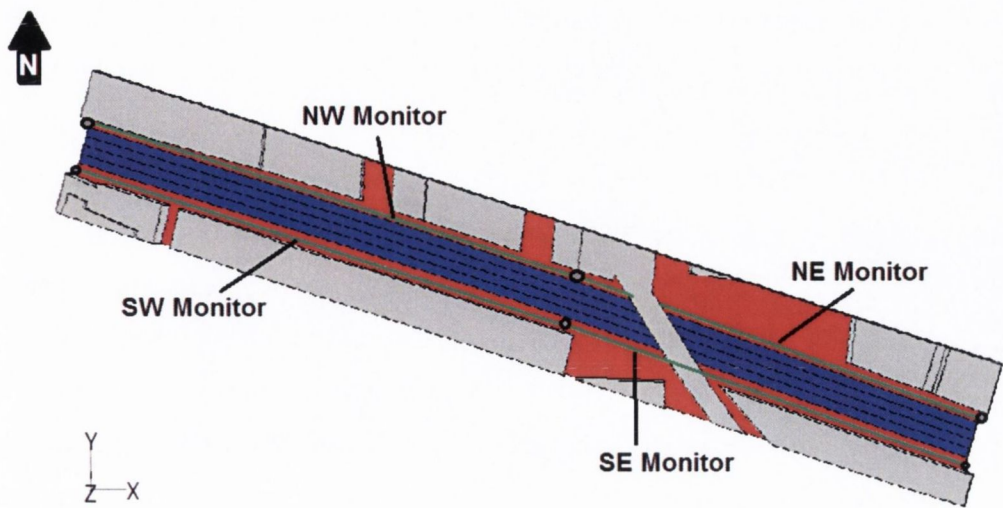


FIGURE 6.29. PLAN VIEW OF PEARSE STREET MODEL WITH FOOTPATH MONITORING LOCATIONS.

6.5.1 PARKED CARS MODEL

Parking bays currently exist on the north side of Pearse Street; therefore the first part of the investigation was to identify the effectiveness of these parallel parked cars as passive controls in different wind conditions. The investigation assumed the parking bays (although not continuous along the whole north side of the street) was at full capacity. The distribution of traffic varies between lanes at different times of the day. Therefore, the results display the range of percentage differences both peak and off-peak traffic volumes at each of the monitoring paths shown in Figure 6.29. The results for the percentage difference in pollutant concentration calculated from the data collected in the parked car passive control model of Pearse Street for different wind conditions is shown in Table 5.5.

TABLE 6.13. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND PARKED CARS MODEL AT PEAK (P) & OFF-PEAK (O) TIMES FOR DIFFERENT WIND DIRECTIONS.

Predominant Wind Direction	Traffic	Footpath Monitor Location			
		NW	SW	NE	SE
Parallel	Peak	16-19%	4-5%	50-53%	(13-14%)
	Off-Peak	5-6%	5-6%	(3-4%)	(13-14%)
Perpendicular	Peak	(6-15%)	(34-40%)	(20-24%)	50-52%
	Off-Peak	12-15%	(39-40%)	(35-36%)	41-43%
Predominant	Peak	4-5%	21-22%	24-26%	18-22%
	Off-Peak	0-1%	20-21%	18-19%	15-17%

Note: Negative percentage differences in pollutant concentrations are indicated by values in brackets.

The results displayed ranges of reductions and increases in pollutant concentrations on the footpaths due to the introduction of parked cars. A parallel wind to the direction of the street (from West to East) is a common wind direction as it falls marginally outside the predominant wind direction range from 290° to 310° . The results from the parallel wind scenario showed improvements in air quality of up to 19% and 53% in peak traffic conditions on the NW and NE footpaths, respectively. The parked cars acted as a baffle wall on the northerly footpath as the air travelled from the east to west along the canyon. The 39% parking bay occupancy on the north side of the canyon varied between the west (25%) and east (58%) sides of the canyon, thus the differences measured between the NE and NW monitoring lines correlated to the fraction of parked cars in each section. A reduction in the pollutant concentration of up to 6% was calculated on the SW footpath and an increase of up to 4% occurred on the SE footpath and in off-peak traffic conditions. Similar results were observed on the southerly footpath for both peak and off-peak traffic conditions. A reduction of up to 6% was measured on the SW footpath and an increase of up to 14% was calculated on the SW footpath.

The results of the perpendicular wind speed model (which occurred approximately 1% over the monitoring period) displayed increases in pollutant concentrations during peak traffic conditions of up to 15% and 24% on the NW and NE footpaths, respectively. A further increase of up to 36% occurred on the NE footpath and a reduction of up to 15% on the NW footpath in off-peak traffic conditions. The occupancy rate in the Pearse Street model related to similar increases in pollutant concentrations to the parked car modelling investigation. On the south side of the street canyon, an increase of up to 40% was measured on the SW section of the footpath and a reduction of up to 42% was calculated on the SW footpath. The results were similar on these footpaths in both peak and off-peak traffic times. The northern footpath translated as the windward footpath and the south footpath as the leeward footpath in the perpendicular model, due to the behaviour of the wind entering and exiting the canyon. The typical reductions in pollutant concentrations on the windward footpath and the increases on the leeward footpath commonly identified in past passive control investigations (McNabola et al., 2009; Gallagher et al., 2011) did not occur in the parked car Pearse Street model.

Lastly, the predominant wind direction (~300°) displayed reductions in pollutant concentrations on the footpaths in peak and off-peak conditions. The results also maintained clear similarities between peak and off-peak traffic conditions. The results for the predominant wind speed model showed reductions of up to 5% and 26% on the NW and NE footpaths in peak traffic conditions. Reductions of up to 22% were measured on the SW and SE sections of the footpath. This provides positive evidence of the benefits of the parked cars in the street in predominant wind conditions for both peak and off-peak traffic. It also suggests that the overall effectiveness of passive controls in a given street canyon scenario can be assessed on the basis of a wind rose displaying the local wind direction.

6.5.2 LBW MODEL

The second part of the investigation is to assess the removal of the parking bays and introduce footpath LBW in the canyon. Unlike past investigations, the LBW are not continuous as a number of openings are required at junctions, bus stops and emergency exits. Table 6.14 displays the results for the percentage difference in pollutant concentrations in the LBW passive control model for Pearse Street in different wind conditions.

TABLE 6.14. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW’S MODEL AT PEAK (P) & OFF-PEAK (O) TIMES FOR DIFFERENT WIND DIRECTIONS.

Predominant Wind Direction	Traffic	Footpath Monitor Location			
		NW	SW	NE	SE
Parallel	Peak	(19-20%)	5-6%	(5-6%)	(0-2%)
	Off-Peak	(21-22%)	7-8%	(8-9%)	(0-1%)
Perpendicular	Peak	2-3%	(14-21%)	16-17%	3-5%
	Off-Peak	(1-2%)	(24-25%)	18-19%	(5-6%)
Predominant	Peak	(3-5%)	6-7%	(1-3%)	31-36%
	Off-Peak	(0-1%)	4-5%	4-5%	28-31%

Note: Negative percentage differences in pollutant concentrations are indicated by values in brackets.

The results displayed reductions and increases in pollutant concentrations on the footpaths in the parallel wind models due to the introduction of the footpath LBWs. The results of the parallel wind speed model displayed increases of up to 22% and 9% on the NW and NE footpaths. Only a small difference was measured of up to 4% in peak and off-peak traffic conditions. On the south side of the street canyon, a

reduction of up to 8% was measured on the SW section of the footpath and an increase of up to 2% was calculated on the SE footpath. The results were similar on these sections of the footpath (maximum 2% difference) in both peak and off-peak traffic times.

In perpendicular wind conditions, the results displayed improvements in air quality on the northern footpath compared to the parked car scenario. The results showed small improvements in air quality of up to 3% and a deterioration of 2% on the NW footpath for peak and off-peak traffic conditions, respectively. More significant reductions ranging from 16% to 19% were calculated on the NW footpath section in peak and off-peak traffic conditions. Increases of up to 21% and 25% were calculated in peak and off-peak traffic on the SW footpath. A reduction of up to 5% occurred on the SW footpath in peak traffic conditions, with up to a 6% increase occurring in off-peak traffic conditions. Similar results were observed on both footpaths (average difference of 7%) for both peak and off-peak traffic conditions.

In the predominant wind models, the results displayed increases and reductions in pollutant concentrations on the northern footpath compared to the parked car scenario. The results showed deteriorations in air quality of up to 5% on the NW footpath for peak and off-peak traffic conditions. An increase in pollutant concentrations of up to 3% was calculated on the NW footpath section in peak traffic, yet a 5% improvement in air quality was measured in off-peak traffic conditions. Reductions of up to 7% and 36% were calculated in peak and off-peak traffic on the SW and SE footpaths, respectively. Similar results were observed on both sections of the southerly footpath (differences of 2% and 7%) between both peak and off-peak traffic conditions.

6.5.3 PARKED CARS & LBW MODEL

The model included a footpath LBW on the south side of the canyon and parked cars on the north side of the canyon. The results for the percentage difference in pollutant concentrations in the combined passive control model for Pearse Street in different wind conditions are shown in Table 6.15.

The results displayed reductions and increases in pollutant concentrations on the footpaths due to the introduction of both the parked cars and footpath LBW in parallel wind conditions. The combined passive control models displayed predominant improvements in air quality on the footpaths with the exception of a small increase in pollutant concentrations on the SW section of the footpath. The results showed improvements in air quality of up to 25% and 49% in peak traffic conditions on the NW and NE footpaths, respectively. In off-peak conditions, the improvements in air quality were much smaller with reductions of up to 15% and 20% measured on the NW and NE sections of footpath, respectively. An increase of up to 4% was calculated on the SW footpath and a reduction of up to 14% occurred on the SE footpath. Similar results were observed on the southerly footpath (maximum 2% difference in results) for both peak and off-peak traffic conditions.

TABLE 6.15. PERCENTAGE DIFFERENCE IN POLLUTANT CONCENTRATION BETWEEN REFERENCE AND LBW/CARS MODEL AT PEAK (P) & OFF-PEAK (O) TIMES FOR DIFFERENT WIND DIRECTIONS.

Predominant Wind Direction	Traffic	Footpath Monitor Location			
		NW	SW	NE	SE
Parallel	Peak	22-25%	(3-4%)	44-49%	13-14%
	Off-Peak	14-15%	(1-3%)	17-20%	13-14%
Perpendicular	Peak	(10-11%)	(38-44%)	(19-20%)	50-51%
	Off-Peak	6-7%	(41-42%)	(27-28%)	41-43%
Predominant	Peak	1-2%	(3-4%)	19-22%	36-38%
	Off-Peak	(1-2%)	(5-6%)	13-14%	34-35%

Note: Negative percentage differences in pollutant concentrations are indicated by values in brackets.

The results of the perpendicular wind speed model displayed increases of up to 11% and 20% on the NW and NE footpaths in peak traffic conditions. In off-peak traffic conditions, an increase of up to 7% and a further reduction of up to 28% were noted on the NW and NW section of footpath, respectively. On the south side of the street canyon, a reduction of up to 44% was measured on the SW section of the footpath and an increase of up to 51% was calculated on the SW footpath. The results were similar on these sections of the footpath in both peak and off-peak traffic times. The parked car model scenario presented very similar patterns of results to the footpaths to the combined passive control model.

The results of the predominant wind models displayed a majority of reductions in pollutant concentrations, with some small increases in the combined passive control models. The results showed improvements in air quality of up to 2% and 22% on the NW and NW sections of footpath for peak traffic conditions. An increase in pollutant concentrations of up to 2% on the NW footpath and a reduction of up to 14% was calculated on the NW footpath in off-peak traffic. An increase in pollutant concentrations of up to 6% was calculated on the SW footpath and an improvement in air quality on the SE footpath of up to 38% was calculated in different traffic conditions. Similar results were observed on both sections of the southerly footpath (maximum difference of 3%) between both peak and off-peak traffic conditions.

6.5.4 EFFECTS OF PASSIVE CONTROLS ON AIR QUALITY

The effectiveness of passive control varies with wind and traffic conditions over time. Therefore, based on the results from the individual passive control investigations, the improvements or deteriorations in air quality have been quantified for a 1-year period, based on counts of pedestrian traffic numbers on a street adjacent to Pearse St. Table 6.16 displays these differences for the passive control models based on an individual respiratory rate of 1.5 m³/hr for walking/light exercise (ICRP, 1994).

Passive Control Model	Reductions in Personal Pollutant Exposure on Footpaths			
	NW	SW	NE	SE
Parked Cars Model	(1.7)	12.6	16.2	7.4
LBW Model	(10.6)	(2.7)	(4.6)	4.0
Parked Cars & LBW Model	8.2	(23.4)	27.5	15.6

Note: Increases are indicated by values in brackets.

The results shown in Table 6.16 made several assumptions due to the variations in pollutant concentrations with the ever-changing traffic and meteorological conditions. The average wind speed and direction were noted in Section 6.3.3 as 2.5 m/s and 290°, respectively. Approximately 75% of the cumulative measured wind parameters fell within ±1.0 m/s and ±30° of these values. Therefore, the parallel and predominant wind data sets were weighted against the perpendicular results to calculate the improvements or deteriorations in air quality on the footpaths for each individual walking along the footpath. Assumptions were made that an average of 5000

pedestrians and 21,000 vehicles used Pearse Street every day, based on approximations of the data collected over the monitoring period.

The results demonstrated the potential reductions/increases in personal exposure due to the implementation of the different passive controls for each individual who walks along the footpaths. The results identify that the parked cars model provided the best overall conditions in comparison to the other passive control models. Reductions of 14.5 and 20.0 $\mu\text{g}/\text{m}^3$ were calculated for pedestrians walking on the north (NW and NE) and south (SW and SE) footpaths, respectively. The LBWs presented less comprehensive reductions on both footpaths in most wind conditions and the combined passive control model presented more extreme range of percentage reductions and increases in pollutant concentrations on the footpaths.

6.6 DISCUSSION

The results for the Pearse Street models are discussed in this section. The results identified changes in air quality of the footpaths due to the implementation of the parked cars and/or LBWs in the canyon. This section will discuss the results findings and highlight the potential of LBWs and/or parked cars as passive controls in a real street canyon.

6.6.1 PARKED CARS MODEL

The inclusion of parked cars as a passive control in the Pearse Street model was aimed at directly assessing the current parking regime in place on the street. This was to identify the positive or negative impacts the parking bays had on pollutant dispersion at street level and air quality on the footpaths. The model assumed full parking occupancy of the parking bays, yet the parked cars only accounted for 29% of the full length of the canyon. The three wind direction models displayed changes in air quality due to the introduction of the parked cars for different traffic conditions. Table 6.17 summarises the percentage distribution of traffic emissions across the street which can be used to gain a better understanding of the changes in pollutant concentrations on the footpaths in the reference and passive controls models.

The primary difference between the peak and off-peak traffic is the significant difference between the fractions of traffic in L4. This difference is due to the parking in L4, reducing the width of the lane as an effective lane for driving is generally chosen to be not feasible for most drivers. In addition, the parking bays do not generally have 100% occupancy in peak traffic times and the results provide a best case scenario in the results. However, a fully occupancy rate is not permitted due to current parking restrictions in Pearse Street during the day.

TABLE 6.17. PERCENTAGE TRAFFIC LANE DISTRIBUTION FOR AVERAGE PEAK & OFF-PEAK TRAFFIC CONDITIONS.

Traffic	Traffic Lane Distribution*			
	L1 ^a	L2	L3	L4
Peak	10%	38%	34%	18%
Off-Peak	14%	43%	40%	3%
Difference	4%	5%	6%	(15%)

Note: Negative percentage differences are indicated by values in brackets.
* Lanes 1 to 4 defines as L1 to L4.
^a Bus Lane.

The plots in this section represent emissions from only one of the lanes, in this case L3. The plots represent a fraction of emissions from the street canyon and the pollutant dispersion patterns at street level. The 6% difference between the percentage in traffic between peak and off-peak traffic times in Lane 3 has also been taken into account and the plots adjusted to display the same conditions for both plots. However, the plots provide a useful visual representation of the typical air flow and pollutant dispersion patterns between the street and the footpath in the canyon. Figure 6.30 to Figure 6.34 display the results from the parked car models in different wind conditions. Figure 6.30 illustrates the pollutant dispersion patterns on the west side of Pearse Street for the reference and parked cars models in parallel wind conditions.

The introduction of parked cars caused both improvements and deteriorations on the sections of footpath in parallel wind conditions as it altered the natural air flow patterns on the canyon floor. Figure 6.30 illustrates the dispersion of pollutants in the reference and parked car model on the west side of the canyon. The parked cars do not provide a continuous boundary between the road and northern footpath. The model displayed improvements in air quality of up to 19% and 6% on the NW footpath with

the introduction of the parked cars for peak and off-peak traffic conditions, respectively.

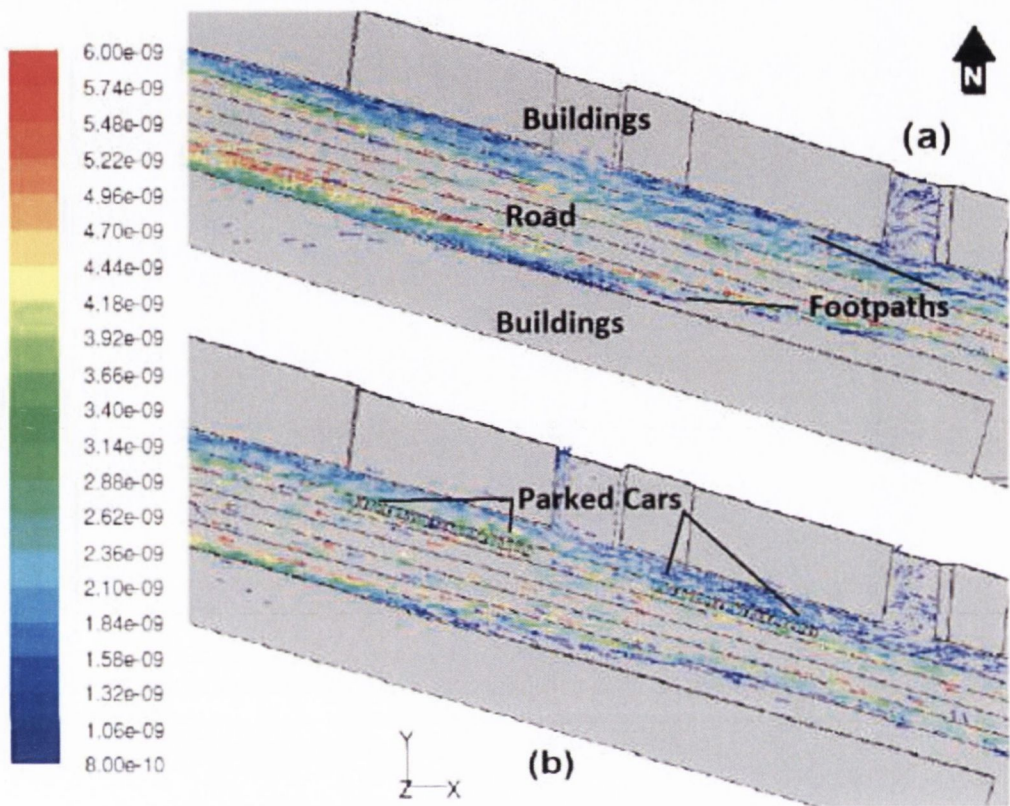


FIGURE 6.30. VELOCITY VECTOR PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M³) ON WEST SIDE OF THE CANYON FOR THE (A) REFERENCE AND (B) PARKED CARS MODELS AT A WIND SPEED OF 2.5 M/S IN PARALLEL WIND CONDITIONS (GALLAGHER ET AL., 2013).

These results resemble the findings of the previous investigation by Gallagher et al. (2011), with the primary difference between the results due to the percentage lane distribution of traffic in the street. The shift of traffic to the other lanes as the volume of traffic in Lane 4 reduced significantly (see Table 6.17) for off-peak times coincided with a reduction in the efficiency of the parked cars as a passive control. The air quality along the SW section of footpath improved by between 4% and 6% in peak and off-peak traffic conditions for parallel wind conditions. The parked cars increased dispersion at street level and no significant difference was noted between the two traffic scenarios as the traffic lane distribution did not affect air flow in this region of the street. The air flow patterns of pollutant concentrations on the east side of Pearse Street are shown in contour format in Figure 6.31 for the reference and parked cars models in parallel wind conditions.

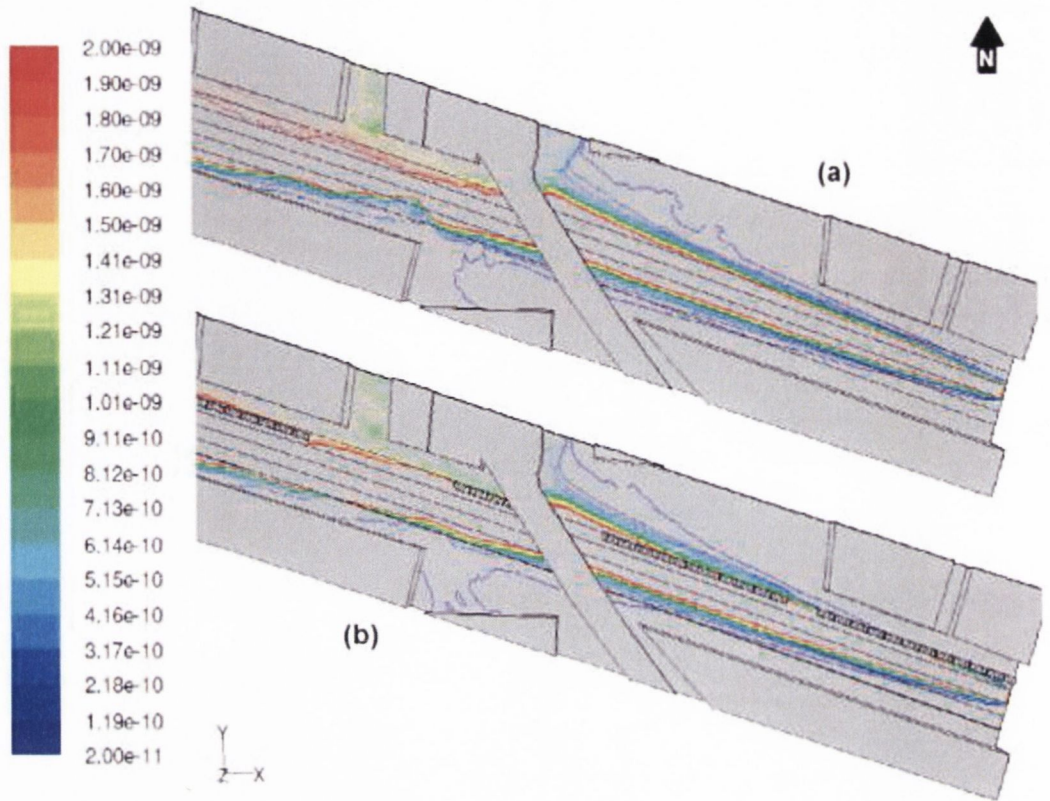


FIGURE 6.31. CONTOUR PLOTS OF POLLUTANT CONCENTRATIONS (kmol/m^3) ON EAST SIDE OF THE CANYON FOR THE (A) REFERENCE AND (B) PARKED CARS MODELS AT A WIND SPEED OF 2.5 M/S IN PARALLEL WIND CONDITIONS.

The east side of the canyon displayed mixed results for air quality on the NE and SE footpath sections. The parked cars on the north side of the street provided a more continuous boundary (51% of section length) compared to the west side of the canyon. On the NE section of footpath, the results displayed a significant reduction in the pollutant concentration of up to 53% in peak traffic and a small increase in off-peak traffic of up to 4%. The parked cars provided an effective boundary wall for the peak traffic condition as it reflected the high pollutant concentrations emitted from Lane 4 unlike the off-peak traffic scenario. An increase in pollutant concentrations of up to 14% on the SE section of footpath was observed for the peak and off-peak traffic conditions. The parked cars increased dispersion at street level and counteracted the shift of traffic distribution between the lanes. Figure 6.32 displays the pollutant concentration for the parked cars model in perpendicular wind conditions.

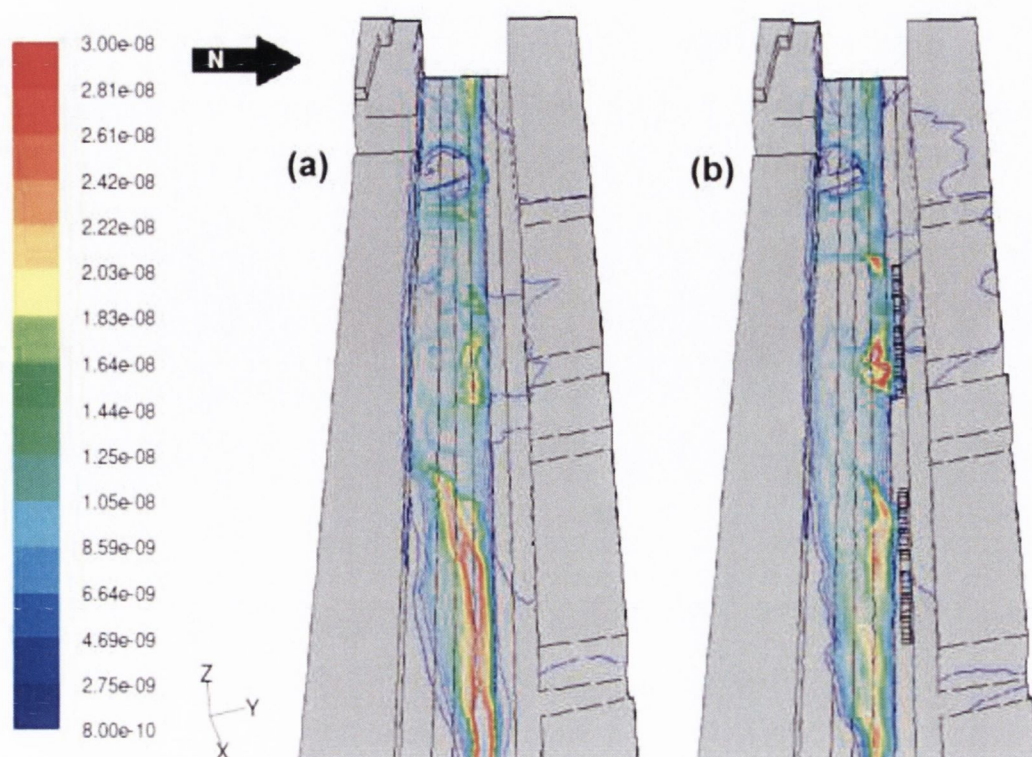


FIGURE 6.32. CONTOUR PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M^3) ON WEST SIDE OF THE CANYON FOR THE (A) REFERENCE AND (B) PARKED CARS MODELS AT A WIND SPEED OF 2.5 M/S IN PERPENDICULAR WIND CONDITIONS.

An increase in pollutant concentrations was measured on the NW (right) and SW (left) sections of footpath. The perpendicular wind travelled from left to right (+Y direction) above the canyon and from right to left (-Y) in the canyon. The parked cars led to an increase in pollutant concentrations of up to 15% on the NW footpath in peak traffic conditions, yet and an improvement in air quality of up to 15% in off-peak traffic. The traffic distribution clearly influenced the effectiveness of the parked cars in perpendicular wind conditions. On the SW section of footpath, the results displayed a significant increase in the pollutant concentration of up to 40% in peak and off-peak traffic. The parked cars reduced the development of the primary vortex in the 2.5 m/s wind speed in the canyon. Therefore, a larger fraction of pollutants were transported towards the SW footpath rather than out of the canyon in the primary vortex. Figure 6.33 displays the pollutant concentration for the reference and parked cars models on the east side of Pearse Street in perpendicular wind conditions.

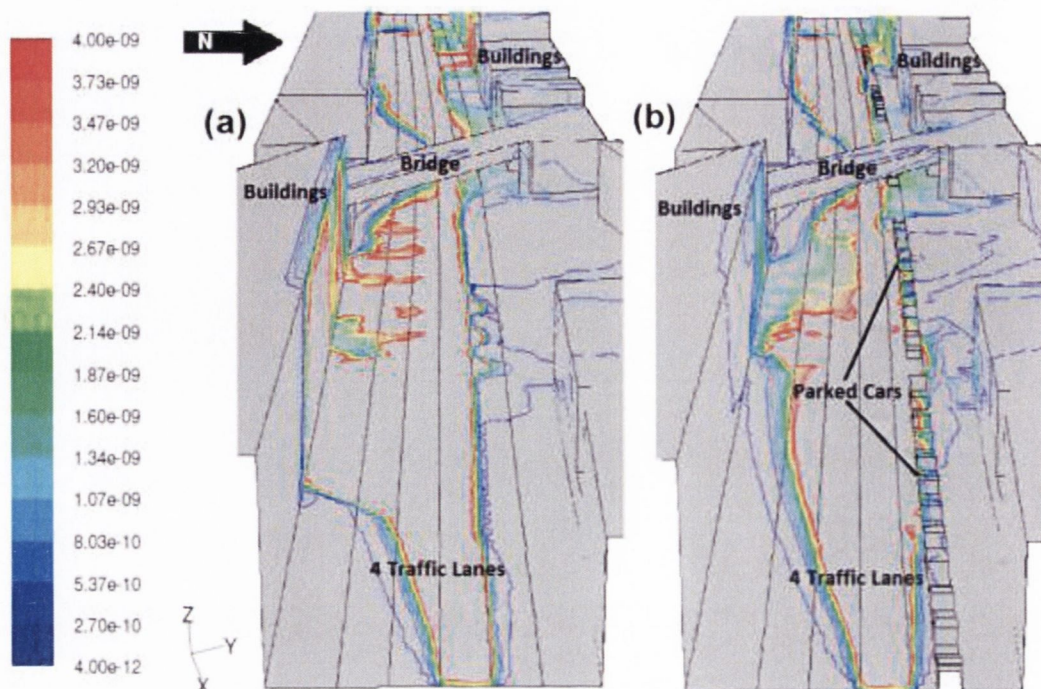


FIGURE 6.33. CONTOUR PLOTS OF POLLUTANT CONCENTRATIONS (kmol/m^3) ON EAST SIDE OF THE CANYON FOR THE (A) REFERENCE AND (B) PARKED CARS MODELS AT A WIND SPEED OF 2.5 M/S IN PERPENDICULAR WIND CONDITIONS (GALLAGHER ET AL., 2013).

On the east side of the canyon, improvements and deteriorations in air quality were noted on the east side of the canyon with the introduction of the parked cars in perpendicular wind conditions. Increases in pollutant concentration of up to 24% and 36% were calculated on the NE footpath in peak and off-peak traffic conditions, respectively. The results displayed a significant reduction in the pollutant concentration of up to 52% and 43% on the SE footpath in peak and off-peak traffic, respectively. The change in traffic distribution in the street from peak to off-peak traffic caused deteriorations in air quality on both footpaths. Due to the large building void on the northern side of the canyon models, the air flow which travelled perpendicular to the traffic lanes changed from a skimming flow to an isolated roughness flow (Oke, 1988). This open area created a different air flow pattern in perpendicular wind conditions and causes an increased fraction of pollutant to be transported away from the SE footpath and towards the NE footpath. The patterns of pollutant dispersion in the predominant wind direction on Pearse Street are presented in Figure 6.34.

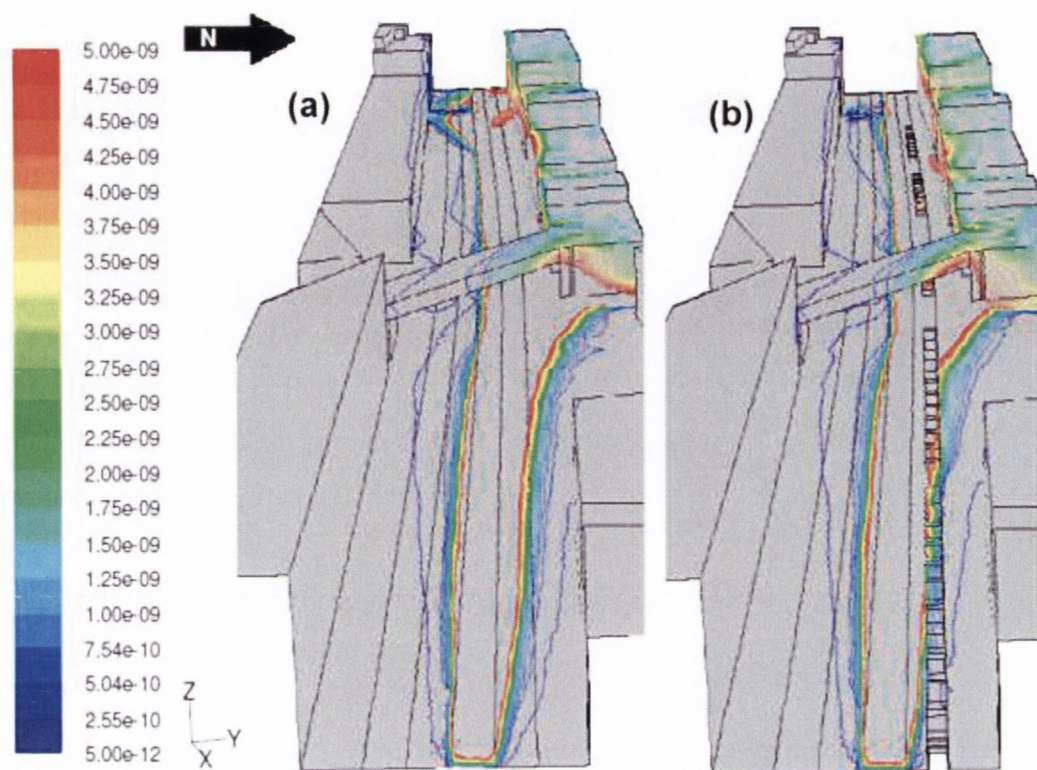


FIGURE 6.34. VELOCITY VECTOR PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M^3) IN CANYON FOR THE (A) REFERENCE AND (B) PARKED CARS MODELS AT A WIND SPEED OF 2.5 M/S IN PREDOMINANT WIND CONDITIONS.

The air quality on the footpaths on the west side of the canyon (the distant section of Figure 6.34) in predominant wind conditions showed consistent improvements in air quality on the footpaths with the introduction of the parked cars. Small reductions of up to 1% and 5% were calculated for the NW section of footpath in peak and off-peak traffic conditions, respectively. The direction of the wind in this model directed pollutants towards the northern side of the street and the low fraction of parking bays in the zone led to only a small improvement in air quality. However, the parked cars did channel the wind along the canyon and reduced lateral dispersion. This led to an improvement in air quality on the SW section of footpath by up to 22% in both peak and off-peak traffic conditions. The east side of the canyon showed improvements in air quality of between 18% and 26% on the NE section of footpath and between 15% and 22% on the SE footpath for different traffic distributions across lanes. The predominant wind direction transported pollutants in the street towards the north side of the street and the parked cars then channelled the pollutants along the street. The parked cars can potentially improve air quality on the footpaths for predominant wind conditions in Pearse Street.

6.6.1.1 COMPARISON OF PEARSE STREET PARKED CARS RESULTS TO PCM STUDY

The findings of this passive control model in comparison to the parked cars study in Chapter 4 displays some differences for parallel, perpendicular and predominant wind conditions. Despite the parked cars being introduced on the north side of the canyon, differences in the measured pollutant concentrations were observed on both footpaths. It was also observed that the alignment of Pearse Street had a small curvature to the left, thus air flow naturally transported pollutants towards the north side of the street.

In parallel winds, the results compared well between the Pearse Street model and the parked cars modelling (PCM) study based on similar parking bay occupancy rates. On the NW section (25% occupancy) of footpath, an average reduction of 12% was calculated for the Pearse Street model and compared closely to the 14% reduction in the PCM study. This small difference was noted to be due to the difference in patterns of parked cars placed along the section on street; the random non-continuous pattern of parked cars in the PCM study compared to the section of parked cars in the Pearse Street model. An average reduction of 27% was calculated on the NE footpath (58% occupancy) which compared well to a similar approximate reduction of 20% in the PCM study. The cars were more effective as an air pollution control along the NE footpath in both the Pearse Street and PCM investigations as the higher parking occupancy rate provided a more continuous barrier between the road and the footpath. The results suggest that similar improvements or deteriorations in air quality can be achieved regardless of the configuration (random or segmented) of parked cars within the parking bays. A reduction of 5% on the SW footpath and an increase of 14% on the SE footpath were calculated in the Pearse Street model. The differences in pollutant concentrations along the south side of the street were considered to be due to the changes in air flow and pollutant dispersion patterns at street level associated with the introduction of the parked cars on the adjacent side of the street.

The results were also compared to the PCM study on the north (windward) footpath in perpendicular wind conditions, as the parked cars trapped clean air on the footpath in the Pearse Street model. On the NW section of footpath, an average reduction of 3% was calculated between peak and off-peak traffic conditions, yet a notable increase of 29% was calculated on the NE section of footpath. In comparison to the PCM study results on the windward footpath, a similar low percentage reduction of 8% was

measured on the NW section of footpath. This section of street has a similar symmetric canyon layout, with the exception of two small side roads, which was responsible for the small difference in the effectiveness of the parked cars in the Pearse Street model. A reduction of approximately 22% was noted from the PCM study in comparison to the results from the NE section of footpath. The improved conditions in the Pearse Street model was due to three main factors which influenced air flow in the street: (i) the bridge, (ii) non-symmetric layout as asymmetric ratios of 0.9 and 0.5 on the west and east side of the canyon and (iii) open area along NE section on model. Each of these elements alters the development of the primary vortex and additional pollutants are transported away from the footpath. Substantial differences in pollutant concentrations were measured on the south footpath in perpendicular wind conditions, as an increase of 38% was noted on the SW section of footpath and a 47% reduction on the SE footpath. The differences between the results from the two sections of footpath were due to the distinctive geometrical differences of the canyon; the air flow behaved like in a symmetric canyon on the west side of the Pearse Street model and an asymmetric canyon on the east side of the canyon.

In predominant wind conditions, reductions in the pollutant concentration of 3% and 22% were measured on the NW and NE sections of footpath, respectively. Reductions of 21% and 19% were also noted on the SW and SE sections of footpath. The parked cars in the Pearse Street model acted as an effective baffle to pollutants being carried along the centre of the canyon. The predominant wind direction travelled 15° off the parallel wind direction and pollutants were transported across the canyon in the direction of the parked cars. Therefore, the pollutants were evidently deflected off the parked cars and concentrated air was transported along the road and reductions in pollutant concentrations occurred on all section of the footpath.

Overall, the parked cars in the Pearse Street model influenced air flow and pollutant dispersion in a similar manner to the PCM study. The primary difference between the results of the two modelling investigations was due to the geometrical variability of the Pearse Street model.

6.6.2 LBW MODEL

The LBW model included boundary walls along both sides of the canyon with gaps for road junctions and bus stops. Therefore, the results were expected to be realistic of the maximum difference that could be expected in Pearse Street upon implementing the LBWs and removing the parking bays in the canyon. Figure 6.35 to Figure 6.38 shows the dispersion of pollutants in the Pearse Street canyon model for the LBW models in different wind conditions. Figure 6.35 displays the plots of the west section of the LBW model in parallel wind conditions.

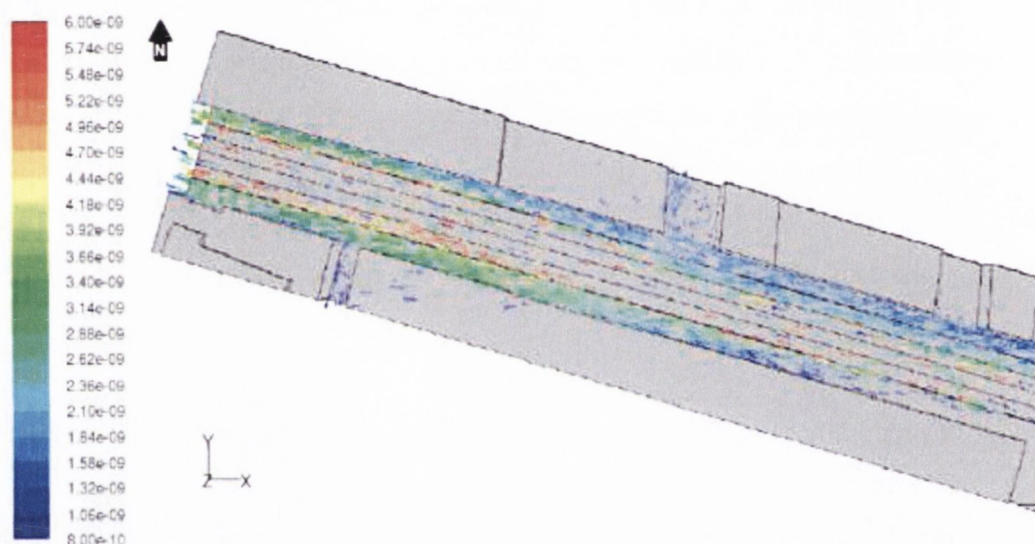


FIGURE 6.35. VELOCITY VECTOR PLOTS OF POLLUTANT CONCENTRATIONS (kmol/m^3) ON WEST SIDE OF THE CANYON FOR THE LBWs MODEL AT A WIND SPEED OF 2.5 m/s IN PERPENDICULAR WIND CONDITIONS.

The 0.5 m LBW displayed improvements and deteriorations in air quality on the west sections of the north and south footpaths in parallel wind conditions. Unlike the parked car model, the results show no significant difference for the percentage difference in pollutant concentrations between peak and off-peak traffic distributions. The wind transported pollutants along the street canyon and increases in pollutant concentrations of between 19% and 22% were calculated on the NW section of footpath. In contrast, an improvement in air quality of between 5% and 8% was noted on the SW footpath as the LBW provided a baffle to pollutants from the road. The LBWs trapped air on the footpaths causing a change in the pollutant concentrations. The increase on the NW footpath and decrease on the SW footpath was due to the channelling of the wind towards the NW footpath. This direction was caused by the

slight change in orientation of Pearse Street at the midpoint of the street. The patterns of pollutant dispersion at street level on the east side of the street for the LBWs model are shown in Figure 6.36.

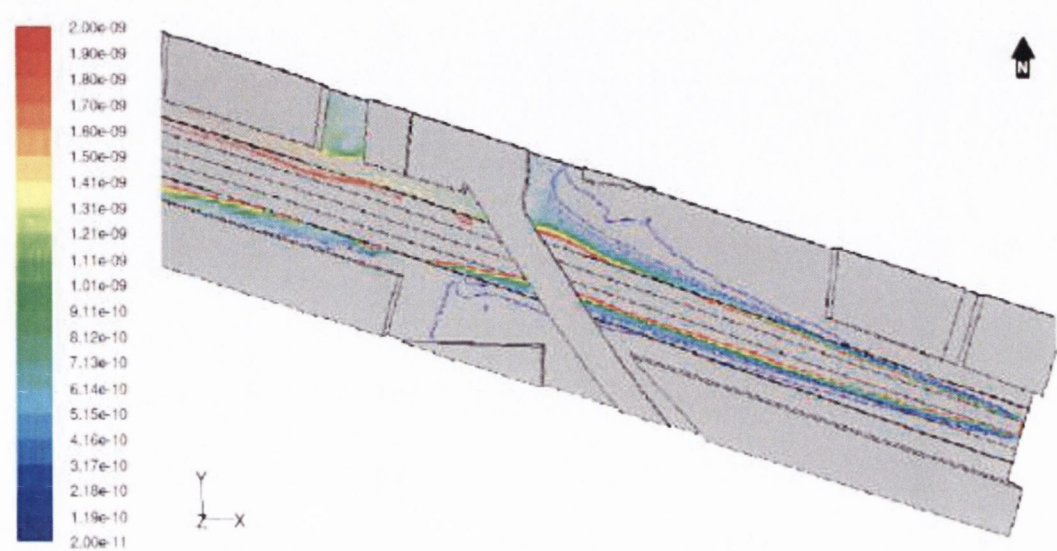


FIGURE 6.36. CONTOUR PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M³) ON EAST SIDE OF THE CANYON FOR THE LBWs MODEL AT A WIND SPEED OF 2.5 M/S IN PARALLEL WIND CONDITIONS.

The air quality on the footpaths on the east side of the canyon showed small deteriorations in air quality with the introduction of the footpath LBWs. An increase of up to 9% and 2% was calculated on the NE and SE footpaths, respectively. The pollutant concentrations increased on the footpaths as pollutants were transported over the wall as air travelled along the canyon and were trapped on the footpaths. The difference between air quality in the peak and off-peak models was due to the shift of traffic between lanes, but did not display a notable influence on the performance of the LBWs. The pollutant concentration in the LBWs model with perpendicular wind conditions is displayed in Figure 6.37.

On the west side of the canyon (Figure 6.37), increases and reductions were observed on the footpaths. A small reduction of up to 3% in the pollutant concentrations was measured on the NW sections of footpath in peak traffic, with an inverse increase of 2% in off-peak traffic conditions. The SW footpath demonstrated potential increases in pollutant concentrations of up to 21% and 25% in peak and off-peak traffic, respectively. The LBW does not provide an effective passive control on the SW

footpath as the NW LBW trapped pollutants in the street and the wind brought an increased fraction towards the SW footpath.

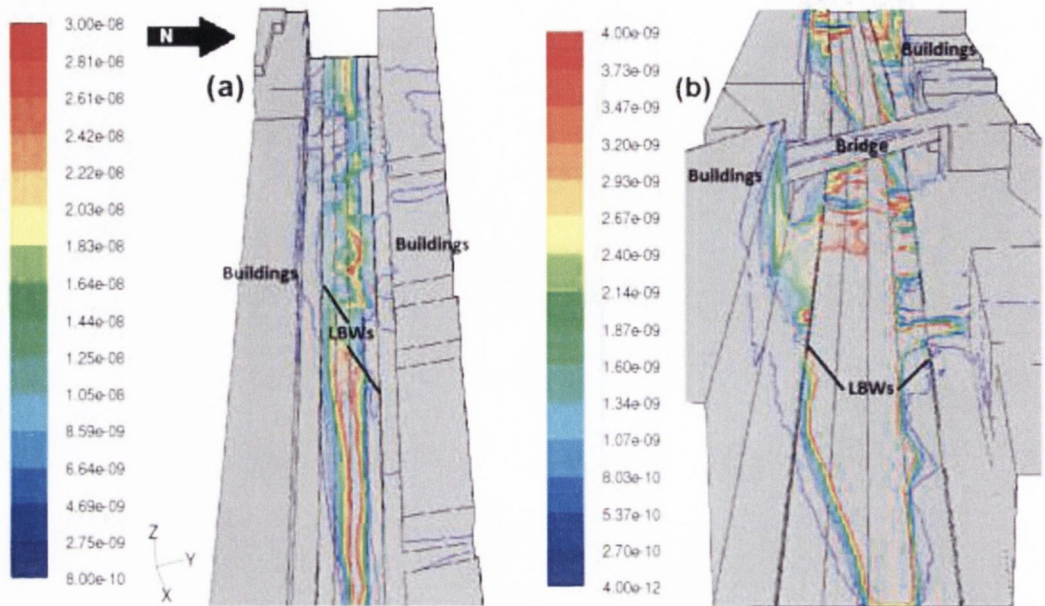


FIGURE 6.37. VELOCITY VECTOR PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M^3) ON (A) WEST AND (B) EAST SIDES OF THE CANYON FOR THE LBWs MODEL AT A WIND SPEED OF 2.5 M/S IN PERPENDICULAR WIND CONDITIONS (GALLAGHER ET AL., 2013).

The air quality on the footpaths on the east side of the canyon showed improvements in air quality with the introduction of the footpath LBWs for peak traffic conditions. Reductions of up to 17% and 5% were calculated on the NE and SE footpaths, respectively. The LBWs channelled the polluted air along the centre of the canyon, improving air quality on the footpaths. A similar reduction of up to 19% was measured on the NE footpath in off-peak conditions, yet a deterioration in air quality on up to 6% was noted on the SE section of footpath in similar off-peak traffic. The shift of traffic distribution between lanes, notably the distribution of the 15% of traffic from Lane 4, allowed for more pollutant to be released closer to the southern side of the canyon and subsequently transported over the LBW. Figure 6.38 displays the patterns of pollutant dispersion in the canyon for the LBW passive control model.

The LBW displayed a small increase in the pollutant concentrations of up to 5% on the NW footpath and a reduction of up to 7% on the SW footpath. The off-peak traffic conditions did not significantly influence air quality on the footpaths as the LBWs provided similar changes in pollutant concentrations with the alternate distribution of

traffic in the street. The wind direction produced lateral dispersion above the LBWs and thus no significant improvements in air quality were found for the predominant wind model in the west side of the canyon.

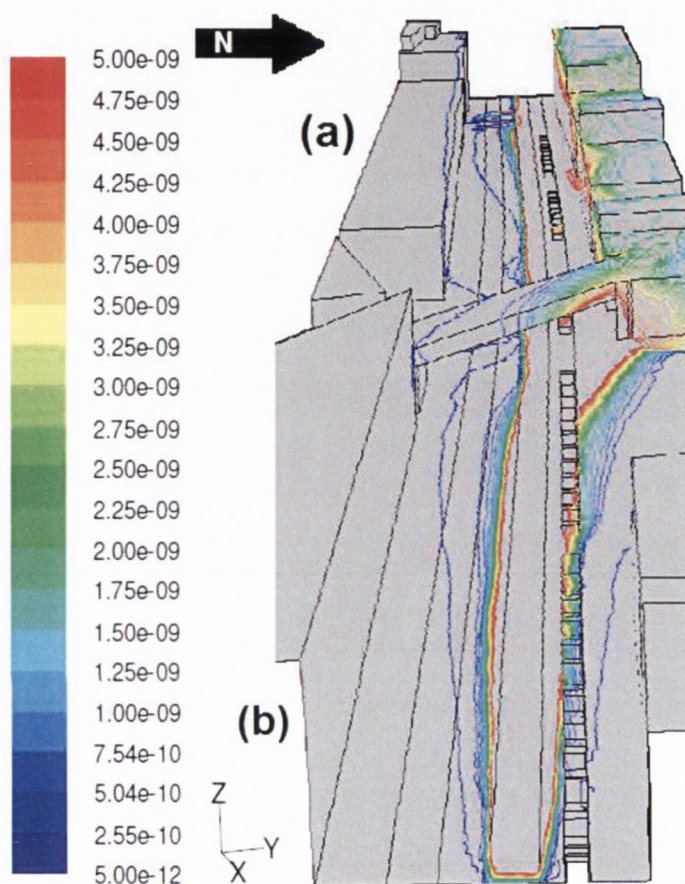


FIGURE 6.38. VELOCITY VECTOR PLOTS OF POLLUTANT CONCENTRATIONS (KMOL/M^3) ON (A) WEST AND (B) EAST SIDES OF THE CANYON FOR THE LBWs MODEL AT A WIND SPEED OF 2.5 M/S IN PREDOMINANT WIND CONDITIONS.

The air quality on the NE section of the footpath marginally changed from a maximum 3% increase in pollutant concentrations in peak traffic to a 5% reduction in off-peak traffic. On the SE footpath, the predominant wind direction and LBW provided an effective passive control with reductions of up to 36% and 31% in peak and off-peak traffic, respectively. The LBW trapped clean air on the SE section of footpath creating a zone of clean air in the street. Overall, the LBWs did not provide a convincing passive control in most footpath sections, with the exception of the SE section.

6.6.2.1 COMPARISON OF PEARSE STREET LBW RESULTS TO ASYMMETRY STUDY

The LBW passive control model of Pearse Street was compared to the asymmetric canyon study in Chapter 5 to compare the effectiveness of the boundary walls in both models for perpendicular wind conditions. The comparison of results for the Pearse Street model and the asymmetric study aims to demonstrate the influence of street geometry on air flow and pollutant dispersion.

The results from the Pearse Street model were compared with the asymmetry study on both the north (windward) and south (leeward) footpaths (based on the perpendicular wind coming from a southerly direction). A small reduction in the pollutant concentration of 1% was calculated on the NW section of footpath, with an increase of 19% on the SW footpath in the Pearse Street model. The results from the asymmetry study displayed a more substantial reduction on the NW footpath of 30% and a 5% reduction on the SW footpath. A 35% reduction was noted in the asymmetry study in comparison to an 18% reduction in the Pearse Street model on the NE section of footpath. On the SE footpath, a 1% increase was noted in the Pearse Street model with an 8% reduction measured in the asymmetry study. The LBWs in the Pearse Street model did not perform as well overall at any of the footpath sections in the asymmetry study. These differences were considered to be due a combination of (i) the non-continuous nature of the LBW in the Pearse Street model (due to gaps required at junctions) and (ii) the lower wind speed used in the Pearse Street model which reduced the strength of the primary vortex in the canyon. This questions the feasibility of LBWs as an effective passive control where the wall is not continuous along the full length of the canyon.

6.6.3 PARKED CARS & LBW MODEL

The combination model including a LBW and parked cars aimed at retrofitting the street with a LBW on the south side of the canyon, in addition to the parked cars on the north side of the canyon. The combination of the LBW and parked cars provided similar patterns of results to the parked cars scenario in different wind conditions, with a mix of reductions and increases in pollutant concentrations on the footpaths.

6.6.3.1 COMPARISON OF COMBINED PASSIVE CONTROL RESULTS TO PCM STUDY

The findings of the combined passive control model in comparison to the previous investigations displays some differences for varying wind conditions. Air quality was compared on the footpaths between the combined passive control model and the PCM study, with the percentage difference in air quality on the south footpath compared to the asymmetry study. In parallel wind conditions, the combined passive control model displayed the best overall reductions in pollutant concentrations. An average percentage reduction of 16% was calculated for the combined passive control model compared to an average reduction of 7% in the parked cars model and an average 5% increase in the LBW model. The results also showed similar results in all three passive control models for perpendicular wind models, with average increases in pollutant concentrations ranging from 1% to 5% on the footpaths. In the predominant wind direction, the parked cars and combined passive control model displayed average reductions of 16% and 12%, respectively, with the LBW model demonstrating an average 25% reduction of air pollutants on the footpaths. The combined LBW and parked cars in the Pearse Street model provided the greatest overall percentage reduction in pollutant exposure on the footpath.

6.6.4 EFFECTS OF PASSIVE CONTROLS ON AIR QUALITY

The Pearse Street study has investigated a series of different passive control layouts and determined that each form of passive control uniquely influences air flow and pollutant dispersion in the street canyon. The building layout in Pearse Street varies significantly compared to the previous investigations and the differences in results are primarily related to these differences in canyon geometry. However, similarities were noted between the results for the previous studies and the Pearse Street model, therefore it allows for passive controls to be assessed in generic modelling investigations and transposed in real street canyons such as Pearse Street.

The different passive control configurations demonstrated benefits and shortcomings in different wind conditions. Despite the combined passive control model displaying the best results on some of the footpaths, the parked cars study demonstrated more steady percentage reductions on both footpaths and during peak traffic times, which typically coincides with peak pedestrian traffic. The results suggest that the current

parking regime, when the parking bays are fully occupied, provide the optimal passive control layout on Pearse Street. The restrictions on parking times in the parking bays do however limit the potential of the parked cars acting as passive controls. The findings of the Pearse Street model provided clear evidence that passive control influence air flow and pollutant dispersion in street canyons. In addition, LBWs and parked cars can provide two distinct options for their implementation as passive controls in any street canyon environment.

6.7 CONCLUSIONS

The Pearse Street modelling investigation developed a calibrated CFD model of a real street canyon in Dublin city centre and effectively assessed the potential of passive controls in a real world environment. The following conclusions summarise the findings of the results and discussion sections of the Pearse Street model.

Calibration data were collected from several sources to evaluate each data set prior to the model calibration process. The calibration of the CFD model was carried out using geometrical data for Pearse Street, measurement of NO_x concentration in the street, traffic counts and meteorological data. A detailed analysis was carried out for the calibration data to independently evaluate each dataset. The CFD model was calibrated in two steps (i) wind speed and direction and (ii) NO emission dispersion.

A semi-empirical equation was developed to calibrate the CFD model for the second calibration step. The equation took into account the complexities and variability in traffic and meteorological conditions, which the CFD model simplified for the purpose of investigating the potential of the passive controls in the street canyon. The semi-empirical equation was used to calibrate the model for three different wind directions: the predominant wind direction ($\sim 300^\circ$), parallel ($\sim 286^\circ$) and perpendicular (196°) winds. The equation took into account the variables which the CFD model could not include; lane distribution of traffic, vehicle type, vehicle NO emissions rate, vehicular speed and vehicular turbulence.

The Pearse Street model introduced three passive control forms; (i) a parked cars model, (ii) footpath LBWs model and (iii) a combined parked cars and LBW model.

Each of the three passive control investigations displayed different percentage reductions and increases in pollutant concentrations on the footpaths. The results compared well in comparable scenarios to the previous two generic modelling studies, namely the parked cars modelling study and the asymmetric street canyon study. Differences in the results between the Pearse Street model and the other investigations was determined to be due to differences in (i) the occupancy rates of the parked cars, (ii) the gaps in the LBWs and (iii) the variability in the street canyon geometry.

The parked cars model provided the most comprehensive reductions in pollutant concentrations on all sections of footpath in all different wind conditions. However, it was noted that the current parking restrictions in Pearse Street limits parking at specific times of the day reducing the potential improvements in air quality. Therefore, ensuring the parked cars are located in the street at peak traffic and pedestrian times would benefit reducing personal pollutant exposure.

The Pearse Street model provides a real street canyon environment in comparison to the generic modelling investigations in the previous chapters. The study highlighted the effect of variability in street canyon geometry on air flow in a street canyon. The generic investigations assessed the passive control in very controlled environmental conditions and the Pearse Street study dealt with the real complexities of variable air flow and traffic conditions which are common in a real urban street canyon. The findings demonstrated that passive controls affect air flow in street canyons and the results echoed that the primary influencers of pollutant dispersion are street geometry and wind conditions. The similarities and differences between the generic and Pearse Street studies demonstrate the level of confidence which can be taken from some generic studies, however these are not accounting for the variability of building heights, irregular traffic flows and variable wind direction and speed. Thus, the study suggests more investigations are required to provide a more inclusive knowledge base for real world applications of passive controls. This may require monitoring and modelling a number of case studies, which could be considered representative of the range of the conditions (i.e. street size and shape, wind conditions etc.) and these results could provide a better understanding of the applicability of passive controls in the urban environment. Overall, the study provided evidence that passive controls

influence air flow and pollutant dispersion in a real street canyon and in some cases, the results compare well with the generic modelling investigations.

7. DISCUSSION

7.1 DISCUSSION

The combined findings from the three modelling investigations are reviewed within this chapter. It provides further evidence for the potential of implementing different types and configurations of passive controls in urban street canyons in specific meteorological conditions.

7.1.1 PARKED CAR MODELLING STUDY

As parked cars are considered a common element in most urban street canyons, this study examined the interaction between air flow in a street and the parked cars at street level to gauge how we might consider introducing a new parking scheme or alter a current parking layout to improve air quality. To summarise, the results found that parallel parked cars provided the most comprehensive improvements in air quality compared to the alternative parking layouts, demonstrating potential improvements in air quality of between 31% and 49% on both footpaths for varying wind conditions. A reduction of up to 27% was measured on the windward footpath in the central parking layout, yet more substantial reductions of up to 41% and 56% were observed in the perpendicular and diagonal parking models, respectively. However, this was counteracted by deteriorations in air quality on the leeward footpath with increases in pollutant concentrations of between 23% and 288% in the other parking layouts. The percentage reductions and increases were noted to be influenced by a number of factors: (i) the wind speed and direction, (ii) the spacing between vehicles and (iii) the orientation of the parked cars. The wind direction influenced the air flow patterns which developed in the canyon and the transport pathways between the road and footpaths. The wind speed influenced the strength of the vortices in the canyon, but also influenced the ratio of pollutants which were transported out of the canyon to the pollutants which were recirculated in the canyon. The magnitude and frequency of the spacing width between vehicles notably affected dispersion conditions as these gaps acted as channels for pollutants to travel between the road and footpaths. The orientation of the vehicles influenced the natural air flow patterns and thus caused different percentage reductions or increases for each of the different parking layouts. The findings clearly suggested that more consideration is required from a planning perspective as to the parking layout decision process to utilise parking bays as a method of protecting urban pedestrians from vehicle emissions.

In reality, full parking occupancy rates in parking bays do not occur instantaneously, nor are they maintained throughout the day. Therefore, there was a need to understand the viability of parking bays as an effective passive control for different parking bay occupancy rates. A further step of the parked car modelling (PCM) study was to assess the effects of different parking bay occupancy rates for the parallel parking layout. The results indicated the reduced efficiency of parked cars as an effective passive control for lower percentage occupancy rates in perpendicular wind conditions. In parallel wind conditions, in particular, the results for parking occupancy rates less than 45% displayed increases in pollutant concentrations on the footpaths as the parked cars channelled and trapped the pollutants on the footpaths. The results from the different occupancy rate models demonstrated the variability in the potential of parked cars as passive controls, which is a factor which urban planners should take into account during the parking layout selection process. The introduction of a new parking bay in a street canyon should be considered only where it is considered necessary and there is adequate demand for parking. A low occupancy rate in a parking bay would lead to deteriorated air quality on the footpaths; therefore, no parking would provide improved air quality conditions in this scenario. This adds another level of complexity to the parking bay selection process and demand for parking is therefore an important consideration. The study identified the need for more real world monitoring studies of this kind of parking scenarios to further develop the knowledge base for parked cars acting as a passive control in urban street canyons.

Reduced parking bay widths and hybrid parking were also considered to reduce the channel widths between vehicles or combine the optimal parking layouts in different meteorological conditions. The reduced parking bay widths improved air quality on the footpaths, yet there is a question arising as to whether this is an acceptable method of improving the potential of parked cars as a passive control. This may affect the minimum acceptable distance required between vehicles for ease of access in to and out of vehicles. The hybrid results considered the best parking configuration on each side of the road as some layouts displayed more significant reductions than others depending on the wind conditions. The results were not as encouraging as expected due to the opposing air flow patterns created across the canyon floor by the opposing parking bay layouts. Considering different parking bay layouts on opposing sides of the road clearly influenced the air flow and pollutant dispersion within a street canyon

and therefore should be noted by urban planners aiming to protect urban pedestrians by implementing parking as a passive control.

The PCM study demonstrated the ability to engineer a street canyon to influence air flow and pollutant dispersion through a street canyon by altering the parking bay layout to achieve improved air quality conditions at street level. Parked cars influence air flow patterns and the pathways for the transport of pollutant concentrations in a street canyon. However, partially occupied parking bays act as a baffle and the pollutants transported to the footpath can be partially impeded in the road and this leads to an inevitable increase in measured pollutant concentrations in the road. In addition, the number of parking spaces available to drivers can influence the level of pollution emitted from a vehicle i.e. the duration spent by a driver locating a parking space could affect the quantity of emissions from that vehicle. Therefore, finding a balance for an optimised parking bay layout is a challenge which requires a detailed understanding of demand for parking in a specific street. In the context of optimal sight distances and providing the safest parking layout, perpendicular parking provides the best conditions in comparison to the other parking layouts. The findings of the PCM study demonstrated conflicting priorities between pedestrian safety and air quality. In addition, to consider introducing new parking bays may cause increased traffic in a street and inadvertently increase pollution, therefore local public transport policy should also be taken into account to ensure street parking is necessary and favourably improves air quality in urban street canyons. Therefore, optimising current parking regimes to reduce pollutant concentrations on the footpaths would be the best way forward for practically adopting the findings of this study as it would require minimal changes to the present layout of any given street canyon.

7.1.2 LBWs IN ASYMMETRIC CANYONS

The purpose of the canyon asymmetry study was to assess the influence of canyon geometry on the effectiveness of low boundary walls (LBWs) as a passive control. Street geometry is one of the most influential parameters on air flow and pollutant dispersion in the urban environment. The results displayed a mixture of percentage improvements and deteriorations in air quality for different asymmetric configurations at low and high wind speed and for two LBW layouts; two footpath LBWs or a single

central LBW. The variability in the percentage differences in pollutant concentrations occurred due to a number of factors: (i) the wind speed, (ii) the asymmetric canyon ratio and (ii) the location of the passive controls. Wind speed influenced the dispersion of pollutant in the canyon and the ratio between the pollutants escaping the canyon at roof level to the pollutants recirculated within the primary vortices. An incremental increase in the asymmetric ratio increased the strength of the vortices which developed within the canyon and subsequently affected the ratio of pollutants escaping the canyon to the pollutants being recirculated in the street. The location of the LBWs at street level also defined the air flow patterns which developed in the canyon.

In particular, the results varied significantly between the two LBW layouts as two distinctive air flow patterns were observed; a single primary vortex developed in the footpath LBW models with two small secondary vortices in the footpath regions, with two primary vortices developing in the central LBW models. For the majority of cases, the footpath LBWs displayed reductions in the pollutant concentrations on the footpaths. On the windward footpath, the clean air transported from roof level in the primary vortex became trapped by the LBW and improved air quality conditions for all asymmetric canyon ratios. However, the air quality on the leeward footpath displayed a mixture of improvements and deteriorations at different monitoring heights due to the vortex strength and its ability to transport pollutants out of the canyon and prevent pollutants being trapped in the leeward zone of the canyon. The development of the vortices in the central LBW models ensured pollutants were transported away from both footpaths and encouraged improvements in air quality on the footpaths at all monitoring heights for all asymmetric canyon ratios. The practical implementation of either LBW configuration in a street canyon poses a number of challenges in a real world scenario. Firstly, the wall(s) present a continuous barrier along the length of the street which may not be feasible, due to the need for allowance of spaces for access to the footpath or other traffic lane in the cases of the footpath LBWs or central LBW, respectively. In addition, the methodology chapter noted that the height of the LBW influenced the percentage difference in pollutant concentrations on the footpaths and an increased height could further improve the potential of the LBWs in certain configurations. This study only investigated the potential of LBWs in perpendicular wind conditions and the scope for further wind

conditions may be required to determine the potential impact of implementing LBWs in a street canyon.

The study additionally reviewed two previously established methods of simulating vehicular emissions, surface and line source, and clearly identified significant differences between both methods. Surface source emissions were considered more suitable than line source emissions as it was more representative of the typical pollutant dispersion pattern in the wake of vehicles. Vehicular dispersion was omitted from these studies to significantly reduce the computational running time of the models. Due to differences in the dispersion patterns from both emission source models, the results from the two sets of models differed significantly. This highlights the need for further analysis of the different source emission models used in air pollution investigations of street canyons.

Previous investigations of LBWs has been limited for the most case to symmetrical canyons; therefore this investigation extends the current depth of knowledge for the implementation of LBWs in asymmetric street canyons, which are considered more representative of a real street canyon layout. The study identified that the strength of the primary vortices is affected by both wind speed and the asymmetric canyon ratio. The variance in the results highlighted the complexities associated with the relationship of local meteorological conditions, street geometry and the LBW configuration. Despite this study assessing canyon asymmetry, the complexity of street geometry can be much greater, as roof shapes, surface roughness and variable buildings heights can provide additional challenges to assessing the potential of passive controls. These factors have all been found to affect air flow and pollutant dispersion within an urban street canyon, yet all add significant demands on the running time of each model. However, in the context of this comparative investigation of passive controls, only the most influential parameters on air flow and pollutant dispersion (wind conditions and asymmetry) were considered.

The complexities of implementing LBWs along the full length of the canyon pose a number of practical implications regarding access between the road and footpath or between the different traffic lanes. Therefore, identifying suitable locations for the

implementation of LBWs needs to be considered as it this significantly influences pollutant dispersion and the air flow patterns which develop in the canyon.

7.1.3 PEARSE STREET MODEL

The previous generic modelling investigations limited the environmental variables which were examined to allow for an extensive series of scenarios to be assessed and to determine relationships which exist between air flow and pollutant dispersion patterns for different meteorological parameters. The Pearse Street measurement and modelling study demonstrated the potential of passive controls in a real street with a more complex geometric and meteorological environment. Therefore, the Pearse Street model aimed to apply the knowledge from the generic modelling studies and gauge the potential of passive controls in a real world street canyon environment through the introduction of parked cars and LBWs.

The investigation took into account a significant quantity of real time data which was collected from multiple sources where possible, to ensure the quality of each of the datasets. The data collected included street geometry, meteorological data, NO concentrations and traffic data. Local wind measurements were compared to several other urban and background sites, manual traffic data were compared to automated SCATS data and the fleet composition and traffic lane distribution was also accounted for. Comparing these data collection methods showed that differences exist between the data sets and required further analysis as these parameters were used for the calibration of the Pearse Street model.

A CFD model was then constructed of a section of Pearse Street and calibrated firstly to local wind measurement data and subsequently to NO emission data collected in the street, which combined the CFD model results with a semi-empirical equation. The adoption of the two stages allowed for a clear step-by-step calibration process and endeavoured that wind conditions were calibrated separately to the pollutant dispersion street model. A poor correlation between the measured pollutant concentrations on the street and traffic counts, demonstrated the need for factors such as fleet composition, lane distribution and vehicular turbulence to be included in the calibration process. Therefore, the output from the models was combined with these

traffic flow parameters using a semi-empirical equation. A series of passive control scenarios were simulated for different wind conditions and the results were extrapolated for different traffic conditions. The use of the semi-empirical equation allowed for the inclusion of a number of factors which had been previously simplified within the generic investigations: variable lane distribution, fleet composition and vehicular turbulence. The comparative results between the generic modelling investigations and the Pearse Street study displayed a good agreement of 76% between the predicted and measured concentrations for varying meteorological and traffic conditions.

The percentage difference in pollutant concentrations was then calculated between the reference and passive control models of Pearse Street for different wind conditions. The study found good agreements between the findings of the generic modelling investigations and the Pearse Street study, in cases where similar meteorological, geometrical and passive control conditions were evident. The Pearse Street study demonstrated the potential application of generic model findings to real world scenarios and the allowance for omitting some parameters in the modelling process without a loss of accuracy in the results. In the context of comparing a reference and passive control model to determine the percentage difference in air quality, the simplified emissions source model used in the generic studies provided similar results to the Pearse Street model. The study also identified the importance of a detailed calibration process and evaluation of collected datasets for street scale models as high quality data is necessary for the best possible model.

7.1.4 POTENTIAL OF PASSIVE CONTROLS

CFD provided a useful tool for the investigation of street scale models. The computational running time for each model was relatively long; therefore a significant amount of time was spent carrying out detailed discretization analyses to minimise the model running time while maintaining a high level of accuracy in the models. The results from each investigation directly compared two model scenarios, which only differed with the inclusion of a passive control in one of the models. The development of new CFD software and faster computers has improved the capabilities of modelling investigations to simulate more complex problems in an acceptable timeframe. The

use of this new software for future passive control investigations (as it considerably reduces the computational running time of CFD simulations) would allow for the investigation of more complex dispersion characteristics to be included in street canyon models.

The studies within this research thesis have only assessed inert gases (CO_2 & SF_6) and Nitrogen Oxide (NO) in winter conditions. The behaviour of each individual pollutant can vary based on its physical properties and the local meteorological conditions in a given street. There is significant scope for further examinations of the dispersion of reactive pollutants, which should include chemical and photochemical reactions in the street canyon models. Particulate pollution has not yet been considered in passive control studies in urban street canyons and requires examination as particulate dispersion can be affected by different processes such as wet or dry deposition, nucleation and coagulation, hygroscopic growth and re-suspension. Within the street canyon, thermal stratification also affects the dispersion of pollutants and should be included in future modelling studies to account for occurrences such as the urban heat island effect. The introduction of multiple pollutants in each model would provide more realistic conditions as reactions between reactive and particulate pollutants could be simulated and which have not yet been considered within the context of passive control research. Therefore, there is a need for further investigations to determine the margin of difference in the results of the passive control studies with the inclusion of these factors in CFD models.

From the PCM investigation, it was noted that a small increase in pollutant concentrations was measured in the road. This is an impact of some passive control configurations and the question arises as to whether this would be considered as an acceptable or negative impact of passive controls. The implementation of LBWs as passive controls, in comparison to parked cars, has a much lower impact on current traffic conditions in a street as no alterations to the current traffic lanes are required. However, continuous LBWs located on the outer edge of the footpaths poses the issue of restricted access to the footpaths from the road by foot traffic. Similarly, the introduction of an LBW in the centre of the canyon would restrict the movement of traffic across lanes. Each of these factors should be considered if implementing LBWs is a viable option. The introduction of parked cars in a street canyon and subsequently

replacing a current lane of traffic with a parking bay can impact the traffic flow in other lanes and in nearby streets. Therefore the impact of a new parking bay can influence pollutant emissions beyond the parking bay zone and should be considered as part of the decision process.

Despite the results from these investigations which have illustrated the potential influences of passive controls on air flow and quality at street level, the comments made by Pugh et al. (2012) regarding the importance of a case-by-case analysis for urban greening should also be heeded in the context of the current state of knowledge for passive controls. However, the comparative analysis between the generic parked cars and LBW asymmetry modelling investigations to the Pearse Street model demonstrated some similarities in results between generic modelling studies to real world scenarios. Yet, the differences observed between the studies highlights the need for further research in the area of passive controls. This combined allows for the future development of a passive control implementation strategy, where the application of findings from generic modelling investigations could apply to real street canyon environments. There is a need to carry out more investigations of passive controls as this research has been limited to specific meteorological conditions and building geometry. However, the development of a simple tool following on from continued research in this field would be beneficial, and would allow for the selection of a suitable passive control based on parameters such as building geometry, predominant wind conditions and traffic flow. This tool could be developed as a series of tables or graphs, which would allow for more universal access to the practical element of the research findings and allow for its application in the urban environment. The tool would categorise the introduction of passive controls for local street geometry (average canyon ratio (H/W) and asymmetric canyon ratio (H_1/H_2) etc.) and wind (average speed and predominant direction) conditions. These two factors would be considered essential to determining the most suitable passive control layout. Based on both these criteria, an understanding of the current street layout and traffic data can be established and the most suitable passive control method can be determined. Passive controls have the potential to improve air quality in street canyons; however, the next step is to deliver the findings in a simple format for its implementation in future urban planning strategies.

8. CONCLUSIONS

8.1 RESEARCH CONCLUSIONS

The separate investigations within the three chapters of this thesis have extended the knowledge for the potential of implementing passive controls in the urban environment. Parked cars were examined as a new form of passive control, an enhanced analysis of a previously considered passive control (LBWs) was carried out, and a real world case study was assessed to determine the potential of passive controls in an urban street canyon.

A number of existing passive controls were identified within the literature review, therefore the first investigation of parked cars aimed at extending the current viable options to potentially increase pollutant dispersion and improve air quality at street level. The PCM study assessed a variety of different parking bay configurations; parallel, perpendicular, diagonal and central parking. Unlike the other parking bay layouts, parallel parking provided improvements in air quality along both footpaths for all varying meteorological conditions. However, the study recognised that full parking bay occupancy is not always common and therefore an assessment of different percentage occupancy rates was carried out. From observations of the occupancy rate results, clear correlations were identified between the percentages of parked cars in the parking bays and the percentage reductions in pollutant concentrations on the footpaths. Parking bays will continue to be part of the infrastructure of urban street canyons and are typically not considered to have a functional role in air flow or as a passive control. This investigation outlined the potential of parked cars as an effective passive control and it highlighted the importance for urban planners to consider all the various elements within a street during a design or review process of the functionality of a street.

Low boundary walls (LBWs) were previously considered as an effective passive control, yet the study was limited to a small selection of geometrical street canyon scenarios. Therefore the canyon asymmetry study extended the current understanding of the interaction of LBWs in street canyons for different asymmetrical canyon ratios and for different wind conditions. Clear differences were observed with regards to the effectiveness of passive controls as percentage reductions or increases along the

footpaths with varying asymmetrical canyon ratios. The study compared two established methods of simulating vehicles emissions (surface and line source) in a street canyon model and found that significant differences existed between the two methods. The study also found that the location of passive controls can significantly influence air flow patterns which develop within a street canyon. This affects pollutant dispersion and therefore gaining an understanding of how air flow can be manipulated through the introduction of different forms of passive controls was considered beneficial to the optimisation of passive control potential. In addition, the study examined the clear effects that street geometry has on passive controls. Urban street canyons are not typically constructed in a symmetrical pattern and therefore ensuring the applicability of the canyon asymmetry study was investigated to match a real world context was considered an important part of the research.

As the generic modelling investigations assessed parked cars and LBWs as passive controls in controlled geometric and meteorological conditions, the Pearse Street model allowed for a case study of their potential in a real world scenario. Pearse Street included the potential for the inclusion of LBWs and parking currently existed within the street, therefore it was a suitable case study for this thesis. In addition, the collection of localised data of meteorological conditions, traffic data and air quality was carried out to calibrate the model. The findings of the investigation determined that the results from generic modelling studies can be translated to real world street canyon scenarios. This is beneficial in that a series of generic modelling investigations can be examined and a detailed methodology can be extracted from these findings for the purpose of creating a passive control implementation strategy for dissemination of the research findings.

The passive control investigations successfully demonstrated the potential for passive controls to engineer the natural air flow patterns and improve pollutant dispersion in the urban environment. The combined results of the previous studies outlined in the literature review and the investigations carried out as part of this thesis define an improved picture of the potential of passive controls. Passive controls have the potential to be a useful method of improving air quality at street level without significant redesign of a current street layout or function. The three modelling investigations provided some evidence of the ability of new or existing passive

controls in pollution control and outlined some additional work that could enhance the overall understanding of passive controls. It is recognised that there is further research required prior to developing practical guidelines for the implementation of passive controls. The proposed guidelines require considerable planning to ensure that they would deliver accurate results upon the implementation of passive controls on a case specific basis. This would ensure that passive controls could be included in future urban planning strategies and be adopted by urban planners as a feasible method of reducing personal pollutant exposure in urban street canyons.

8.2 RECOMMENDATIONS FOR FURTHER RESEARCH

A number of findings were noted within the remit of this thesis where further research would benefit an improved methodology for the effective implementation of passive controls.

- The implementation of passive controls in a street canyon with a long-term monitoring period would be a useful progression for this research and allow for the promotion of the research in a real world context. The study would allow for an assessment of passive controls in a wider range of meteorological conditions i.e. through all seasons of the year. In particular, the alteration of a current parking bay layouts would not require significant planning and a detailed modelling and measurement investigation of this retrofit project would be an interesting approach to the future of passive controls.
- A detailed investigation of the effects of passive controls on particulate and reactive gas pollutant dispersion in street canyons. The study would require a detailed monitoring study of a real world street canyon, but would allow for the introduction of more complex dispersion factors, such as moving vehicles and thermal stratification. The study would allow for the development of a complete street canyon model, which could assess the potential of passive controls for all pollutants and in all meteorological and traffic conditions.
- Develop a detailed passive control implementation strategy which would include the findings of this research and several additional modelling investigations. The additional studies would allow for the development of a broad set of passive control results and the subsequent interpolation of research findings to specific street canyon conditions. The application of the

research findings would require the development of simple and clear tables or graphs, which would allow urban planners to select the most suitable passive control based on a number of controlling parameters.

- The differences in the meteorological data sets were noted to be due to the effects of urban buildings altering air flow patterns compared to other urban sites and background sites. A feasibility study for the use of large scale urban models to generate accurate localised wind data sets would be beneficial to small scale modelling investigations and would remove the need for the high costs of monitoring equipment.

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APPENDIX A

POLLUTANT CONCENTRATION IN ASYMMETRY MODELS

AVERAGE POLLUTANT CONCENTRATIONS FOR REFERENCE AND FOOTPATH LBWs USING SURFACE EMISSIONS SOURCE MODELS AT HEIGHTS OF 1.76 M AND 1.00 M FOR A WIND SPEED ON 8 M/S.

H ₁ /H ₂ Ratio	Reference Model				Footpath LBW			
	1.76m		1.00m		1.76m		1.00m	
	LW	WW	LW	WW	LW	WW	LW	WW
0.5	1.8E-09	3.1E-09	1.9E-09	3.5E-09	1.6E-09	2.0E-09	1.6E-09	1.9E-09
0.6	2.0E-09	2.2E-09	2.1E-09	2.5E-09	1.7E-09	1.5E-09	1.7E-09	1.4E-09
0.7	2.2E-09	1.7E-09	2.5E-09	1.9E-09	2.0E-09	1.3E-09	2.0E-09	1.3E-09
0.8	2.0E-09	1.3E-09	2.4E-09	1.4E-09	1.8E-09	9.7E-10	1.9E-09	9.7E-10
0.9	2.0E-09	2.3E-10	2.3E-09	1.3E-10	2.0E-09	1.6E-10	1.9E-09	8.7E-11
1.0	2.4E-09	9.1E-10	2.7E-09	8.7E-10	2.7E-09	5.8E-10	2.6E-09	5.6E-10
1.1	2.5E-09	1.4E-09	2.9E-09	1.3E-09	2.9E-09	8.4E-10	2.9E-09	8.0E-10
1.2	2.2E-09	1.3E-09	2.7E-09	1.2E-09	2.6E-09	7.9E-10	2.6E-09	7.5E-10
1.3	2.1E-09	1.2E-09	2.7E-09	1.2E-09	2.4E-09	7.3E-10	2.3E-09	6.8E-10
1.4	2.1E-09	1.1E-09	2.8E-09	1.0E-09	2.1E-09	6.3E-10	2.1E-09	5.8E-10
1.5	2.0E-09	1.0E-09	2.8E-09	9.5E-10	2.0E-09	5.3E-10	2.0E-09	4.9E-10

AVERAGE POLLUTANT CONCENTRATIONS FOR REFERENCE AND LBW LAYOUTS USING SURFACE EMISSION SOURCE MODELS AT HEIGHTS OF 1.76 M AND 1.00 M FOR LOW (2 M/S) AND HIGH (8 M/S) WIND SPEEDS.

Wind Speed	H1/H2 Ratio	Reference Model				Footpath LBW				Central LBW			
		1.76m		1.00m		1.76m		1.00m		1.76m		1.00m	
		LW	WW	LW	WW	LW	WW	LW	WW	LW	WW	LW	WW
2 m/s	0.5	1.9E-09	4.1E-09	1.9E-09	4.7E-09	1.8E-09	2.6E-09	1.7E-09	2.5E-09	1.8E-09	2.0E-09	1.9E-09	2.6E-09
	1.0	3.1E-09	1.0E-09	3.7E-09	9.4E-10	3.5E-09	6.7E-10	3.1E-09	5.8E-10	2.5E-09	6.5E-10	2.5E-09	6.4E-10
	1.5	2.7E-09	1.2E-09	3.9E-09	1.1E-09	2.4E-09	6.6E-10	2.4E-09	6.2E-10	1.9E-09	4.7E-10	1.8E-09	4.3E-10
8 m/s	0.5	1.8E-09	3.1E-09	1.8E-09	3.6E-09	1.6E-09	2.0E-09	1.7E-09	2.0E-09	1.7E-09	1.7E-09	1.8E-09	2.0E-09
	1.0	2.4E-09	9.1E-10	2.7E-09	8.7E-10	2.7E-09	5.8E-10	2.6E-09	5.6E-10	2.1E-09	5.3E-10	2.0E-09	5.3E-10
	1.5	2.0E-09	1.0E-09	2.8E-09	9.5E-10	2.0E-09	5.3e-10	2.0E-09	4.9E-10	1.4E-09	3.8E-10	1.4E-09	3.4E-10

AVERAGE POLLUTANT CONCENTRATIONS FOR REFERENCE AND LBW LAYOUTS USING LINE EMISSION SOURCE MODELS AT HEIGHTS OF 1.76 M AND 1.00 M FOR LOW (2 M/S) AND HIGH (8 M/S) WIND SPEEDS.

Wind Speed	H1/H2 Ratio	Reference Model				Footpath LBW				Central LBW			
		1.76m		1.00m		1.76m		1.00m		1.76m		1.00m	
		LW	WW	LW	WW	LW	WW	LW	WW	LW	WW	LW	WW
2 m/s	0.5	3.9E-09	3.0E-08	3.3E-09	3.4E-08	6.8E-09	2.1E-08	5.9E-09	2.0E-08	8.5E-09	1.8E-08	8.6E-09	2.1E-08
	1.0	4.1E-09	3.1E-08	4.8E-09	3.3E-08	7.1E-09	2.2E-08	6.2E-09	2.0E-08	8.2E-09	1.8E-08	9.2E-09	2.2E-08
	1.5	4.1E-09	3.2E-08	4.5E-09	3.6E-08	8.0E-09	2.2E-08	6.6E-09	2.1E-08	9.2E-09	2.0E-08	9.3E-09	2.3E-08
8 m/s	0.5	1.4E-08	1.9E-08	7.7E-09	2.3E-09	9.8E-09	1.1E-08	8.8E-09	1.0E-08	1.0E-08	1.3E-08	1.1E-08	1.5E-08
	1.0	1.6E-08	2.0E-08	8.3E-09	2.6E-09	1.0E-08	1.2E-08	8.9E-09	1.1E-08	1.2E-08	1.4E-08	1.2E-08	1.6E-08
	1.5	1.7E-08	2.0E-08	8.3E-09	2.5E-09	1.1E-08	1.2E-08	1.0E-08	1.1E-08	1.2E-08	1.4E-08	1.2E-08	1.6E-08

AVERAGE POLLUTANT CONCENTRATIONS FOR REFERENCE AND LBW LAYOUTS USING LINE EMISSION SOURCE MODELS WITH STATIC VEHICLES AT HEIGHTS OF 1.76 M AND 1.00 M FOR LOW (2 M/S) AND HIGH (8 M/S) WIND SPEEDS.

Wind Speed	H1/H2 Ratio	Reference Model				Footpath LBW				Central LBW			
		1.76m		1.00m		1.76m		1.00m		1.76m		1.00m	
		LW	WW	LW	WW	LW	WW	LW	WW	LW	WW	LW	WW
2 m/s	0.5	6.5E-09	3.6E-08	5.9E-09	4.1E-08	6.8E-09	2.1E-08	9.5E-09	1.9E-08	8.5E-09	1.8E-08	8.0E-09	2.0E-08
	1.0	8.5E-09	3.9E-08	7.4E-09	4.4E-08	7.1E-09	2.2E-08	1.0E-08	2.0E-08	8.2E-09	1.8E-08	8.5E-09	2.1E-08
	1.5	8.1E-09	4.0E-08	7.2E-09	4.5E-08	8.0E-09	2.2E-08	1.0E-08	2.0E-08	9.2E-09	2.0E-08	8.4E-09	2.2E-08
8 m/s	0.5	1.1E-08	2.2E-08	7.4E-09	2.0E-09	9.8E-09	1.1E-08	9.0E-09	1.1E-08	1.0E-08	1.3E-08	9.0E-09	1.8E-08
	1.0	1.4E-08	2.3E-08	8.7E-09	2.2E-09	1.0E-08	1.2E-08	1.0E-08	1.2E-08	1.2E-08	1.4E-08	1.1E-08	1.9E-08
	1.5	1.4E-08	2.3E-08	8.0E-09	2.1E-09	1.1E-08	1.2E-08	1.1E-08	1.2E-08	1.2E-08	1.4E-08	1.0E-08	1.9E-08