NUMERICAL MODELLING OF THE PASSIVE CONTROL OF AIR POLLUTION IN
ASYMMETRICAL URBAN STREET CANYONS USING REFINED MESH
DISCRETIZATION SCHEMES.

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Abstract
This study evaluates the potential of passive controls in asymmetrical street canyons to reduce personal exposure to air pollutants on footpaths. A passive control in the form of a low boundary wall (LBW) may act as a baffle within a street canyon, producing modified airflow patterns and increase pollutant dispersion at street level. This numerical modelling study assessed the spatial distribution of concentrations of a tracer pollutant in a street canyon. Concentrations were measured along the centre of both footpaths at breathing height to determine the percentage difference between pollutant concentrations in canyons with and without passive controls. The investigation assessed asymmetrical street canyons of different building height ratios ($H_1/H_2$ ratio ranging from 0.5–1.5 in 0.1 intervals) in perpendicular wind conditions. The results indicated that the $H_1/H_2$ ratio affects pollutant dispersion and the implementation of a passive control can reduce the pollutant concentration on the footpaths. The percentage difference in concentrations induced by the presence of footpath LBWs ranged from an increase of up to 19\% to a reduction of 30\% on the leeward footpath, with reductions between 26\% and 50\% on the windward footpath with varying $H_1/H_2$ ratios. Comparing the results to a central LBW configuration identified the creation of two distinct
vortices in the street canyon. The results also identified the effect of wind speed on the development of primary vortices. For urban planners, passive controls offer a method of increasing dispersion by modifying normal air flow patterns and potentially improve air quality in urban street canyons.

**Keywords:** Air Pollution; Passive Controls; Low Boundary Walls; Asymmetrical Canyons; Personal Exposure.

1. **Introduction**

A functional urban centre comprises a range of vital services to cater for its inhabitants. To maintain these services, large quantities of energy are required, and this energy has associated air pollution emissions. Vehicular emissions contribute to the majority of urban air pollution, despite significant improvements in vehicle technology [1]. In the UK, two hundred air pollution hotspots were identified that were caused by heavy volumes of traffic in urban street canyons [2]. The combination of increasing global and urban populations has led to the introduction of additional public services and the physical expansion of cities [3]. The construction of high rise buildings to cater for growing populations has led to a deterioration in air quality in urban streets and the development of the urban heat island (UHI), as canyons with high aspect ratios reduce the rate of air exchange between roof and the street, leading to trapped air at street level [4-6]. Other researchers concur with these findings, additionally identifying vehicular turbulence [7-10] and the layout and orientation of a street [11, 12] as other influential parameters that effect pollutant dispersion in urban canyons.

The geometry of an urban street canyon is a crucial element which can influence air flow and pollutant dispersion within an urban microenvironment. Studies such as that of Santiago and Martín [13] identified the creation of multiple vortices in asymmetric street canyons. The spatial
distribution of pollutants differs in canyons of different geometrical configurations [9]. Another study similarly highlighted the governing effect of canyon geometry on the flow patterns and turbulence properties [14]. Research by Oke [15] defined three different flow regimes (isolated roughness, wake interference and skimming) that occur for varying two dimensional canyon aspect ratios with flat roof configurations. The dependency of pollutant ventilation on the canyon geometry was identified, as wider canyons promote ventilation [16]. These findings correspond with the results from another modelling study of varying asymmetry aspect ratios [4], using Computational Fluid Dynamic (CFD) modelling to assess the effects of varying asymmetrical building heights on pollutant dispersion.

The implementation of passive controls in the urban environment is a current approach to protect human health by manipulating natural air flow patterns [17]. Previous research identified common physical urban features such as solid free standing walls [18], trees [19] or on-street parked cars [20] that act as baffle plates, disrupting the normal distribution of air pollutants when located in street canyons. In a rural context, researchers identified roadside noise barriers as a method of controlling air flow and turbulent conditions, thus affecting the dispersion patterns of pollutant concentrations [21-23]. Passive controls can be configured in street canyons to reduce air pollutant exposure for pedestrians on footpaths through the manipulation of natural dispersion patterns. A combined monitoring and numerical modelling study was carried out to highlight the role of an existing low boundary wall (LBW) in an urban street in Dublin, Ireland [18]. The LBW was situated between the roadway footpath and the pedestrian boardwalk; an extended walkway along the edge of the river Liffey. The results of the measurement study indicated greater personal exposure to PM$_{2.5}$ and VOCs on the roadside footpath compared to the boardwalk by factors of approximately 2.8 and 2.0, respectively. Previous investigators have also examined the influence of avenue like trees on
pollutant dispersion in a typical street canyon using CFD and wind tunnel models. Overall, these studies concluded that the in-canyon air quality can be significantly altered by avenue-like tree planting in a canyon with a H/W of 1, which found an increase in concentrations at the leeward wall and a moderate pollutant concentration decrease near the windward wall during perpendicular wind conditions [19, 24]. These studies highlighted the H/W ratio as the crucial parameter of pollutant dispersion compared to the density or porosity of the trees. The most recent research of passive controls assessed the capabilities of on-street parked cars as a form of passive control by means of a numerical modelling investigation [20]. The study examined a series of different parking layouts (parallel, perpendicular and 45° parking) under different meteorological conditions (varying wind speed and direction). The results identified that parallel parking provided the best overall scenario to reduce pollutant concentrations on urban street canyon footpaths. The study further concluded that the fraction of the parking bays occupied by vehicles influenced the results of parked cars as a potential passive control [20].

Research in this area to date has focused on the effectiveness of passive controls operating in symmetrical street canyons. Therefore, this study focuses on the performance of passive controls in reducing personal exposure from vehicular pollutants in asymmetrical street canyons for varying meteorological conditions. A numerical modelling investigation using the commercial CFD software Fluent 6.3 [25] was carried out, to assess the potential percentage reductions in personal exposure to air pollution on footpaths, between canyons with and without passive controls.

2. Methodology

2.1 Asymmetrical Canyon Models
This 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 a series of three dimensional models which differed from one another with the inclusion of LBWs located on the footpath or in the centre of the canyon at a height of 0.5m and strategically located to increase dispersion and potentially reduce pollutant concentrations at street level. The cases investigated the percentage reduction in pedestrian exposure of an inert virtual tracer pollutant for a range of asymmetrical canyon configurations with vehicular emissions represented as an area source across the road surface. Two sets of models were constructed for each H\textsubscript{1}/H\textsubscript{2} ratio in the first case; the first set consisted of a reference model (200 metres 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. Fig. 1 illustrates examples of two of the asymmetrical street canyon models with H\textsubscript{1}/H\textsubscript{2} ratios of 0.5 and 1.5, respectively. The leeward building height (H\textsubscript{2}) was equal to the width of the canyon floor (W) of 14m in all of the models, for both the reference and LBW models. The windward building height, H\textsubscript{1} was proportional to the leeward building height, H\textsubscript{2} as the H\textsubscript{1}/H\textsubscript{2} ratio varied in the model configurations from 0.5–1.5 in 0.1 intervals to allow a detailed investigation of asymmetrical canyons. Fig. 1(a) displays a cross section of a typical street canyon model with a H\textsubscript{1}/H\textsubscript{2} ratio of 0.5, consisting of two footpath LBWs, two 4m wide traffic lanes and two 3m footpaths. The models were created for different H\textsubscript{1}/H\textsubscript{2} ratios in 0.1 intervals to identify precise changes in the air flow patterns due to canyon asymmetry. The pollutant concentration measured in both configurations was then compared to yield the percentage difference between the two models. 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\textsubscript{1}/H\textsubscript{2} ratios.
Fig. 1. Cross section of three-dimensional asymmetrical canyon models (a) $0.5 \ H_1/H_2$ with two footpath LBWs and (b) $1.5 \ H_1/H_2$ with one central LBW.

Two monitoring lines were inserted at the centre of both footpaths in each model at heights of 1.00m and 1.76m, to represent the path of a child and adult walking the full length of the canyon. 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, once a steady state was observed in the monitoring path lines. Convergence was deemed adequate when model predictions reached a relatively steady state for a moving average value of approximately 50 time steps (seconds). The mean difference in pollutant concentration was then calculated between the reference and LBW configurations and expressed as a percentage reduction of the mean reference pollutant concentration. Fig. 2 shows a typical output for the measured pollutant concentration of the tracer gas and the difference in pollutant concentrations between the reference and LBW models. In this particular example the difference between the pollutant concentration on the windward footpath between the two model configurations was negative i.e. personal exposure to an air pollutant was reduced due to the presence of a passive control.

Fig. 2. Determining the percentage difference in the pollutant concentration achieved by comparing a LBW model to the reference model on the windward footpath.

2.2 Footpath and Central LBW Layouts

A second modelling case extended the findings of the first case by modelling an additional configuration with a LBW of 0.5m in height in the centre of the canyon between the two traffic lanes (as shown in Fig. 1(b)). The $H_1/H_2$ ratio varied in this case from 0.5–1.5 in 0.5 intervals to
allow a comparison between the LBW models. The pollutant concentration measured on both footpaths was then compared to the equivalent models for the previous modelling case. The central LBW models were run at the same inlet wind velocity as the previous case and in addition, were also run for a low wind speed of 2 m/s to determine the effects of wind speed on the development of vortices.

2.3 Numerical Modelling

The solver used to simulate the turbulent flow of air in the street canyon models was the large eddy simulation (LES) turbulence model. The numerical modelling of air pollutant dispersion using CFD has been carried out by previous investigators commonly using either the k-ε turbulence model [12, 26, 27] or the LES turbulence model [5, 20, 28]. The LES model was used in this investigation rather than k-ε model due to a more complex geometry at street level in a typical street canyon [28, 29]. Several studies have evaluated the LES turbulence model to simulate turbulent air flow and pollutant dispersion in urban canyons and found a strong agreement between the CFD models and wind tunnel experiments [30, 31].

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 more problem-dependent, they 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):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \bar{u}_i) = 0,$$

(1)

Where $\rho$ is the density of the fluid and $u$ is the velocity and:

$$\frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_j} \left[ \rho \bar{u}_i \bar{u}_j \right] = \frac{\partial}{\partial x_j} (\mu \frac{\partial \bar{u}_i}{\partial x_j}) - \frac{\partial P}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j},$$

(2)

Where $\mu$ is the viscosity of the fluid and $P$ is the pressure; $\sigma_{ij}$ is the stress tensor due to molecular viscosity, given below; $\tau_{ij}$ is the subgrid-scale stress given:

$$\sigma_{ij} = \left[ \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right] - \frac{2}{3} \mu \frac{\partial \bar{u}_i}{\partial x_i} \delta_{ij},$$

(3)

$$\tau_{ij} = \rho \bar{u}_i \bar{u}_j - \rho \bar{u}_i \bar{u}_j$$

(4)

LES turbulence modelling has been used for a series of numerical modelling investigations of passive controls. This study has used similar preparation techniques for the solution of street canyon models [18, 20, 32].

2.4 Model Preparation & Mesh Discretization

The generic canyon models were constructed using Gambit v2.3, a CFD model development and meshing tool. The surfaces of the canyon floor and buildings were constructed as wall boundaries to resemble the impermeable nature of their characteristic materials. Additional faces of the model domain were constructed as atmospheric boundaries 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. The road lane and footpath widths remained constant in all model configurations to maintain a level of continuity between each model. The width of the roadway also remained constant in each model configuration to maintain a similar emissions rate. 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. Fig. 2 illustrates the arrangement of some of the model layouts with different $H_1/H_2$ ratios and LBW configurations, where $H_1$ is the building height on the windward building side of the canyon and $H_2$ is the height of buildings on the leeward side of the canyon.

Initially, a detailed mesh discretization analysis was carried out to determine suitable mesh parameters for the asymmetry study. Previous investigations have stated that a grid sensitivity study is crucial for independent cases, as conditions vary depending on canyon geometry [33, 34]. A typical computational domain was meshed with a series of grid density schemes combining a surface mesh at canyon floor level with a proportionate volume mesh. Based on the results, a tapered surface grid mesh was selected for the canyon floor with a uniform volumetric mesh. This was due to converging results for larger meshes on the windward footpath than on the leeward footpath as shown in Fig. 3. The canyon floor was meshed with triangular mesh elements of 0.2m on the leeward footpath, 0.3m on the road surface and 0.4m on the windward footpath with the overall volume meshed with a 1.0m tetrahedral mesh. The virtual tracer emissions were released from the road surface at ground level (i.e. $Z = 0$) in the asymmetrical canyon models. The inert tracer acts as an indicator pollutant to assess the dispersion of any pollutant common to an urban street canyon.

**Fig. 3.** Leeward and windward footpath concentrations of tracer gas for models with varying mesh discretization schemes.
A series of model configurations were also examined with extended heights above the rooftop of the buildings of Hr (Hr equals to the maximum height of H₁ or H₂ multiplied by an extended height factor, X) to allow air flow to enter or exit the canyon above the buildings. Values of Hr (see Fig. 2) where X = 0.25, 0.5, 1.0 & 2 times the greater value of H₁ or H₂ were examined. Fig. 4 illustrates the plot of the measured pollutant concentrations for each of the model configurations. Observing the 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.

**Fig. 4.** Leeward and windward footpath concentration of tracer gas for models with varying extension height above rooftop.

In addition, to optimise the computational time of a typical model configuration, an analysis of 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 and the number of iterations could be reduced per time step at different stages during the model run. The default convergence criteria in Fluent are typically 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 test are displayed in Table 1. The results identified the allowance for a reduction in iterations over time to reduce the cumulative running time of the models. A reduction in the number of iterations was
considered adequate when a convergence level of over 99.99% (values less than 0.01% in Table 1) was identified.

Table 1. Iteration per time step test to optimise model computational running times (displayed as percentage of value of iteration divided by value of final iteration).

3. Results

3.1 Asymmetrical Canyon Models

The results of the investigation for the asymmetrical canyon models of varying $H_1/H_2$ ratios are presented in Figs. 5 & 6. The results compare the pollutant concentration between the reference and footpath LBW models and present the difference as a percentage for each $H_1/H_2$ ratio at heights of 1.00m and 1.76m, respectively. The results showed that the presence of two footpath LBWs provides varied results on both footpaths.

The results varied on the leeward footpath (Fig. 5) with an initial reduction in the pollutant concentration of 17% for a $H_1/H_2$ of 0.5 at a height of 1.76m. The difference reduced with increases in the $H_1/H_2$ ratio up to 1.1, where an increase in the pollutant concentration of 9% was calculated between the model configurations. An upward trend was identified from a $H_1/H_2$ of 1.1, reaching a reduction in the pollutant concentration of 3% for a $H_1/H_2$ of 1.5. A similar pattern of reductions and increases in the differences between the model configurations was noted at a child height of 1.00m. The percentage reduction in pollutant concentration ranged from 24% for a $H_1/H_2$ ratio of 0.5, to an increase of 2% for a $H_1/H_2$ of 1.1 and a maximum reduction of 30% for a $H_1/H_2$ of 1.5.
Fig. 5. Plot of average percentage pollutant concentration on leeward footpath in different $H_1/H_2$ ratio canyons at respective heights.

On the windward footpath, the results (displayed in Fig. 6) showed reductions in the pollutant concentration for all $H_1/H_2$ for all asymmetrical ratios. At adult height of 1.76m, the reductions calculated ranged from a minimum of 26% for a $H_1/H_2$ ratio of 0.8 with incremental increases in the reduction to 40% and 48% for a $H_1/H_2$ of 0.5 and 1.5, respectively. The percentages reduction at child height of 1.00m ranged from a minimum of 30% for a $H_1/H_2$ ratio of 0.8. 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.

Fig. 6. Plot of average percentage pollutant concentration on windward footpath in different $H_1/H_2$ ratio canyons at respective heights.

3.2 Footpath and Central LBW Layouts

The comparative results for the footpath and central LBW configurations are shown in Table 2 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. The results show a reduction in almost all asymmetrical layouts on both the leeward (LW) and windward (WW) footpaths. The pollutant concentration was reduced by up to 30% on the leeward footpath at a height of 1.00m for a $H_1/H_2$ ratio of 1.5, however, and increase was observed for a $H_1/H_2$ of 1.0 on the leeward footpath of 14% with the introduction of footpath LBWs at a height of 1.76m. The implementation of a central LBW provides reductions in pollutant concentrations for all $H_1/H_2$ ratios on the leeward footpath, with concentration reductions ranging
from 12% ($H_1/H_2$ of 1.0 at 1.76m height) to a maximum of 50% ($H_1/H_2$ of 1.5 at 1.00m height).

Reductions in pollutant concentrations were calculated for all $H_1/H_2$ asymmetrical ratios in both LBW layouts on the windward footpaths. The reductions ranged from 36% to 50% on the windward footpath with footpath LBWs, at 1.00m heights for a $H_1/H_2$ ratio of 1.0 and 0.5, respectively. The reduction in pollutant concentrations were more prominent on the windward footpath for a central LBW as reductions ranged from 39% to 64%, at a height of 1.00m for a $H_1/H_2$ ratio of 1.0 and 1.5, respectively.

Table 2. Percentage difference of reference model to footpath and central LBW models for a high (8 m/s) wind speed in a perpendicular direction to street canyon.

For a low wind speed of 2 m/s in a perpendicular wind direction, the comparative results for the footpath and central LBW configurations are shown in Table 3. The results show a combination of reductions and increases in pollutant concentrations on both the leeward (LW) and windward (WW) footpaths. A small increase in the pollutant concentration of 13% ($H_1/H_2$ of 1.0 at 1.76m height) occurred on the leeward footpath with the implementation of the footpath LBWs, with reductions of up to 38% measured at a height of 1.00m for a $H_1/H_2$ ratio of 1.5. A significant increase in the pollutant concentration of 92% was evident on the leeward footpath for a $H_1/H_2$ of 0.5 at a height of 1.00m with a central LBW, yet a larger reduction was evident for a $H_1/H_2$ of 1.5 at a height of 1.00m of 53%. On the windward footpaths, reductions in the pollutant concentrations occurred for all $H_1/H_2$ asymmetrical ratios in both the footpath and central LBW layouts. The reduction in pollutant concentrations on the windward footpath with footpath LBWs ranged from 34% to 59% (at 1.76m height) for $H_1/H_2$ ratios of 1.0 and 0.5, respectively. The reduction on the windward footpath for the
central LBW ranged from 32% to 61%, at a height of 1.00m for \( H_1/H_2 \) ratios of 1.0 and 1.5, respectively.

Table 3. Percentage difference of reference model to footpath and central LBW models for a low (2 m/s) wind speed in a perpendicular direction to street canyon.

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 for different wind speeds ranged from as little as 1%, to a maximum of 17% on the leeward footpaths at a height of 1.76m for \( H_1/H_2 \) ratios of 1.0 and 0.5, respectively. For the central LBW models, the differences were more significant, ranging from 1% to 106% on the leeward footpath for \( H_1/H_2 \) ratios of 1.5 and 0.5, respectively.

4. **Discussion**

4.1 *Asymmetrical Canyon Models*

The implementation of 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 [19, 32]. 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 that a change in the canyon asymmetrical ratio creates different air flow patterns which effects pollutant dispersion at street level [4, 35]. Fig. 7 illustrates the dispersion patterns in the footpath LBW models for a range of \( H_1/H_2 \) ratios on the leeward footpath. The plots also display the magnitude of the resultant velocity vectors for the tracer gas concentration. The pollutant concentrations generally increased from a \( H_1/H_2 \) of 0.5 (Fig. 7(a)) to
1.1 (Fig. 7(d)) in the reference and footpath LBW models, with steady concentration reductions
from a $H_1/H_2$ of 1.1 to 1.5 (Fig. 7(f)) at adult and child heights. The increase of the pollutant
concentration on the leeward footpath from a $H_1/H_2$ of 0.5 to 1.1 is due to the velocity vectors
entering the canyon and transporting additional pollutants to the leeward footpath. The increase of
the $H_1/H_2$ ratio from 1.1 to 1.5 forces increased volumes of clean air with higher magnitudes of
velocity which causes the development of a more prominent primary vortex and transports more
pollutants from street to roof level.

From a calculation of the percentage difference in pollutant concentration between the reference and
LBW models, a similar trend was identified between the models as the minimum percentage
difference occurred for a $H_1/H_2$ of 1.1 with incremental increases in the percentage difference
occurring for both smaller and larger $H_1/H_2$ ratios. As the $H_1/H_2$ ratio increased from 0.5 (Fig. 7(a))
to 0.9 (Fig. 7(c)), a notable change was identified between a $H_1/H_2$ of 0.9 and 1.1 (Fig. 7(d)) as the
lateral (+Z direction) velocity vectors became less prominent and was replaced by a counter
clockwise rotational eddy (in XY plane) in the canyon. Between a $H_1/H_2$ ratio of 1.1 (Fig. 7(d)) and
1.5 (Fig. 7(f)), it can be 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.

Fig. 7. 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.

Fig. 8 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 pollutant concentrations followed the same patterns in both the reference
and LBW models on the windward footpath, with reduced concentrations for an increasing $H_1/H_2$ from 0.5 (Fig. 8(a)) to 0.9 (Fig. 8(c)), followed by an increase from a $H_1/H_2$ of 0.9 to 1.1 (Fig. 8(d)) and a near linear reduction in the pollutant concentration from a $H_1/H_2$ of 1.1 to 1.5 (Fig. 8(f)). The reduction of the pollutant concentration on the windward footpath from a $H_1/H_2$ of 0.5 to 0.9 is due to the velocity vectors transporting increased fractions of clean air to the windward footpath. The development of the primary vortex in the canyon caused an increase in the pollutant concentration on the windward footpath between a $H_1/H_2$ of 0.9 and 1.1. A reduction in the pollutant concentration occurred between a $H_1/H_2$ ratio of 1.1 and 1.5 as the larger windward building height increased the volume of clean air directed downwards towards the windward footpath and increased the effectiveness of the primary vortex to transport pollutants away from the windward footpath.

The percentage difference in the pollutant concentration between the reference and LBW models identified a reduction in the effectiveness of the LBW from a $H_1/H_2$ ratio of 0.5 to 0.8 and a steady improvement of air quality from a $H_1/H_2$ of 0.8 to 1.5. A similar change like that observed in the leeward LBW models is evident, as the $H_1/H_2$ ratio increases from 0.5 (Fig. 8(a)) to 0.8 and this is evident in the plot for a $H_1/H_2$ of 0.9 (Fig. 8(d)) as the lateral (+Z direction) velocity vectors increase in magnitude and direction to counter clockwise rotational vectors (in XY plane). An increased fraction of clean air was directed into the canyon and downward along the face of the windward building between a $H_1/H_2$ of 0.9 and 1.5. The clean air entering the canyon combined with the implementation of the LBW incrementally reduced the transport of pollutants to the windward footpath and retained increased fractions of clean air along the footpath.

**Fig. 8.** Plots of pollutant concentrations (kmol/m3) 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.
4.2 Footpath and Central LBW Layouts

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 and urban street canyon and therefore effect the dispersion of air pollutants at street level. In addition, the results aimed to identify the effect of wind speed on the dispersion patterns of air pollutants in the urban canyons. After comparing the data and the graphical plots of the tracer pollutants in the asymmetrical models, it was identified that two very distinct patterns of air flow occur with different LBW configurations (Fig. 9). A central LBW (Fig. 9(b)) creates two distinctive primary eddies as opposed to a single primary eddy created in a footpath LBWs (Fig. 9(a)) model, and these vortices are responsible for the transport of pollutants from street level to the roof of the canyon.

Fig. 9. Displays plots of pollutant dispersion in footpath and central LBW models for a H₁/H₂ ratio of 1.0 for high (8 m/s) perpendicular wind conditions (pollutant concentrations in kmol/m³).

The reduction in pollutant concentrations differs between the two LBW configurations, but a general trend of improved air quality is evident with an increase in the H₁/H₂ ratio. The reduction in the pollutant concentration in the central LBW models generally exceeds the reduction in the counterpart footpath LBW models. This is due to the formation of two eddies (Fig. 9(b)) in the central LBW models as the H₁/H₂ ratio increases as pollutants are transported away from both the leeward and windward footpaths before escaping the street canyon at roof level. On the leeward footpath, there is a reduction in the pollutant concentration of up to 50% and an increase in the transport of clean air with an increase in the H₁/H₂ in both LBW layouts. A reduction is more prominent for the central LBW models. Reductions of approximately 24% and 17% are evident for
both LBW models between $H_1/H_2$ ratios of 1.0 to 1.5 at heights of 1.00m and 1.76m, respectively. This is 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 primary eddies in the canyon and transporting pollutant away from the leeward footpath (Fig. 9(b)). There is a large and consistent reduction in the pollutants concentration of the windward footpath. The results show evidence of the lowest reduction for a $H_1/H_2$ of 1.0 (36% to 42%) for all LBW configurations with small increases in the rate of reduction for a $H_1/H_2$ of 0.5 (40% to 50%) and the most significant reduction (48% to 64%) evident for a $H_1/H_2$ ratio of 1.5.

Examining the lower wind speed models, a broader range of percentage differences was identified between the reference models and the two LBW model configurations. The most notable difference in pollutant concentration between the model configurations was evident on the leeward footpath with a canyon $H_1/H_2$ ratio of 0.5. A significant increase of 91% was calculated for the central LBW model, due to less clean air entering the canyon and the reduced wind velocity entering downwards on the windward footpath, which reduces the strength of the primary vortex and thus trap pollutants in the leeward region of the canyon. This agrees with the findings by a previous study, which stated that vortices are unstable in low wind speeds [36]. As the $H_1/H_2$ ratio is increased to 1.0 and 1.5, reductions in the pollutant concentration become more prominent with reductions reaching up to 31% and 53% for their respective asymmetrical ratios. A consistent reduction in the pollutant concentration was evident in all models of the windward footpath for a wind speed of 2 m/s. The results ranged from a minimum reduction of 32% to a maximum of 61%. The lowest reduction occurred for a $H_1/H_2$ of 1.0, with reductions ranging from 32% to 38%. Reductions of between 44% and 59% were identified for a $H_1/H_2$ of 0.5 (44% to 59%) with the most significant reductions evident for a $H_1/H_2$ ratio of 1.5 of between 44% and 61%.
Fig. 10 illustrates the difference in the dispersion flow patterns and the pollutant concentration at street level in the street canyons for a $H_1/H_2$ of 1.0 in different wind speeds. Differences in the pollutant concentration are evident after comparing each of the model configurations at different wind speeds. 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 identifies the influence of wind speed on pollutant dispersion and the strength of the vortices created which transport pollutants out of the street canyon.

Fig. 10. Displays plots of pollutant dispersion in footpath and central LBW models for a $H_1/H_2$ ratio of 1.0 for (a) high (8 m/s) and (b) low (2 m/s) wind velocities (pollutant concentrations in kmol/m3).

5. Conclusions

The results of this investigation identified the potential of LBW passive controls acting as a baffle in asymmetrical street canyons to control pollutant flow and improve air quality at street level. The implementation of footpath LBWs can lead to both increases and reductions in the pollutant concentration along the centre of the leeward and windward footpaths, depending on the asymmetrical $H_1/H_2$ ratio of the canyon. From the results of the footpath LBW models, the percentage difference in the pollutant concentration ranged from 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.

The results for the central LBW case were also compared to the findings from the asymmetrical modelling reference case. The results identified two air flow and pollutant dispersion patterns; one
primary vortex was created in the footpath LBW models, while two distinctive primary vortices
develop in the central LBW models. The results show that central LBW performs better for all
$H_1/H_2$ ratios for a high wind speed of 8 m/s. Results for both LBW configurations identified the
reduction in strength of the vortices for a low wind speed, specifically the lack of development of
one of the vortices in the central LBW model for a $H_1/H_2$ ratio of 0.5. Low wind speeds can
therefore reduce the fraction of pollutants that are transported from street level to roof level due to
the lack of development of the primary vortices.

The results of this paper informs those in urban planning and public policy makers on local street
canyon dispersion and the effects of introducing passive controls to urban canyons to improve air
quality at street level.

**Acknowledgements**

The authors would like to thank the programme for research and training in third level institutions
(PRTLI 4) for funding this research.
References


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Fig. 9. Displays plots of pollutant dispersion in footpath and central LBW models for a $H_1/H_2$ ratio of 1.0 for high (8 m/s) perpendicular wind conditions (pollutant concentrations in kmol/m³).

Fig. 10. Displays pollutant dispersion plots of footpath and central LBWs for a $H_1/H_2$ ratio of 1.0 for (a) high (8 m/s) and (b) low (2 m/s) wind velocities (pollutant concentrations in kmol/m³).
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Table 3. Percentage difference of reference model to footpath and central LBW models for a low (2 m/s) wind speed in a perpendicular direction to street canyon.
Research Highlights

- Canyon asymmetry influences air flow and pollutant dispersion in an urban canyon.
- LBWs acts as a passive control to alter the natural air flow patterns in a canyon.
- Two different passive control layouts led to distinct vortex and air flow patterns.
- Wind speed influences the formation of vortices in a canyon.
Table 1

<table>
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<th>Time Step (s)</th>
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Table 2

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<th>Central LBW</th>
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<td>1.76m 1.00m</td>
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<td></td>
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<td>LW WW LW WW</td>
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<tr>
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<td>17% 40% 24% 50%</td>
<td>15% 48% 13% 43%</td>
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<td>1.0</td>
<td>-14% 37% 7% 36%</td>
<td>12% 42% 26% 39%</td>
</tr>
<tr>
<td>1.5</td>
<td>3% 48% 30% 48%</td>
<td>29% 63% 50% 64%</td>
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Table 3

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$H_1/H_2$ of 0.5-1.5 (Windward Footpath)

Reduction in Pollutant Concentration (%)

$H_1/H_2$ Ratio

- 1.09m
- 1.76m
Pollutant Concentration on Leeward Footpath

(a) 1.00e-08
(b) 9.50e-09
(c) 9.00e-09
(d) 8.50e-09
(e) 8.00e-09
(f) 7.50e-09
(g) 7.00e-09
(h) 6.50e-09
(i) 6.00e-09
(j) 5.50e-09
(k) 5.00e-09
(l) 4.50e-09
(m) 4.00e-09
(n) 3.50e-09
(o) 3.00e-09
(p) 2.50e-09
(q) 2.00e-09
(r) 1.50e-09
(s) 1.00e-09
(t) 5.00e-10
(u) 0.00e+00

Road
Footpath
Pollutant Concentration on Windward Footpath

(a) 
(b) 
(c) 
(d) 
(e) 
(f)