A modelling exercise to examine variations of NOx concentrations on adjacent footpaths in a street canyon

Gallagher, John

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A modelling exercise to examine variations of NO_x concentrations on adjacent footpaths in a street canyon: the importance of accounting for wind conditions and fleet composition.

J. Gallagher[a,*]

[a] Department of Civil, Structural & Environmental Engineering, Trinity College Dublin, Ireland.

* Corresponding author. Tel: (+353) 1 896 2781

Email address: gallagj2@tcd.ie

Abstract

Personal measurement studies and modelling investigations are used to examine pollutant exposure for pedestrians in the urban environment: each presenting various strengths and weaknesses in relation to labour and equipment costs, a sufficient sampling period and the accuracy of results. This modelling exercise considers the potential benefits of modelling results over personal measurement studies and aims to demonstrate how variations in fleet composition affects exposure results (presented as mean concentrations along the centre of both footpaths) in different traffic scenarios. A model of Pearse Street in Dublin, Ireland was developed by combining a computational fluid dynamic (CFD) model and a semi-empirical equation to simulate pollutant dispersion in the street. Using local NO_x concentrations, traffic and meteorological data from a two-week period in 2011, the model were validated and a good fit was presented. To explore the long-term variations in personal exposure due to variations in fleet composition, synthesised traffic data was used to compare short-term personal exposure data (over a two-week period) with the results for an extended one-year period. Personal exposure during the two-week period underestimated the one-year results by between 8% and 65% on adjacent footpaths. The findings demonstrate the potential for relative

differences in pedestrian exposure to exist between the north and south footpaths due to changing wind conditions in both peak and off-peak traffic scenarios. This modelling approach may help overcome potential under- or over-estimations of concentrations in personal measurement studies on the footpaths. Further research aims to measure pollutant concentrations on adjacent footpaths in different traffic and wind conditions and to develop a simpler modelling system to identify pollutant hotspots on our city footpaths so that urban planners can implement improvement strategies to improve urban air quality.

Keywords: personal exposure; urban street canyon; CFD modelling; footpaths; vehicle emissions; fleet composition.

1 Introduction

In the urban environment, vehicular emissions are the predominant source of air pollution (Wang et al., 2008). Clean air is a fundamental requirement for the well-being of human health, yet vehicle emissions impacts air quality for pedestrians in urban street canyons. The impact of air pollution on human health has been examined in numerous epidemiological studies; highlighting the links to respiratory and cardiovascular diseases (Pope et al., 1999; Gauderman et al., 2004; Garcia et al., 2014). Personal exposure is dependent on the quantity and intensity of these emissions, which is impacted by vehicle flows and speeds, meteorological conditions and the movements of individuals in the urban environment (O'Mahony et al., 2000; Kaur et al., 2007; Goel & Kumar, 2014).

To address air pollution, a number of strategies have been adopted to improve air quality in the built environment (Atkinson et al., 2009; McNabola, 2010; Zhang et al., 2011). Recently, Gallagher et al.

(2015) suggests that these strategies can be categorised based on how they can reduce personal exposure: (i) controlling the quantity of pollution (g) e.g. congestion charges and improved public transport (Johansson et al., 2009; Thøgersen, 2009); (ii) controlling the emission intensity (g km^{-1}) e.g. carbon taxes and greener vehicles (Giblin & McNabola, 2009; Brady & O'Mahony, 2011); and (iii) controlling source-receptor pathways (g m^{-3}) e.g. solid or porous barriers acting as passive methods for improving air quality (Bowker et al., 2007; Gromke & Ruck, 2007; McNabola et al., 2009; Gallagher et al., 2011; 2012).

A range of real-world measurement studies, modelling investigations and wind-tunnel experiments have been adopted to quantify the potential of these strategies (Gallagher et al., 2015). Each method of assessment has different benefits and limitations relating to the quality and quantity of data collated, and their demand on resources.

In recent years, numerous personal exposure studies have been undertaken by the research community (McCreddin et al., 2013; Steinle et al., 2013; Nyhan et al., 2014). These studies can be expensive and labour-intensive, yet monitoring pollutant concentrations is considered the most accurate method of determining personal exposure (O'Donoghue et al., 2007; McNabola et al., 2008a; McNabola et al., 2011; McCreddin et al., 2013). A range of activity-based investigations have been undertaken to capture the factors which impact day-to-day personal exposure: smoking (Koistinen et al., 2001); cooking (Abdullahi et al., 2013); indoor activities (McCreddin et al., 2013); and mode of transport and commuting (McNabola et al., 2008b).

Alternatively, modelling provides a method for investigating air quality impacts for multiple traffic and meteorological conditions, two factors that are significantly impact the results of personal exposure studies (Int Panis et al., 2010). Various modelling studies have been used to examine personal exposure to pollution in the urban environment: e.g. Zhou & Levy (2008) adopting the Operational Street Pollution Model (OSPM) to simulate pollutant dispersion; Gualiteri & Tartaglia (1997) adopted a semi-empirical model to estimate NO_x concentrations from traffic; or Pospisil et al. (2004) using a computational fluid dynamic (CFD) model to examine pollutant dispersion in cities. Exposure models have been developed and used effectively in the prediction of personal exposure (McCreddin et al., 2015; Pilla & Broderick, 2015).

CFD micro-scale street canyon modelling has improved significantly in recent years with an ability to accurately simulate air flow patterns and vehicular emissions (Tominaga et al., 2008; Yassin et al., 2009; Gallagher et al., 2011; Solazzo et al., 2011). Most recently, an investigation by Gallagher et al. (2013) combined a CFD model with a semi-empirical equation to accurately quantify personal exposure of pedestrians based on known traffic and meteorological conditions. As studies by Rakowska et al. (2014) and Batterman et al. (2015) have noted the impact of varying traffic scenarios on pollution exposure, this type of model system can account for fleet composition when calculating personal exposure on the footpaths. Also, with the improved performance of computers, CFD modelling presents a feasible method of assessing personal exposure in the built environment.

This study examines the impacts of local wind conditions and the composition of traffic on personal exposure to NO_x concentrations in an urban street canyon. Using the street canyon model developed by Gallagher et al. (2013), pollutant concentrations on the footpaths are measured in different wind

and traffic scenarios. The model was developed by combining (i) a CFD model to simulate air flow and pollutant dispersion and (ii) a semi-empirical equation to account for fleet composition and traffic lane distribution in the street canyon. This model allows for the consideration of different wind speeds and directions, fleet composition across lanes and peak and off-peak traffic scenarios. The study will compare relative differences in concentrations between a typical short-term personal exposure study and long-term assessment.

2 Methodology

This investigation considered a 200m section of Pearse Street in Dublin, Ireland (Figure 1). It adopts the modelling methodology developed from a previous investigation by Gallagher et al. (2013).

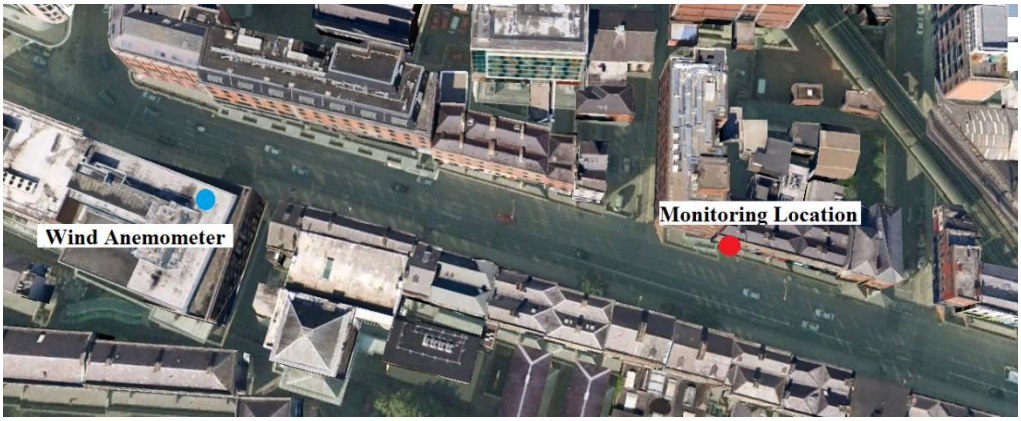

Figure 1. Plan view of Pearse Street in Dublin, Ireland. Locations of wind anemometer (blue) on building rooftop and NO_x monitoring location (red) at 7.8m height identified in the street (adapted from Gallagher et al. (2013)).

2.1 Data collection

Table 1 presents a summary of data collected in Pearse Street for the purpose of model calibration and examining personal exposure to vehicle emissions. The results are presented as mean concentrations along the centre of both footpaths. The model simulated air flow and pollutant

dispersion and was calibrated using local traffic data, nitrogen oxides (NO_x) concentrations and wind conditions.

Table 1. Summary details of data collection in Pearse Street (Gallagher et al., 2013).

Data	Specific details
Collection	• 2nd to 19th of December, 2011 (traffic, meteorology and NO_x pollution)
Geometry	• 3D GIS shapefiles of buildings imported using AutoCAD
Meteorology	• Wind anemometer and CR200 series data logger (see Figure 1) • Located at 19.3m above street level, high roof along street
Traffic	• Manual traffic counts over 14 1-hour periods (five-minute average data) • Automated SCATS traffic data (omitted as errors specifically in bus lane data)
Pollution	• Chemiluminescent $NO/NO_2/NO_x$ Analysers (Model 200EU) • The NO_x analyser was positioned at a height of 7.8m on the north side of the street, which allowed for the measurement of pollutant concentrations in the primary vortex of the canyon (see Figure 1) • NO_x concentrations considered as a tracer gas for vehicle emissions and measurements taken during winter conditions to suppress photochemical reactions

Wind conditions

Ever-changing local wind conditions impact upon pollutant dispersion in a street canyon. The CFD model was used to simulate air flow and pollutant dispersion based on local wind data (Figure 2a). Three wind directions were found to be representative of approximately 77% of the total conditions during the monitoring period: the predominant direction (~300°), parallel (~286°) and perpendicular (~186°) to the traffic lanes in the street. The three scenarios were simulated for a range of wind speeds (Figure 2b), which were used to generate polynomial equations for the calibration process, to calculate the concentration at various locations for any wind speed. Three sets of equations were generated and these represented the distinct relationship between NO_x concentrations emitted from each traffic lane and the concentration measured on the footpaths in different wind conditions.

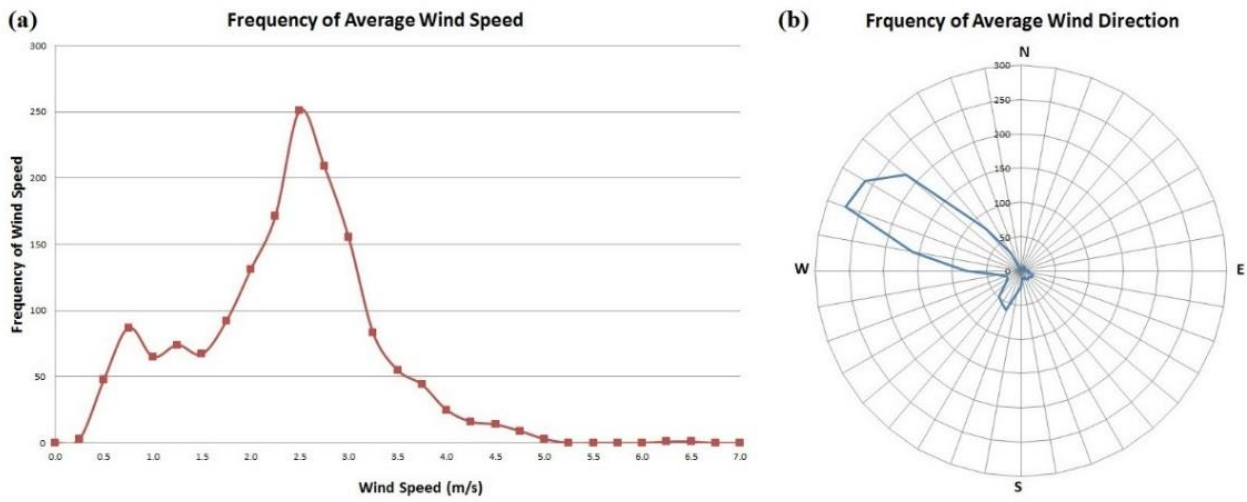

Figure 2. Local meteorological conditions in Pearse Street: frequency of (a) wind speed and (b) wind direction based on fifteen-minute averages during monitoring period in 2011 (Gallagher et al., 2013).

Traffic scenarios

The fleet composition in the street and the distribution of vehicles between lanes are considered as influential factors on personal exposure in the built environment. Figure 3 presents the differences in the fleet composition at different times of the day and their contribution to NO_x concentrations.

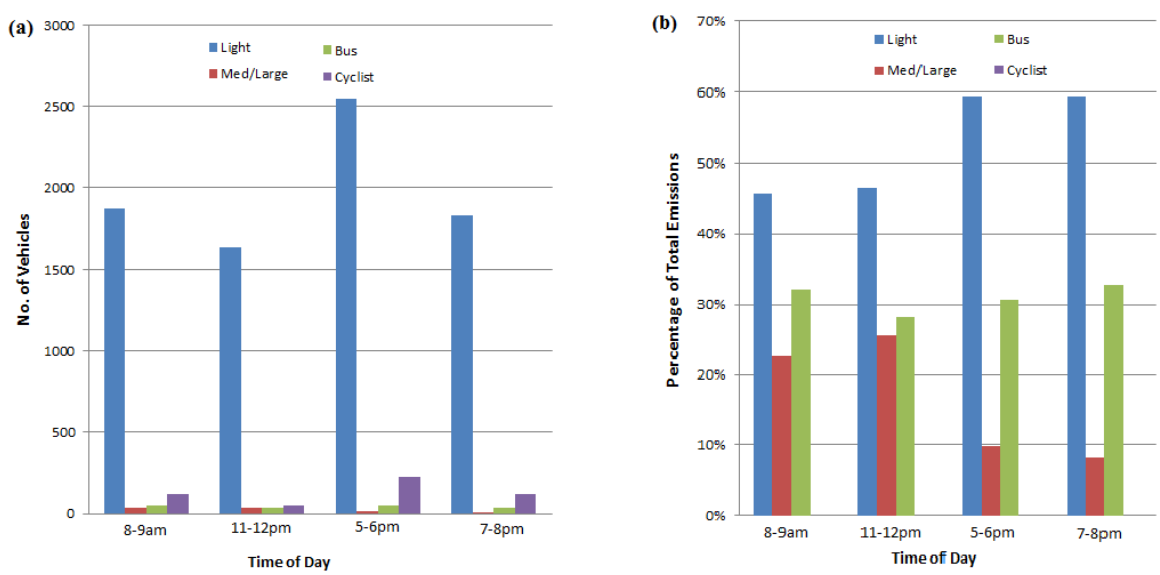

Figure 3. Local traffic scenarios in Pearse Street: (a) fleet composition in the street and (b) associated NO_x concentrations of total emissions at peak and off-peak times in the day.

In addition, changes in vehicle numbers across the four lanes were observed during peak (8-9 am and 5-6 pm) and off-peak (11-12 pm and 7-8 pm) traffic scenarios. Therefore, these factors were considered important to accounted for in the model as the impacted upon traffic congestion, thus affecting emission rates from vehicles throughout the day.

Table 2. Information of manual traffic data collection in Pearse Street (background wind direction and speed were also collected during this period, but local data was used in the calibration of the model).

Survey information	**Peak traffic times**		**Off-peak traffic times**	
	Morning 08:00 – 09:00	**Evening 17:00 – 18:00**	**Morning 11:00 – 12:00**	**Evening 19:00 – 20:00**
Date	06/12/11	06/12/11	05/12/11	06/12/11
Total traffic	1,898	2,467	1,516	1,862
Temperature	4 °C	6 °C	2 °C	4 °C
Date	07/12/11	07/12/11	06/12/11	12/12/11
Total traffic	1,942	2,728	1,695	1,661
Temperature	3 °C	5 °C	4 °C	9 °C
Date	08/12/11	13/12/11	07/12/11	13/12/11
Total traffic	2,012	2,636	1,720	2,115
Temperature	9 °C	2 °C	5 °C	9 °C
Date			08/12/11	
Total traffic			1,895	
Temperature			8 °C	

2.2 Street canyon model

Model preparation and selection

The summary details of Pearse Street and the CFD model is provided in Table 3 and a detailed description of the model is included in the previous publication (Gallagher et al., 2013).

Table 3. Summary details of constructing and calibrating Pearse Street model (Gallagher et al., 2013).

Model	**Specific details**

Pearse Street	• 0.2 km section of 1.2 km street in Dublin city centre (Figure 1) • 4 lanes of 1-direction traffic • Traffic: eight million vehicles per annum • Layout: minimal gaps between buildings, two narrow junctions, one on either side of the street • Buildings: variable heights and rooftop shapes (average H/W ratio, 1.1; average H_1/H_2 ratio, 0.9)
Modelling	• 3D model constructed and meshed in Gambit v2.3 (using GIS shapefile data) • Independent mesh discretization analysis was carried out (0.25 m triangular mesh on canyon floor and 1.0 m tetrahedral volume mesh) • Simulations using commercial CFD software code Fluent 6.3 • LES turbulence model to simulate air flow and pollutant dispersion • Release of NO_x at ground level from each lane (surface emissions at Z = 0)

The large eddy simulation (LES) model was used to simulate turbulent flows in the street canyon model. The rationale for selecting the LES model was based on its use in a large number of previous studies of air flow and pollutant dispersion in street canyon models (Baker et al., 2004; Liu et al., 2005; McNabola et al., 2009). The default parameters (e.g. subgrid-scale model) were used in the LES model.

Turbulent flows are characterised by eddies with a wide range of length and time scales. The largest eddies are typically comparable in size to the characteristic length of the mean flow. The smallest scales are responsible for the dissipation of turbulence kinetic energy. The quantities of momentum, mass, energy, and other passive scalars are transported mostly by large eddies. Large eddies are dictated by the geometries and boundary conditions of the flow involved. Small eddies are less dependent on the geometry, tend to be more isotropic, and are consequently more universal. As a result in LES, large eddies are resolved directly, while small eddies are modelled. LES modelling uses a filtered Navier-Stokes equation and is suitable for more complex geometries than the k-ε model but is more computationally expensive. The complete system of the LES model is given in Equations (1)-(4):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \bar{u}_i) = 0, \qquad \text{(Eqn. 1)}$$

Where ρ is the density of the fluid and u is the velocity and:

$$\frac{\partial}{\partial t}(\rho \bar{u}_i) + \frac{\partial}{\partial x_j}\left[\rho \bar{u}_i \bar{u}_j\right] = \frac{\partial}{\partial x_j}(\mu \frac{\partial \sigma_{ij}}{\partial x_j}) - \frac{\partial \bar{\mathrm{P}}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j}, \qquad \text{(Eqn. 2)}$$

Where μ is the viscosity of the fluid and P is the pressure; σ_{ij} is the stress tensor due to molecular viscosity, given below; τ_{ij} is the subgrid-scale stress given:

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

$$\tau_{ij} = \rho \overline{u_i u_j} - \rho \bar{u}_i \bar{u}_j \qquad \text{(Eqn. 4)}$$

The airflow in the models was simulated from the flow of air over the top of the buildings and at either end of the street section as velocity inlets or pressure outlets. This was to replicate the wind conditions in Pearse Street.

Model development

The model was developed by combining (i) a CFD model which simulated air flow and pollutant dispersion in the street and (ii) a semi-empirical equation to account for fleet composition in the street canyon (Equations (5)-(6) from Gallagher et al. (2013)).

$$NO_M = \frac{E_C}{S_A}.\left(\sum_{L=1}^{4} V_C.D_L + 28\sum_{L=1}^{4} V_O.D_L\right).T_C.C_R.C_{IO} \qquad \text{(Eqn. 5)}$$

$$T_C = S_F\left({V_S}/{W_S}\right)^2 \qquad \text{(Eqn. 6)}$$

Where;

NO_M	NO_x measured at monitor location in Pearse Street (10^{-9} g m^{-3})
E_C	NO_x emissions rate for cars (based on average vehicle speed in different traffic scenarios) (10^{-3} g m^{-1})
E_O	NO_x emissions rate for other vehicles 28 times greater than car ($E_O = 28E_C$) (10^{-3} g m^{-1})
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 Equation 6
C_R	Adjustment coefficient based on measured to calculated concentration ratio against wind speed
C_{IO}	I/O coefficient to ensure calculated concentration (y) equals measured concentration (x)
S_F	Vehicle shape factor based on vehicle counts and fleet composition in street
V_S	Average vehicle speed (m s^{-1}) at respective time of day
W_S	Average wind speed at corresponding time of day (m s^{-1})

From the data collected, fifteen-minute averaged data was to be used for calibrating the model, however it was only included in this process if it met the following conditions: (i) the local wind direction was similar to the model (±10°), and (ii) each of the three averaged five-minute wind directions were relatively similar within each fifteen-minute interval to ensure a consistent wind direction (±20°). This reduced the potential 52 samples to be reduced to 32 samples, as they provided the most consistent and stable conditions for calibration of the model to measured data.

The equations were developed due to the poor correlation of NO_x emissions at the monitoring location to emissions associated with traffic counts. This allowed for the inclusion of additional variables omitted by the CFD component, such as fleet composition and traffic lane distribution in the street. Simulations of air flow and pollutant dispersion in the street were made for the three wind directions examined (perpendicular, parallel and predominant) and for a range of wind speeds. This

process was replicated for each traffic lane separately, and from this equations were developed to calculate the concentration of NO_x at the monitoring location based on different wind conditions. These equations were manipulated and factors to account for the emission rates (E_c and E_o) and traffic counts (V_c and V_o) of different vehicles, as well as vehicular turbulence (T_c in Equation 2) were included to develop Equation 1.

Based on a comparison of the measured NO_x data and the predictive model output for the point source location for the 32 sample periods, a good fit (R^2 = 0.76) is presented in Figure 4. Comparison of measurement and modelling results for 32 sample periods used in the calibration of the Pearse Street model. As the model outputs presented results for a constant wind direction as compared to the constantly variable wind direction taken from real world conditions this was considered to be a good comparison fit. Furthermore, the real world conditions where all three of the 5-minute averages remained close to that of the 15-minute results presented some of the better predictions.

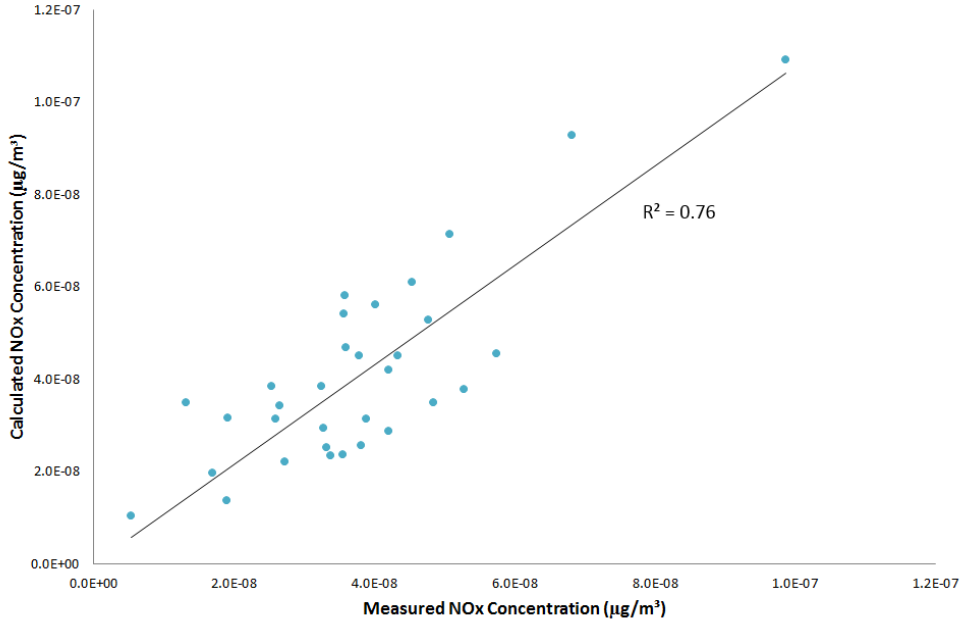

Figure 4. Comparison of measurement and modelling results for 32 sample periods used in the calibration of the Pearse Street model.

The results from the combined CFD and semi-empirical models presented a good representation for assessing relative differences in pollutant concentrations on the footpaths in different traffic and wind conditions. Due to the constant variation of traffic and wind in a real-world environment, the results from the model aim to serve as an indicator of the differences that occur in a street canyon. It also examines the impact of accounting for fleet composition and distribution between lanes.

2.3 Short-term results for personal exposure

Using the model, NO_x concentrations were calculated along the 200m section of street at an adult breathing height of 1.76 m and along the centre of the north and south footpaths (Figure 5). The model results were considered representative of the mean NO_x concentrations that pedestrians are exposed to when walking the full length of adjacent footpaths in the street.

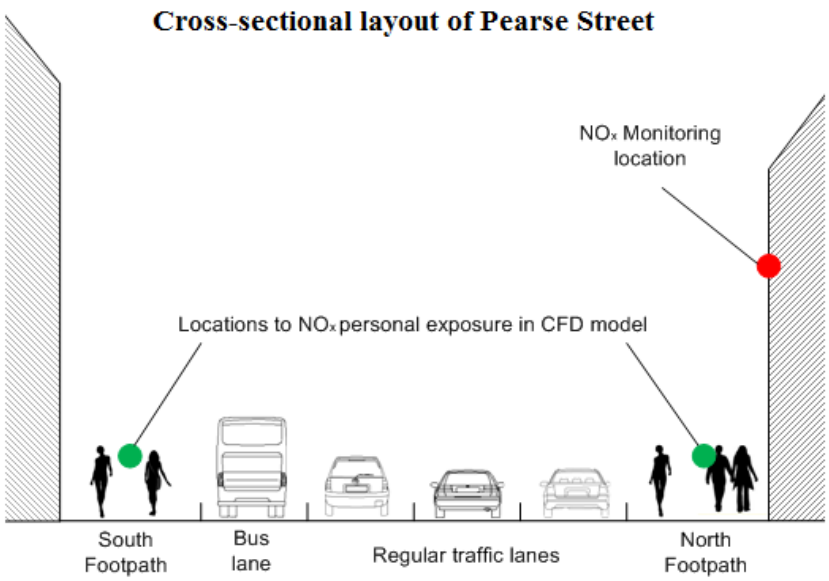

Figure 5. Representation of cross-section of Pearse Street including location of NO_x analyser and paths of pedestrian for measuring personal exposure in CFD model (this cross section is dimensionless).

Based on the short-term data collection period, the personal exposure results from the model is presented as an example of 32 personal exposure results on both footpaths. The results for mean personal exposure concentrations were 53.7±23.8 μg m^{-3} and 81.9±72.0 μg m^{-3} on the north and south footpaths, respectively. The large standard deviation evident in the results was due to significant differences between concentrations measured in the three wind directions. However, this model allows for a relative comparison of personal exposure results as long as the results recorded match the wind profile conditions typical to a specific street. These results were representative of different wind speeds (2.5±1.2 m s^{-1} and a range of between 0.4 and 4.6 m s^{-1}) and wind directions (17 parallel, 7 perpendicular and 8 predominant) in the street at times of the day with peak and off-peak traffic scenarios.

2.4 Synthesis of traffic and wind conditions for long-term assessment

To demonstrate the relative long-term variation in personal exposure to NO_x concentrations in Pearse Street, one year of data was synthesised for the peak and off-peak traffic times. In a similar manner to Rakowska et al. (2014), this study focuses on the impacts of fleet composition on personal exposure to pollution on adjacent footpaths. This study considers the next step to delivering a tool, in the form of a simplified model, which can identify pollutant hotspots in city streets based on local traffic and wind conditions.

The automated SCATS traffic data presented significant gaps and inconsistencies in the data for 2011 and no data for the bus lane, therefore synthesising the data was considered effective for the purpose of comparing short-term and long-term variations in personal exposure to vehicle emissions. The manual traffic count data during the two-week period in 2011 was used to synthesise fleet composition and traffic lane distribution for peak and off-peak traffic scenarios over a one-year period. A sample of fifty synthesised 15-minute mean traffic counts across all four lanes this is provided in Figure 6. In addition, the wind profile from Figure 2 provided a basis for generating local conditions that would occur in the street over the long-term assessment period.

Using the collected data, the minimum and maximum number of vehicle numbers in each lane was calculated and used as the limit values for generating traffic data. Based on these limits, the 'randbetween' function in Microsoft Excel was used as a simple tool to generating traffic counts for each lane in peak and off-peak scenarios. This provided the composition and number of vehicles in each lane to allow for an examination of variations in personal exposure to NO_x in different traffic scenarios. However, based on this method of data synthesis the mean and standard deviation are assumed to be the same for the short-term and long-term traffic counts.

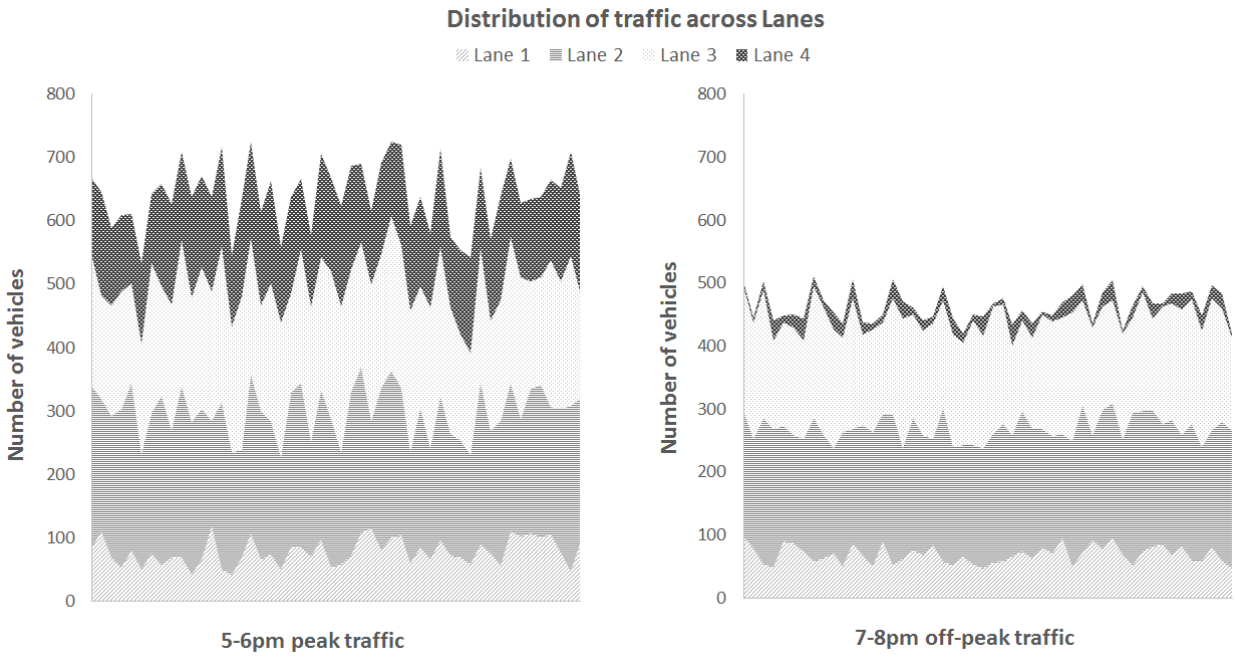

Figure 6. Sample of synthesised traffic data in peak and off-peak traffic conditions (15-minute averages based on sum of three five minute traffic counts).

In a similar manner, the wind conditions measured during the two-week period provided the range of wind speeds and distribution of wind directions in the street. The conditions measured during this period was also considered representative of the range of wind speed and direction in the street canyon. This data profile for wind conditions were maintained and one-year of data was randomly generated. A simple approach presents a potential solution for examining long-term variations in personal exposure in an urban street canyon that can deliver information to urban planners for better air quality strategies.

3 Results and discussion

3.1 Personal exposure

Impact of wind on personal exposure

Using the synthesised traffic data, air quality on both footpaths was calculated using the CFD model and semi-empirical equation. This aims to illustrate the range of NO_x concentrations that a pedestrian may be exposed to (expressed as the mean concentration along the 200 m length of road at a height of 1.76 m) if a wind direction was constant over a one-year period (but maintaining the same frequency and pattern of the wind speed observed in Figure 2(a)). The calculated concentrations for each footpaths and the corresponding percentage of time that this wind direction occurs in the street is shown in Table 4.

Table 4. Details of personal exposure on footpaths in different wind conditions.

Wind conditions in the street		**Concentration on footpath (mean ± St.Dev μg/m^3)**	
Direction	**Frequency**	**North**	**South**
Parallel (286°)	17%	61.2±5.8	110.1±11.9
Perpendicular (196°)	11%	91.1±24.1	217.5±49.9
Predominant (300°)	49%	54.4±14.8	2.8±1.0

The results from Table 4 show the differences in concentrations on both footpaths for different wind directions. In particular, the low concentrations in a predominant wind direction and the high concentrations in perpendicular wind direction are evident on the south footpath. Therefore, an additional factor is required to improve the model outputs for concentrations on the footpaths, which would need to consider the orientation of the footpath in relation to the oncoming wind direction. Yet for the purpose of this study, the model outputs are satisfactory for comparing short- and long-term variations in concentrations due to different wind conditions.

Figure 7 – 9 illustrates the distribution of concentrations measured on the north and south footpaths in different wind directions, as combined they represent the majority of wind conditions in the street.

The influence of wind direction presents a clear distinction in results of measured NO_x concentrations on both footpaths. For parallel winds (Figure 7), which represents 17% of the general wind direction in the street, pollutant concentrations were notably higher on the south footpath Figure 7(b)) compared to the north footpath Figure 7(a)). This was due to the distribution of a larger proportion of vehicles, specifically buses and HGVs in the traffic lanes closer to the south side of the street. The standard deviation for NO_x concentrations was approximately 9-11% of the mean value for both footpaths, and from a visual inspection of the results in Figure 7, this distribution shows that wind speed does not impact upon the results in parallel wind conditions.

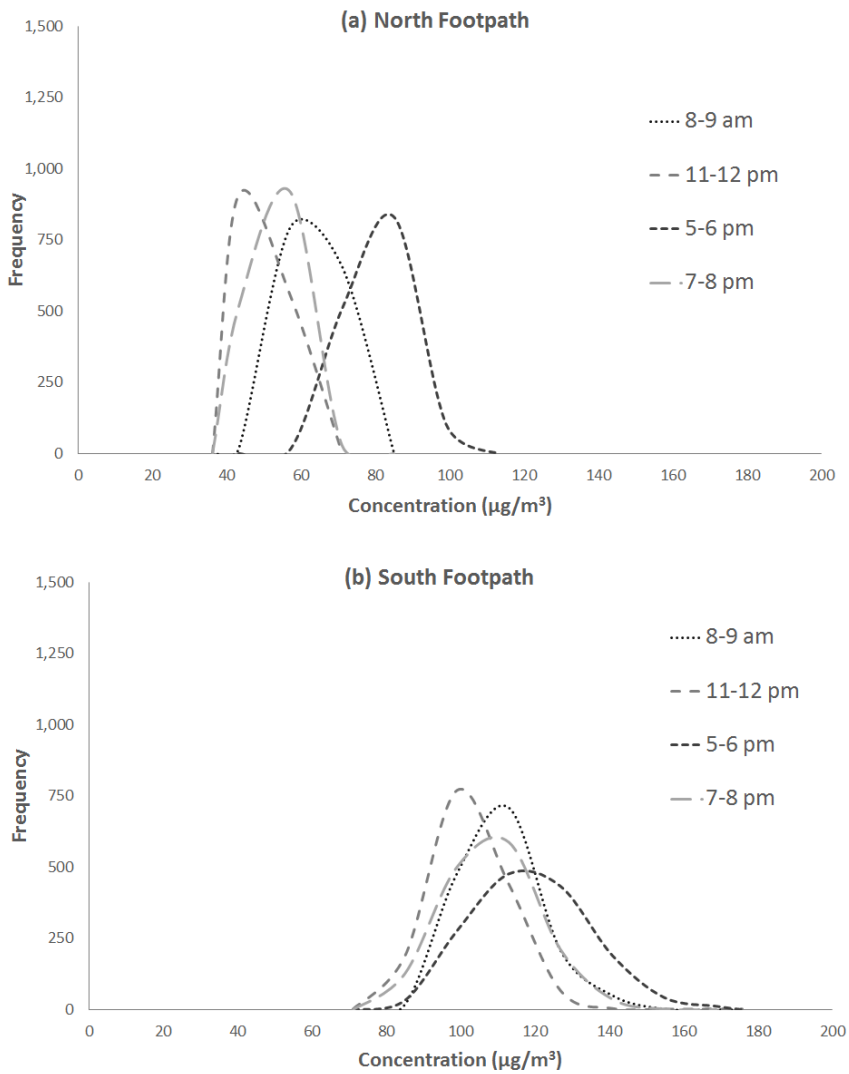

Figure 7. Frequency distribution of NO_x concentrations on the (a) north and (b) south footpaths for the parallel wind direction in peak and off-peak traffic scenarios.

The perpendicular wind results represents 11% of the conditions in Pearse Street, and led to the highest means and distribution (standard deviation of mean is 23-26%) of concentrations on both the footpaths. The concentrations calculated for the north footpath (Figure 8(a)) was lower than on the south footpath (Figure 8(b)).

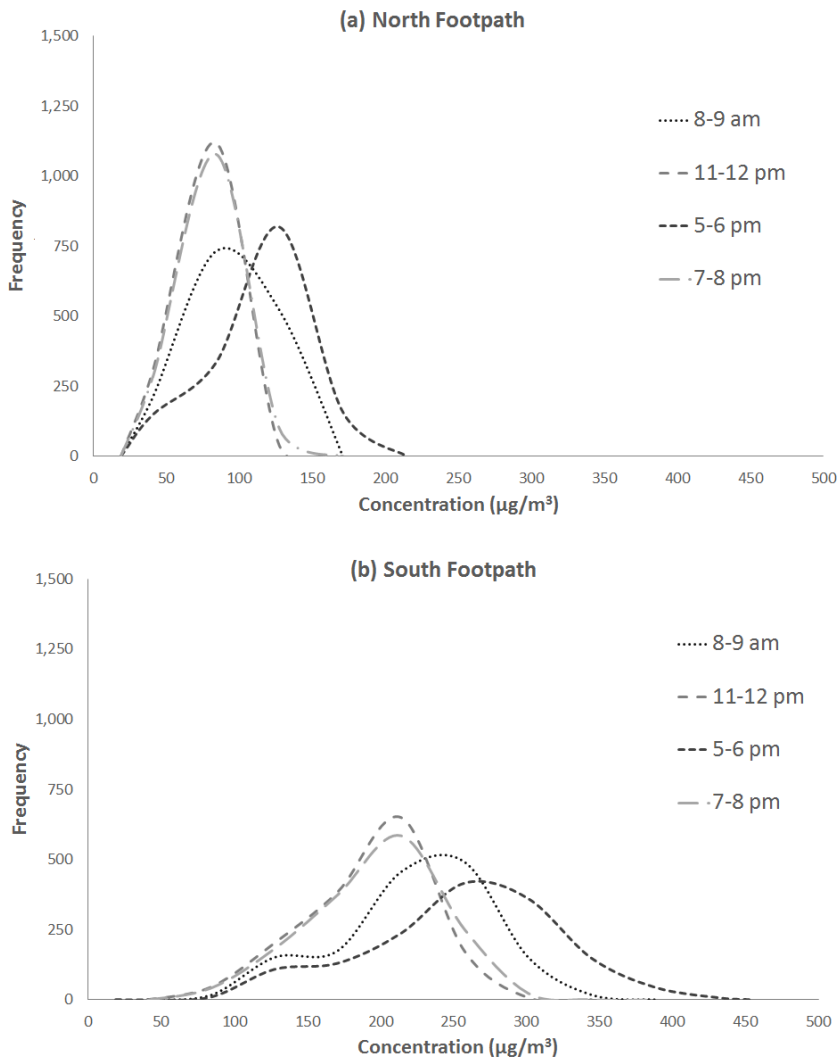

Figure 8. Frequency distribution of NO_x concentrations on the (a) north and (b) south footpaths for the perpendicular wind direction in peak and off-peak traffic scenarios.

This was due to air flow patterns associated with the development of a primary vortex in the street canyon, whereby pollutants were transported away from the leeward (north) footpath and towards the windward (south) side of the street. Deteriorations in air quality on the footpaths were shown to correlate to incremental increases of the wind speed in the street canyon. The results suggest that the development of the primary vortex does not have a distinct effect on the relationship on NO_x concentrations on the footpaths within the range of wind speeds measured in this study.

Representing 49% of the wind conditions in Pearse Street, the predominant wind direction was measured at a 15° angle to the street. It was vital to the accuracy of a monitoring study to account for air quality results in the predominant wind direction and should be considered for all air quality studies in street canyons. The lowest pollutant concentrations on both footpaths were found for predominant wind conditions (Figure 9), which suggest that an acute wind direction may promote enhanced mixing, allowing for more pollutants escaping the canyon.

The mean concentrations on the north footpath was notably higher than on the south side of the street. Similar to perpendicular wind conditions, a standard deviation was evident (27-35% of mean concentration), suggesting a lot of variability was evident for the pollutant concentrations measured on both footpaths.

The larger range of concentrations measured on the footpaths in perpendicular and predominant wind conditions as opposed to parallel winds indicates that a potential limitation of the combination of the CFD model and the semi-empirical equation. Specifically, this is in relation to determining the coefficient for vehicular turbulence, T_c, in a wind direction that is neither in line nor at right angles to the traffic flow. Therefore, to use this model in other street canyons, another 'wind index' factor and a separate factor for calibrating the concentrations on both footpaths is required. The current model can provides good representation of results for relative differences in concentrations, such as in the previous investigation by Gallagher et al. (2013), but may over- or under-estimate air quality in real world conditions.

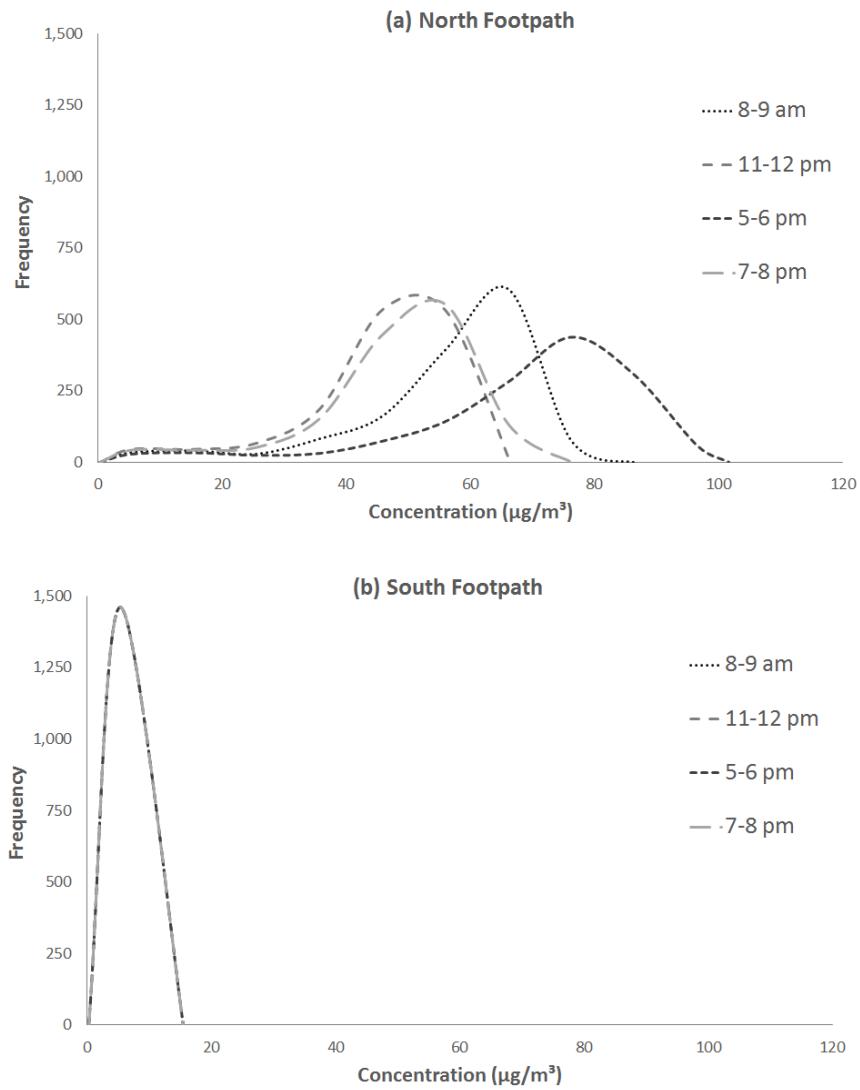

Figure 9. Frequency distribution of NO_x concentrations on the (a) north and (b) south footpaths for the predominant wind direction in peak and off-peak traffic scenarios.

Impact of fleet composition on personal exposure

The results in this section aims to demonstrate how the impact of fleet mix and distribution of vehicles between lanes on air quality along the footpaths. Traffic emissions at different times of the day presented distinct distribution patterns for mean concentrations on the footpaths. The 8-9 am and 5-6 pm peak traffic times suggested poorer air quality conditions i.e. higher concentrations on the footpaths than during off-peak times. The mean concentrations on the north footpath ranged

from 63-72 μg m^{-3} in peak traffic as opposed to 47-50 μg m^{-3} in off-peak traffic for parallel wind conditions.

The range of NO_x concentrations that occurred on the footpaths in peak traffic was larger for all wind directions. This was due to several factors: (i) a higher numbers of vehicles; (ii) increased fraction of large diesel vehicles (i.e. buses); and (iii) increased emissions due to slower driving speeds at these times of the day (free flowing or traffic congestion). A comparison of the standard deviation values as a percentage to the respective mean concentration demonstrated that the variance in air quality in peak-traffic was up to 17% higher than for off-peak traffic scenarios. This indicated that a broader range of pollutant concentrations are likely in peak traffic.

The number of vehicles in the street at any time of day is an indicator of the quantity of emissions and air quality at street level. The flow of traffic and the distribution of vehicles between lanes clearly impacts on pollutant concentrations on the footpaths, and is therefore a vital component in micro-scale modelling of air flow and pollutant dispersion in street canyon.

3.2 Short-term versus long-term assessment

The personal exposure results from the 32 calibrated simulations (mean 15-minute concentrations) present a mix of different wind speeds and the three modelled wind directions. However, these short term results may not be representative of the range of wind conditions observed in Figure 2.

Long-term variations in pollutant concentrations occur on the footpaths based on a combination of emissions associated with traffic flow and wind conditions. Therefore, the synthesised traffic and

wind data was combined (by randomly allocating a traffic scenario with a given wind conditions), ensuring that the weighting of parallel, perpendicular and predominant winds were accounted for in the long-term exposure results. As illustrated in Figure 2, the three wind directions used to calibrate the model accounted for over three-quarters of the complete mix of wind conditions through the street. In the calculation process, a separate set of results were acquired for peak and off-peak traffic scenarios. Figure 10 shows the distribution of NO_x concentrations on the footpaths for peak and off-peak traffic scenarios for the 32 samples i.e. the short-term, and the long-term exposure results for both footpaths.

An examination of the frequency distribution shows the differences between the short-term and long-term results. It must be recognised that the 32 samples did not follow the same breakdown of wind conditions represented in Figure 2, but the random nature of the data was representative of a typical sampling period of personal exposure.

Examining the breakdown of sampling data on the north footpath for different wind directions, the mean concentrations in parallel and predominant winds were within 2 μg m^{-3} of the modelling results. However, the difference between mean NO_x concentrations for perpendicular wind conditions was over 20 μg m^{-3} which is equivalent to a difference of 36%. Overall, the mean concentration during the sampling period (Figure 10(a)) was underestimated by a small margin of 4 μg m^{-3} (8%) compared to the long-term results for personal exposure. This demonstrates how the number of samples provides a relatively accurate mean NO_x concentration on the north footpath in different wind conditions for peak and off-peak traffic.

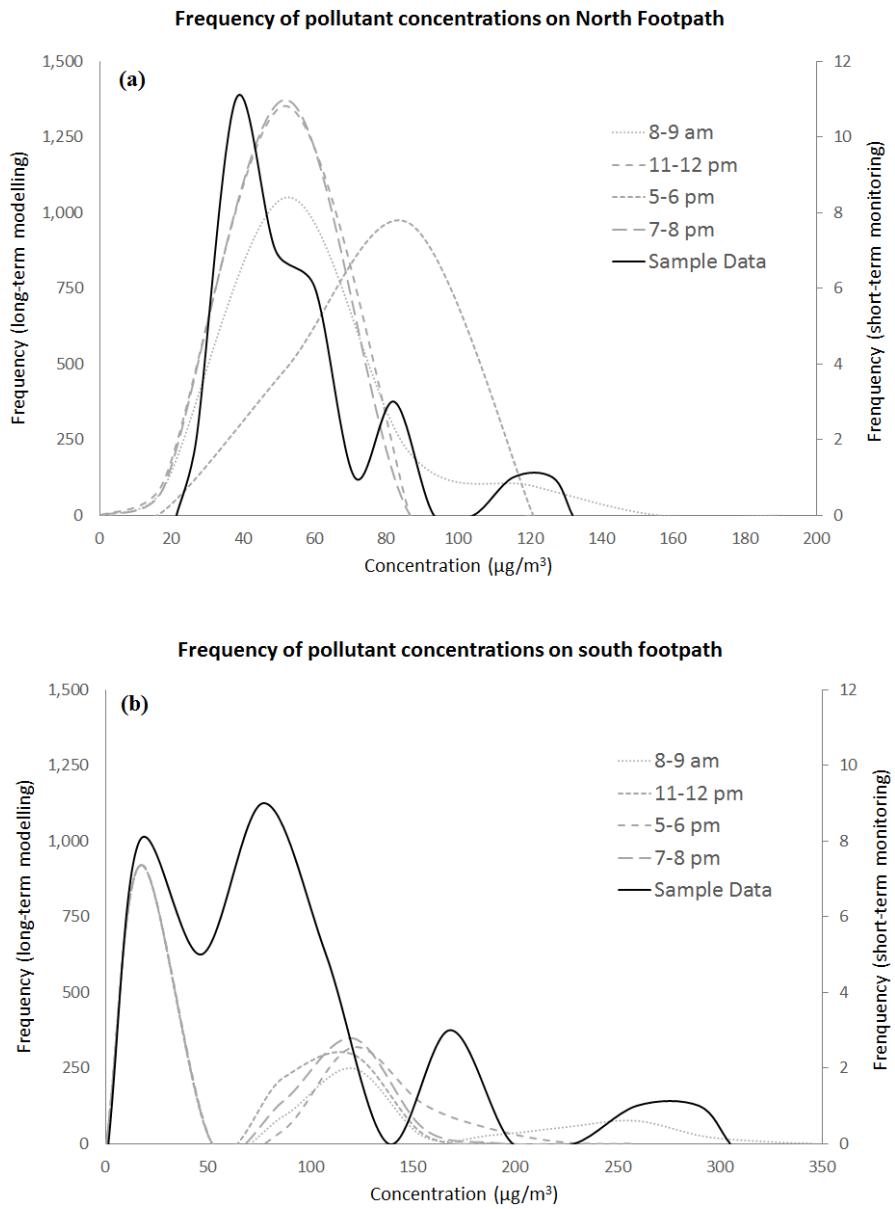

Figure 10. Comparison of results of NO_x concentrations on the (a) north and (b) south footpaths in peak and off-peak traffic scenarios between short-term monitoring and long-term assessment.

A comparison between the short- and long-term results for personal exposure on the south footpath displayed a significant over- or under-estimation of pollutant concentrations for all traffic scenarios. Figure 10(b) illustrates that the 32 samples do not represent the likely distribution of NO_x concentrations in the street. An underestimation of 65% was calculated for the mean concentration

on the south footpath between the sampling data (82 μg m^{-3}) and the long-term exposure results (50 μg m^{-3}). Furthermore, the variation between the mean sampling results for different wind direction ranged from 3.6 μg m^{-3} in predominant conditions to 100 and 111 μg m^{-3} in perpendicular and parallel winds, respectively.

The findings clearly demonstrate the importance of considering the number of samples required to provide an accurate results for personal exposure, as varying wind and traffic scenarios influence the results. The results from a fully-calibrated model has the potential to provide a more versatile tool for calculating mean and standard deviations for pollutants concentrations at street level over a long period of time in ever-changing environmental and traffic flows.

4 Conclusions

Based on the duration of data collection for a personal measurement study, differences in results may occur due to capturing results in non-predominant local wind and traffic conditions. Using the model developed by Gallagher et al. (2013), the combination of a CFD model and semi-empirical equation can provide a method of examining long-term variations in personal exposure results when compared to short-term data. This model allowed for a detailed analysis of the impacts of wind conditions and fleet composition on pollutant concentrations on adjacent footpaths during different peak and off-peak traffic scenarios.

Accounting for local wind conditions was identified as a significant parameter in the calculation of air quality on the footpaths. The mean concentrations on both footpaths differed for each direction as the frequency of each wind direction changed i.e. 11% perpendicular, 17% parallel and 49%

predominant winds. The results demonstrates the importance of accounting for the predominant wind as significant differences may exist between results for personal exposure in different wind directions.

The composition of fleet across traffic lanes, including considerations for the type of vehicle, impacts upon air quality on adjacent footpaths in peak and off-peak traffic. The results demonstrate the range of mean NO_x concentrations on the north (63-72 μg m^{-3}) and south (47-50 μg m^{-3}) footpaths for different traffic scenarios, which identifies the importance of accounting for traffic composition in modelling studies of urban air quality. Difference is air quality on the footpaths were due to a combination of (i) the numbers of vehicles in the street; (ii) the types of vehicles (petrol or diesel, increased fraction of buses); and (iii) the driving speed (free flow or congested traffic).

The modelling results for mean pollutant concentrations between the short two-week period and the long one-year period demonstrated an underestimation of between 8% and 65% on adjacent footpaths. This suggests that short-term measurement studies need to account for the frequency distribution of wind conditions (direction and speeds) specific to any street canyon, or it may lead to an over- or under-estimations of personal exposure results.

The combination of the CFD model and semi-empirical equation can help account for variations in fleet composition, which has been identified as a key factor for variations in pollutant concentrations between footpaths in an urban street canyon. The model was also developed to include different wind speeds and directions using a semi-empirical equation, which allowed for an examination of a large number of traffic scenarios. It has the potential to help identify pollutant hotspots and provide

guidance for implementing solutions to poor air quality on our city's footpaths. However, further work is required (i) to improve the accuracy of the model by measuring pollutant concentrations on the footpaths in different traffic and wind conditions and (ii) to reduce the complexity of this modelling system for urban planners to adopt as a tool to help implement strategies for improved air quality in the urban environment.

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