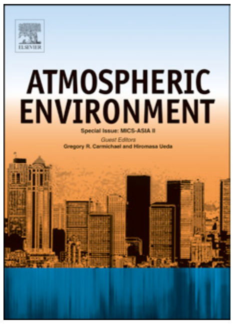

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OPTIMIZING THE USE OF ON-STREET CAR PARKING SYSTEM AS A PASSIVE CONTROL OF AIR POLLUTION EXPOSURE IN STREET CANYONS BY LARGE EDDY SIMULATION.

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Abstract

An investigation was carried out to establish the effectiveness of parked cars in urban street canyons as passive controls on pedestrian pollutant exposure. A numerical model of a generic street canyon was developed using a large eddy simulation (LES) model to compare personal exposure on the footpath with and without the presence of parked cars. Three configurations of car parking systems were investigated (parallel, perpendicular & 45° parking) in addition to the influence of wind speed, wind direction and car parking occupancy. A tracer gas (CO_2) was used as a representative pollutant from vehicular sources within the street canyon models. The results indicated that parked cars may act as a temporary baffle plate between traffic emissions and pedestrians on the footpath. Reductions in exposure of up to 35% and 49% were attained on the leeward and windward footpaths in perpendicular wind conditions, with parallel winds allowing up to 33% pollutant reduction on both footpaths for parallel parking. The perpendicular and 45° car parking configurations investigated proved less successful as passive controls on air pollution exposure and an increase in pollutant concentration occurred in some models. An investigation of parking space occupancy rates was carried out for parallel parked cars. The fraction of parked cars influenced the level of reduction of pollutants on the footpaths with steady reductions in perpendicular winds, yet reductions were only evident for occupancy rates greater than approximately 45% in parallel wind conditions. One negative impact associated with the parked cars study was the increase of pollutant levels on the roadway as the parked cars acted as a baffle wall, which trapped pollutants in the road. The paper underlines the potential of on-street car parking for reducing the personal exposure of pollutants by pedestrians and the optimum parking layout to achieve maximum health protection.

Keywords: Street Canyon; Car Parking; Air Pollution; Passive Controls; LES.

1. Introduction

Air pollution in the urban atmosphere continues to receive a great deal of research focus in order to address the various adverse impacts it has on climate change, the environment and on human health. The transport sector has been shown to be responsible for a significant proportion of air pollution emissions in the urban environment (O' Mahony et al., 2000). While the majority of commuters in many western cities travel by private car, the next largest group are often pedestrians (DTO, 2004). Indeed pedestrians globally represent one of the largest groups of commuters, a group that are often omitted from investigations of commuter exposure (Kaur et al., 2007). In general, pedestrian exposure to traffic air pollutants has been widely reported as being lower than other modes of transport such as the private car, taxi, bus and cyclists (Taylor and Ferguson, 1997; McNabola et al., 2008b). However, as this zero emissions form of transport does not contribute to urban air pollution, efforts should be made to reduce their exposure to air pollutants further in order to encourage more commuters to walk. Much international effort from governments to vehicle manufacturers is underway to reduce emissions intensity and the overall CO_2 emissions (ENCom, 2005; DCMNR, 2006) through the introduction of carbon based tax systems (Pearce, 1991; Giblin and McNabola, 2009), improvements in vehicle technology and increases in public transport usage. Research among traffic engineers and urban planners is ongoing with a view to reducing congestion and emissions through congestion charging and intelligent transport systems (Washbrook, 2002). The development and implementation of alternative fuels has also aimed to reduce transport emissions. All of these measures aim to reduce air pollution concentrations in the atmosphere to help combat climate change, alongside minimising impacts on the environment and human health.

An approach which has focused purely on human health protection in recent years is that of passive controls on air pollutant dispersion in urban street canyons (McNabola, 2010). This research identified common physical urban features such as solid free standing walls, trees or bushes (McNabola et al., 2008a; Buccolieri et al., 2009) to act as baffle plates, disrupting the normal dispersion of air pollutants when located in street canyons. Passive controls can be configured in street canyons in order to reduce air pollution exposure on footpaths through the manipulation of natural dispersion patterns. McNabola et al. (2008a) carried out a combined monitoring and numerical modelling study to highlight the role of an existing low boundary wall (LBW) in an urban street in Dublin, Ireland. The LBW was situated between the roadway footpath and the pedestrian boardwalk. The results of the study indicated greater 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. A generic street canyon model with a centrally located LBW was found to yield reductions in pedestrian exposure of up to 46% during perpendicular wind flow conditions and up to 75% during parallel wind conditions. The percentage reduction achieved using LBWs was found to be unaffected by the magnitude of the wind speed. A configuration consisting of two LBWs located adjacent to each footpath was also investigated and predicted reductions in pedestrian exposure of up to 65% for parallel wind conditions (McNabola et al., 2009).

Previous investigators have also examined the influence of avenue like tree planting on the dispersion of pollutants 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 (Gromke et al., 2008; Buccolieri et al., 2009). These studies highlighted the H/W ratio as the crucial parameter of pollutant dispersion compared to the density or porosity of the trees. Street canyon geometry is therefore a crucial factor of air dispersion. Studies such as that of Santiago & Martin (2005) identified the creation of multiple vortices in asymmetric street canyons. Further studies similarly highlight the effects of geometry on the flow pattern and turbulence properties (Xie et al., 2005; Liu et al., 2005; Di Sabatino et al., 2008)

Heist et al., (2009) investigated the effects of roadway configuration on pollutant dispersion, identifying the recirculation of air flow due to noise barriers on either side of the road. This form of passive control caused a reduction of ground level concentrations and an accumulation of pollutants on the roadside of the barrier which extends downwind of the pollutant source. The development of a pedestrian ventilation system in high rise urban canyons poses as another method of air exchange and enhanced mixing between pollutants at ground level with clean air at roof level. The system utilises the urban heat island created across the canyon floor and the thermal stratification common to high rise canyons to promote natural and forced convection which provides the pressure gradient for a vertical duct system (Mirzaei and Haghighat, 2010).

Within this framework, the present study focuses on the potential of on-street parked cars to act as a passive control on air pollutant dispersion in a similar manner to that of previous investigations into LBWs, noise pollution barriers, road design and avenue trees. By developing numerical models of typical urban street canyons using the commercial CFD software code Fluent 6.3 (Fluent, 2008), the potential percentage reductions in pedestrian exposure was investigated for different on-street car parking configurations. The investigation examined the potential reductions achievable using parallel, perpendicular and 45^o parking configurations as passive controls. The impact of car space occupancy was also investigated as were the impacts of wind speed and wind direction.

The methodology section to follow outlines the modelling requirements and procedures for the different cases investigated. The results section identifies the outcome of each of the individual cases and the subsequent car space occupancy modelling study. A detailed analysis of the results was carried out in the discussion section with the main conclusions drawn from this section to conclude the paper for the context of future urban planning strategies. The results of this paper inform those in urban planning and public policy makers on the optimum urban street canyon layout, incorporating an on-street car parking regime while improving air quality on footpaths. Implementation of the findings presented herein will help to promote healthy living and improve human health for pedestrians.

2. Methodology

This study comprised four numerical tests to assess the potential of on-street parking as a passive control on air pollutants in urban street canyon. The first three series of tests investigated the percentage reduction in pedestrian exposure to the tracer pollutant (CO_2) as a result of three different car parking configurations in a street canyon with a height to width ratio (H/W) = 1.0 for scenarios of varying inlet velocity wind speeds (2, 4, 8 & 16m/s) and direction (0^o & 90^o). Two sets of models were constructed for each scenario; the first was a reference model containing no parked cars and the second was an identical model containing cars parked parallel to the footpath on both sides of the road. The personal exposure of pedestrians in both models was then compared to yield the percentage difference between the two models. The three tests included Case 1, which investigated parked cars parallel to the footpath, Case 2 investigated cars parked perpendicular to the footpath and Case 3 carried out an identical evaluation for cars parked at 45^o to the footpath. Figure 1(a) displays the generic model dimensions to maintain a H/W ratio of 1.0 and the dimensions of the medium-sized car (1.7 x 4.6 x 1.8m high) used in the models are illustrated in Figure 1(b). The roadway consisted of two 4m wide traffic lanes with two-directional traffic, two 3m footpaths and two parking bays on both sides of the road with varying width for each of the three cases.

Figure 1, (a) model geometry cross-section through generic street canyon model, (b) dimensions of medium-sized car (all dimensions in metres).

Following an assessment of the results of the first three cases the optimum car parking configuration for passive control of air pollutants was selected and further investigated whereby the impact of varying car parking occupancy rates were examined in Case 4. This investigation of different occupancy rates determined the effect of different percentages of car parking spaces occupied at any one time. A comparison of low versus high occupancy rates was then made to determine their associated positive or negative impacts on pollutant dispersion and their ability to improve air quality on the footpath. The occupancy rates were chosen to identify any pattern or relationship between the rate of pollutant reduction and the fraction of car parking spaces not occupied.

2.1 Numerical Modelling

The solver used to simulate the turbulent flow of air in the street canyon models was the large eddy simulation (LES) model. The modelling of the dispersion of air pollutants using CFD has been carried out by previous investigators commonly using either the k-ε turbulent model or the LES model (Ning et al., 2005; Tsai and Chen, 2004). The LES model was used here rather than k-ε due to a more complex geometry from the typical street canyon in the region of the parked cars at street level (So et al., 2005). Several studies have evaluated the LES models to simulate air flow and pollutant dispersion in urban canyons and found that a strong agreement between the CFD models and wind tunnel experiments (Baker et al., 2004; Liu and Barth, 2002).

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 to 4 below:

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

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

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

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 below:

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

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

The airflow in the model was simulated from the flow of air over the top of the buildings and at either end of the street section by the velocity inlets, according to the wind speed and direction selected. The dispersion of the tracer gas in the turbulent air stream from traffic was simulated by releasing concentrations of the gas at the street level along the roadway surface.

2.2 Modelling Setup & Procedure

The generic canyon models were constructed using Gambit v2.3, a CFD model development and meshing tool as shown in Figures 1 & 2. The surfaces of the canyon floor, buildings and vehicles were constructed as wall boundaries to resemble the impermeable nature of their characteristic materials. Additional faces of the model 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. Each model was constructed with a H/W ratio of 1 to maintain a similar shaped primary eddy for each model. The road lane and footpath widths remained constant in all of the models, with a varying parking bay width in each model case. This created a canyon of different width in each of the three case models. The width of the roadway was kept the same to maintain a similar emissions rate in each model and a constant footpath width was important to compare the pollutant concentration on the footpath in each case. The model was extended above the rooftop of the buildings by a height of H/2 to allow for air flow entering or exiting the canyon above the buildings.

Figure 2, Generic street canyon layout for Cases 1-3 with H/W of 1.

Tominaga et al. (2008) advises a grid discretization test prior to proceeding with a modelling study to ensure accurate results. Therefore, a sensitivity test was carried out to obtain the optimum mesh type and size in terms of model prediction accuracy and computational timeframe requirements. Three grid schemes were assessed where the mesh was configured with a high density on the canyon floor decreasing to a lower density above roof top level as the canyon floor was the location of interest. The sensitivity test varied the mesh dimensions with triangular mesh elements of 0.4 and 0.6m on the canyon floor and the rest of the volume with either a 1.0 or 2.0m tetrahedral mesh. The largest floor mesh of 0.6m was considered unsuitable due to the minimum spacing of 0.4m between vehicles in the parked car models. The 0.4m floor mesh provided a strong agreement in results for both volumetric meshes; therefore the large 2.0m mesh was chosen to optimise computational requirements. The floor of the canyon model was meshed with 0.4m spaced triangular mesh elements in a paved grid configuration with the overall model frame subsequently meshed with a 2.0m tetrahedral mesh. The minimum requirements for grid geometry set out by the COST Action 732 were adhered to for the construction of the CFD models (COST Action 732, 2005; Franke et al., 2007). Franke et al. (2007) advised a minimum of two grid nodes between a solid surface and a monitoring point, which improved the accuracy of monitoring predictions.

Emissions of the tracer gas (CO_2) were released from the road surface at ground level (i.e. $Z = 0$) in each model at a fixed generic emissions rate of 1 x 10^{-5} kg/s as shown in Figure 2. The CO_2 acts as an indicator pollutant to assess the dispersion of any pollutant common to an urban street canyon and as an indicator pollutant it has no health effects within the canyon. A comparative study was carried out to compare CO_2 (44.01 g/mol) with a validated tracer gas, C_2H_6 (30.07 g/mol) to justify the use of the gas in the models (Moryń-Kucharczyk and Gnatowska, 2007; Shao and Riffat, 1994; Heist et al., 2009). A 94% agreement was observed between the results for the comparative study, which was deemed satisfactory in assessing the pollutant concentration on canyon footpaths. The dispersion of the tracer gas within the reference and parked cars model utilises the species transport and reaction equations to predict the flow emitted from road surface. The road boundary face was oriented parallel to the horizontal axis and acted as the emissions surface in all models for the mass fraction of the tracer gas. The continuous release of the tracer pollutant was attached to the road surface to replicate an uninterrupted flow of vehicle emissions across the road the road surface area. Each model was run using the large eddy simulation (LES) model for varying durations of time until each model converged. The LES model was selected as a high level of geometrical complexity existed within the domain of the canyon models. A default value was taken for the turbulence intensity at 10% in the velocity inlet properties of the models. Each model was run for several hundred time steps with 100 iterations per time step. Convergence was deemed adequate when the model reached a steady state value when compared to a minimum moving average value of 50-100 time steps. Vehicular turbulence was simplified in the models to reduce the computational running time of the CFD models. Due to the generic layout of the models and the use of similar surface emissions in each model, the results of the study provided accurate evidence of the optimum car parking layout to reduce emissions of adjacent footpaths.

2.3 Cases 1-3: Parallel, Perpendicular and 45° Parking

Each modelling investigation comprised two nearly identical models which differed by the absence of parked cars in the reference case. Figure 2 shows the cross section of the generic street canyon layout. Each model comprised a street canyon with a H/W ratio of 1.0, with the canyon width (W_c) equal to the building height (H_b) on both sides of the symmetrical canyon. The roadway was divided by two 4m wide traffic lanes, two 3m footpaths and two parking areas of width, P_w on either side of the street canyon. The measurements for preparing the individual case studies, in conjunction with Figure 2 are shown in Table 1. In the reference model the car parking area were empty while in the parallel parking model, medium-sized cars were positioned into each space on both sides of the street until no empty parking spaces were available (i.e. occupancy = 100%).

Table 1 – Cross sectional dimensions for Cases 1-3 models (all dimensions in metres).

The spacing between vehicles varied for each modelling study and this is represented by the value of perpendicular vehicle distance (V_d) in Table 1. Figure 3 shows the plan and side view layouts for the three parked car layouts investigated in this study.

Figure 3, Plan and side view of geometry for Cases 1-3 of parked car configuration.

A monitoring line was inserted into each model at a height of 1.76m, to represent the path of a pedestrian walking the full length of the canyon at the centre of each footpath. The data output from each monitoring line recorded the area weighted average of the pollutant concentration across the entire line every second. A result was obtained for each model by taking an average value from the output data from the models where a steady was observed in the monitoring path lines. Once concentrations in the canyon had reached a steady state, the mean difference in exposure between the reference and parked car models was then calculated from the data and expressed as a percentage reduction of the mean reference exposure concentration. The models were solved for scenarios of varying wind speed and direction and the average pedestrian exposure concentrations along the centre of both footpaths was monitored over time. Figure 4 shows a typical model output for the personal exposure of the tracer gas and the difference in pollutant concentrations between the parked cars model and the reference case. In this particular example the difference between the personal exposure to the pollutant on the leeward footpath between the two models was negative i.e. personal exposure to an air pollutant was reduced due to the presence of parked cars. Expressing this as percentage reduction over the reference case places this reduction in exposure into a format suitable for comparison to other car parking systems.

Figure 4, Determining the percentage reduction in CO_2 pedestrian personal exposure achieved using parked cars in Case 1 compared to the reference model (leeward footpath; wind speed = 16m/s; wind direction = 90^o).

2.4 Case 4: Parking Space Occupancy

Based on the outcome of the modelling results for the three parked car studies, Case 1 was chosen for further analysis as a reduction in pollutant concentration was evident for all model scenarios of different wind directions and velocities. This part of the modelling study investigated the relationship of pollutant reduction for different car occupancy rates in the parking bays. The number of cars parked on the 200m stretch of road modelled in Case 1 amounted to 40 cars on each side of the street in comparison to a full capacity of 66 and 39 on both sides of the street for the Case 2 and Case 3 models, respectively. 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 and windward sides of the canyon were numbered 1 to 40. The Excel tool chose a random number between 1 and 40 corresponding to a vehicle in the model to be removed. 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 were removed to correspond to a 90% occupancy rate. This random number generator was used for the leeward and windward sides of the canyon separately, to replicate the random pattern that would be normal in a canyon with car parking. Case 4 investigated these occupancy rates for the same conditions as the previous cases, namely the range of wind speeds, wind directions and the CO_2 emissions rate of 1×10^{-5} kg/s released from the roadway.

3. Results

3.1 Case 1: Parallel Parking

The results of the Case 1 investigation for parallel parked cars are presented in Table 2. The data show that for a perpendicular wind flow the presence of parallel parked cars provides a reduction in pedestrian exposure compared to the absence of parked cars of up to 35% on the leeward footpath and up to 49% on the windward footpath. For a parallel wind direction, a symmetrical layout was constructed for Case 1, as the average concentration for the leeward and windward footpaths was determined to be the same for the reference and parallel car model. The average reduction in pedestrian exposure was found to be up to 33% in the parallel wind models. The differences between pollutant concentrations for low and high wind speeds amounted to a maximum of 4% for parallel and perpendicular wind conditions.

Table 2 – Case 1 percentage reduction data.

3.2 Case 2: Perpendicular Parking

Table 3 displays the results of the Case 2 investigation for perpendicular parked cars. A combination of positive and negative results was identified in Case 2, as numbers with an associated negative sign constituting an increase to the measured pollutant levels between models. The data shows that the presence of perpendicular parked cars provided a decrease in pollutant concentration of up to 41% on the windward footpath and an average increase of up to 37% on the leeward footpath. The increase in wind speed incurred a small deviation of up to 4% of the pollutant concentration for perpendicular winds. In parallel wind conditions, an average increase in pedestrian exposure of up to 30% on both footpaths was found between the reference and perpendicular car models. A significant difference of 18% in pollutant reduction was also noted between low and high wind speeds, suggesting the influence of wind was more significant in parallel wind conditions.

Table 3 – Case 2 percentage reduction data.

3.3 Case 3: 45^o Parking

Table 4 presents the results of the Case 3 investigation for 45^o parking cars. Increases in pollutant concentrations were observed in some of the parked car models in Case 3. These increases are represented as negative reductions in Table 3 in a similar manner to the previous case results. For a perpendicular wind flow, the data shows that the introduction of 45^o parked cars causes an average increase in pedestrian exposure compared to their absence of up to 28% on the leeward footpath. Pollutant reduction was observed on the windward footpath of up to 56% for perpendicular winds. Due to the 45^o parking configuration, a symmetrical layout was not present in the canyon and therefore separate results were attained for both the leeward and windward footpaths in parallel wind conditions. The presence of parked cars was found to provide an increase in pedestrian exposure compared to their absence on average of 2% on the leeward footpath and a significant increase of up to 288% on the windward footpath with parallel wind conditions. The difference in pollutant concentration with a change in wind speed was noted to be most significant for parallel winds in the canyon.

Table 4 – Case 3 percentage reduction data.

3.4 Case 4: Parking Space Occupancy

The occupancy rate of the parking bays on either side of the road was considered to be influential to the level of reduction of the pollutant concentration on the adjacent footpaths. From Case 1, a reduction of up to 33% was observed between the reference models and the 100% occupancy models for parallel wind conditions. From Figure 5, an initial increase of pollutant concentration occurred from 0% to 45% parking space occupancy, which was followed by an incremental reduction in pollutant levels for subsequent increasing occupancy rates. The results show an influence of wind speed on pollutant reduction with respect to low occupancy rates, with the pattern of the plot indicating this effect was not substantial for higher occupancy rates.

Figure 5, Plot of average footpath pollutant concentration versus occupancy rates for a Case 4 model in parallel wind conditions.

The plots of occupancy rate against the average pollutant exposure reduction for a prevailing wind perpendicular to the canyon are displayed in Figures 6 and 7. The results indicate a relationship between the occupancy rates of cars in the parking bays to the percentage reduction of pollutant concentrations for all wind speeds. The figures show an overall reduction in pollutant concentration as the occupancy rate was increased on both footpaths for perpendicular winds. The pollutant concentrations on the leeward side of the canyon are influenced by the occupancy rates of the adjacent parking bay. From observations of Figure 7, an exponential reduction in pollutant levels was found across all occupancy rates from 0% to 100%, with the most significant reduction evident between the 90% and 100% occupancy rates. A similar pattern was observed for each wind speed, suggesting that it has no significant impact on the reduction of pollutants.

Figure 6, Plot of average leeward footpath pollutant concentration versus occupancy rates for a Case 4 model with perpendicular wind conditions.

The plot of the windward footpath data, as shown in Figure 7, presents a visible sigmoid or s-curve. This plot identified a negligible difference between occupancy rates ranging from 0% to 10% and from 90% to 100%. A curvilinear relationship was found between occupancy rates of 10% to 90% with an overall steady decrease in pollutant concentration between the different occupancy rates modelled in this study.

Figure 7, Plot of average windward footpath pollutant concentration versus occupancy rates for a Case 4 model with perpendicular wind conditions.

4. Discussion

4.1 Case 1: Parallel Parking

Despite the fact that the parallel parked cars present a temporary 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 boundary walls include the fact that despite the presence of gaps between the cars, in cross section they present a much wider and taller boundary than the solid wall investigated by studies such as McNabola et al. (2009). Pollutants emitted at road 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 8, shows a plot of the pattern of air flow through 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 8, Resultant velocity vectors plot for the concentration of CO_2 tracer emissions for a 4m/s perpendicular wind in Case 1 for (a) reference model without parked cars and (b) model with parallel parked cars.

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 air flow in the canyon in a similar fashion to boundary walls. Figure 9 illustrates the direction of air flow for a primary vortex and a secondary vortex within the canyon in perpendicular wind conditions. The plot identifies the direction that air flows through the canyon and which pollutants are carried from the road towards the leeward side of the canyon. 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 combination of this clean air and the parallel parked cars acting as a baffle wall improve the air quality on the windward footpath and reduce the pollutant concentration by up to 49%. The boundary created by the parallel parked cars reduces pollutant levels on the leeward footpath by up to 35% with only a small decline in the level of pollutant reduction for increasing wind speeds. The rate of reduction was not as significant on this footpath as the primary vortex carries pollutants towards the leeward footpath and secondary vortices located in this region causes mixing with the clean air. Small wind channels are also created on the leeward footpath as the air travelling through the 0.4m spacing between vehicles. This air diverges when it reaches the footpath; producing additional secondary eddies as the air spreads both clockwise and anti-clockwise. The increase in wind speed incrementally decreases the percentage reduction of the parked cars on the leeward footpath. This decrease was due to the higher wind speeds increasing the penetration of pollutants into the leeward footpath, reducing the fraction of pollutants that escape to the canyon floor in less active flow scenarios. The parked cars provide a baffle wall in parallel wind conditions to reduce the pollutant concentration by up to 33%. The wind speed does not make a significant difference to the potential reduction of pollutants between the reference and parked car models in both wind velocities.

Figure 9, Resultant velocity vectors plot for the concentration of CO_2 tracer emissions in street canyon for a Case 1 model in perpendicular wind conditions.

4.2 Case 2: Perpendicular Parking

The perpendicular parked car model reduced pollutant concentrations in a similar manner to Case 1, and presents a much wider parking bay than the parallel parked cars. The spacing between vehicles was 1.3m in width, and this void contributes to approximately 43% of the total canyon length. The effect of this large void space for the perpendicular parked cars configuration reduces the potential for pollutant reduction compared to Case 1. Larger pathways for emissions are presented by greater voids between vehicles to travel between the road and the footpaths in Case 2. The alignment of the perpendicular parked car promotes pollutant flow towards the footpath as the wind flows over the car with more ease to the parallel parked cars layout for perpendicular wind conditions. The increase on the leeward side identifies the reduced effectiveness of the perpendicular parked car layout, as the large void spaces give rise to an increase in pollutant levels of up to 37%. The increase in pollutant concentrations was incremental to the reduction of the wind speed, as higher wind speeds promotes some improved dispersion in the large voids between the cars and reduces the time taken for pollutants to escape upwards towards roof level. The larger spacing width of cars in the Case 2 layout reduces their effectiveness as a baffle wall in comparison to Case 1, leading to an increase in pollutants travelling from the road to the footpath. A reduction of up to 41% on the windward sides gives evidence that the perpendicular parked cars can act as an effective baffle wall for pollutants travelling against the natural flow of air through a canyon for perpendicular wind conditions. The direction and spacing of perpendicular parked cars promotes increased turbulence and transport pathways for pollutants to disperse across the footpaths in parallel wind conditions. This large void spacing induces an increase of pollutant levels on both footpaths ranging from 12% to 30% for low to high wind speeds, respectively. An increase in wind speed enhances mixing of pollutants in the canyon and increases their penetration into the footpath zones, reducing the effectiveness of the perpendicular parked car in parallel wind conditions. The increase in pollutant concentration in Case 2 in comparison to the reduction in Case 1 highlights the influence of car spacing widths on pollutant penetration from the road to the footpath. Figure 10, 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.

Figure 10, Resultant velocity vectors plot for the concentration of CO_2 tracer emissions for a 4m/s perpendicular wind in Case 2 for (a) reference model without parked cars and (b) model with perpendicular parked cars.

A reduction of the spacing between perpendicular parked cars would improve the potential of the perpendicular layout as a passive control. However, this solution may not be feasible as a reduction in spacing would not allow sufficient width for car occupants to get into or exit their cars with ease.

4.3 Case 3: 45^o Parking

In Case 3, the 45^o parked car configuration provides an alternative layout to the conventional parallel and perpendicular parking cases. It requires the widest parking bay in comparison to the Cases 1 and 2, and it disturbs the natural flow of air for both parallel and perpendicular wind conditions. However, 45^o parking is considered the safest 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 configuration (Berger, 1975; Retting et al., 2003). An increase in pollutant levels of up to 28% was found on the leeward footpath, due to the channelling of the pollutants from the road to the footpath.

The diagonal parking layout provides the largest decrease in pollutant concentrations on the windward footpath, up to 56%. Higher wind speeds caused small increases of pollution on the leeward footpath and small decreases on the windward footpath for perpendicular wind conditions. The largest increase and decrease in pollutant concentrations on the leeward and windward footpaths, respectively, are due to the increased dispersion due to the 45^o parked cars manipulating the natural flow path of air through the canyon. In parallel wind conditions, the 45^o parked cars channels the wind to flow 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^o parked cars promote air flow away from the leeward zone. The increase of wind speed in the 45^o parking models increases the dispersion of pollutants and reduces the fraction of pollutants that penetrate the parked car boundary into the windward footpath. The dispersion pattern of a reference and parked car model for Case 3 is shown in Figure 11 as a resultant velocity vector plot of the concentration of the tracer pollutant. The increase of wind speed influences the flow and spatial distribution of pollutants by reducing the effectiveness of the parked cars on the windward footpath and inversely improving air quality on the leeward footpath.

Figure 11, Resultant velocity vectors plot for the concentration of CO_2 tracer emissions for a 4m/s perpendicular wind in Case 3 for (a) reference model without parked cars and (b) model with 45^o parked cars.

4.4 *Case 4: Parking Space Occupancy*

The results of the car occupancy study identified different patterns of pollutant penetration 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, an increase in pollutant concentration on the adjacent footpaths was identified for occupancy rates of 10% and 25%, with a relatively steady reduction occurring from 25% to full occupancy of 100%. The increase in pollutant concentration for low occupancy rates was due to the influence of individual cars directing pollutants towards the footpath and promoting mixing with the clean air on the footpath and the polluted air from the road. This indicates a negative effect that low occupancy rates can have for urban pedestrians, as pollutant levels can be increased by low fractions of parked cars in street canyons. As discussed in Case 1, the parked cars trap clean air from roof level along the windward footpath and increase dispersion on the leeward footpath.

Figure 12 is a velocity vector plot of the concentration of the trace pollutant and shows the pollutant dispersion across the canyon floor for a 25% and 75% occupancy rate with perpendicular wind conditions. From visual comparison of the two cases, larger pathways are identified in the lower occupancy model compared to the high occupancy model with less direct pathways for pollutants to travel from the road to the footpath. On both footpaths, lower occupancy rates created wider pathways from the pollutant source on the road to the footpath. In parallel wind conditions small wake zones are created after the vehicle, reducing the spacing effect between them. However, with reduced occupancy rates, the wake zone provides reduced aid in maintaining the baffle wall effect and minimises the reduction of pollutants travelling from the road to the footpath. The change in occupancy rate on the leeward side on the canyon proved to have an exponential relationship from full parked car occupancy of 100% to an empty parking bay with a 0% occupancy rate. Low occupancy rates provided very little reduction in pollutant levels, compared to the greater fraction of reduction which occurred with occupancy rates greater than 75%. A s-curve pattern was evident in the plot of occupancy rates against the percentage pollutant reduction. The penetration of pollutants on the windward footpath was not significant between low and high occupancy rates i.e. between 0% to 10% and 90% to 100%. However, a curvilinear pattern of pollutant reduction was observed between an occupancy rate of 10% and 90%. The plots of occupancy rates against the percentage pollutant reduction do not identify any significant influence of changes in wind speed.

Figure 12, Resultant velocity vectors plot for the concentration of CO_2 tracer emissions of a Case 4 model with a 4m/s perpendicular wind for (a) 25% occupancy rate and (b) 75% occupancy rate.

In each of the case models, a detrimental increase in pollutant concentration was identified in the roadway as the parked cars acted as a baffle wall and impedes pollutants in the road. This was considered an unavoidable impact of parked cars as a passive control, which aims to protect pedestrian welfare.

5. Conclusions

The results of this parked car study highlights 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. Parallel parked cars (Case 1) provided the best overall option in comparison to its two counterpart layouts as a rate of reduction was evident in all model scenarios, with a minimum reduction of 31% and up to 49% in varying wind conditions. Reductions and increases in pollutant concentrations were observed on the footpaths in the perpendicular and 45° parked car models. Wind speed provided no significant influence to improve the percentage reduction of pollutants on the footpaths for either wind directions in any of the three cases. Due to the results of the parked car cases, parallel parked cars provided the most suitable option for further investigations of car space occupancy rates. The investigation of different occupancy rates found that low occupancy rates can be detrimental to pollutant levels 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.

This study does not take into account the factor of the time and subsequent contribution to urban air pollution associated with a driver seeking an empty parking area. Full parking occupancy commonly occurs at peak vehicle and pedestrian traffic times, allowing the high occupancy rates to maximise the reduction of pollutants on the footpath and improve pedestrian health. Further modelling studies to investigate road layout modifications and mechanical dispersion by vehicles would be beneficial to assess the potential of parked cars acting as a passive control for air pollutants.

This investigation demonstrates the benefits of on-street car parking to reduce pedestrian personal exposure on footpaths, highlights the optimum 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 optimum parking configuration and prevailing wind directions. The results obtained in this study can be incorporated into future urban planning strategies for the protection of pedestrian health.

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Research Highlights

- Investigation of 3 parked cars configurations to reduce urban pollutant exposure.
- Parallel parking provided the best layout compared to perpendicular and 45° parking.
- Parking space occupancy influences the pollution concentration on the footpath.
- Parked cars provide an alternative form to a conventional passive control.

Table 1

Street Canyon Model Dimensions

Case	P_w	W_c	W_t	H_b	H_t	V_d
1	*3.00*	*20.0*	*40.0*	*20.0*	*30.00*	*0.4*
2	*5.00*	*24.0*	*48.0*	*24.0*	*36.00*	*1.3*
3	*5.65*	*25.3*	*50.6*	*25.3*	*37.95*	*1.3*

Table 2

Percentage Reductions

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%*

Table 3

Percentage Reductions

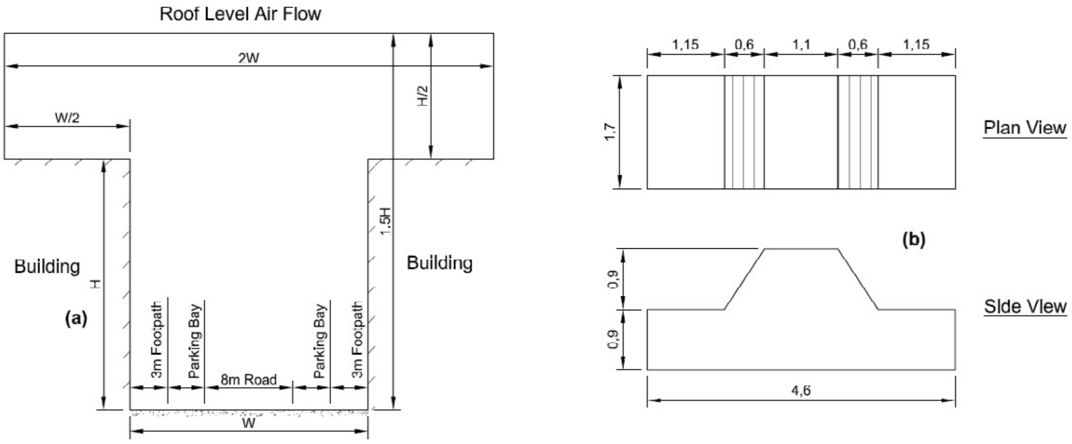
Wind Direction	90°		0°
Wind Speed (m/s)	Leeward	Windward	Average
2	*-37%*	*41%*	*-12%*
4	*-36%*	*41%*	*-19%*
8	*-35%*	*39%*	*-25%*
16	*-34%*	*37%*	*-30%*
Mean	*-35%*	*40%*	*-22%*

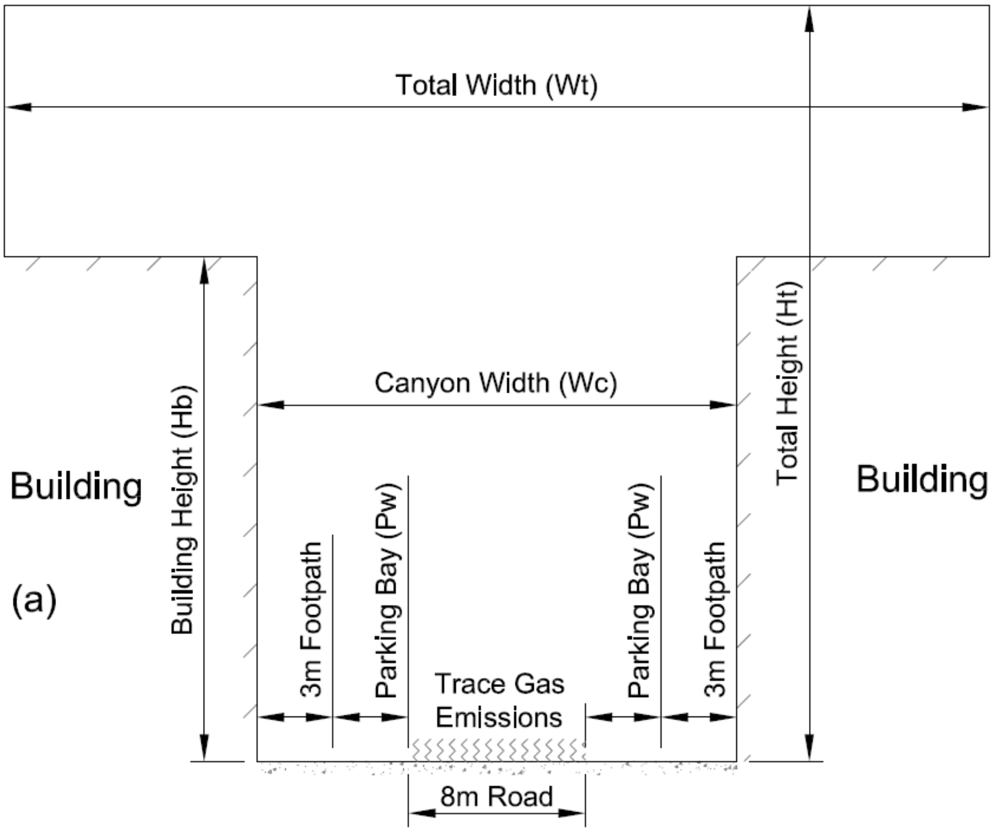
Note: A negative percentage value corresponds to an increase in pollutant concentration.

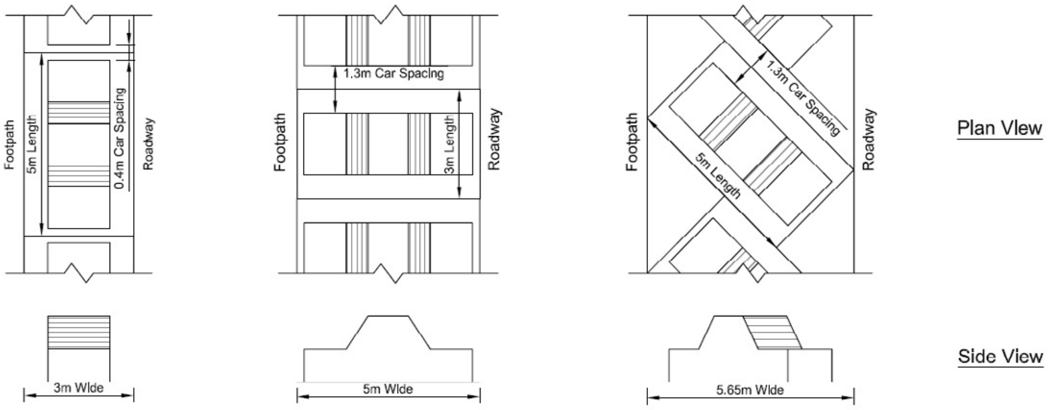
Table 4

	Percentage Reductions			
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 value corresponds to an increase in pollutant concentration.


Roof Level Air Flow
2W
W/2
H/2
1.5H
H
Building
Building
(a)
3m Footpath
Parking Bay
8m Road
Parking Bay
3m Footpath
W
1,15
0,6
1,1
0,6
1,15
1,7
Plan View
(b)
0,9
0,9
Side View
4,6

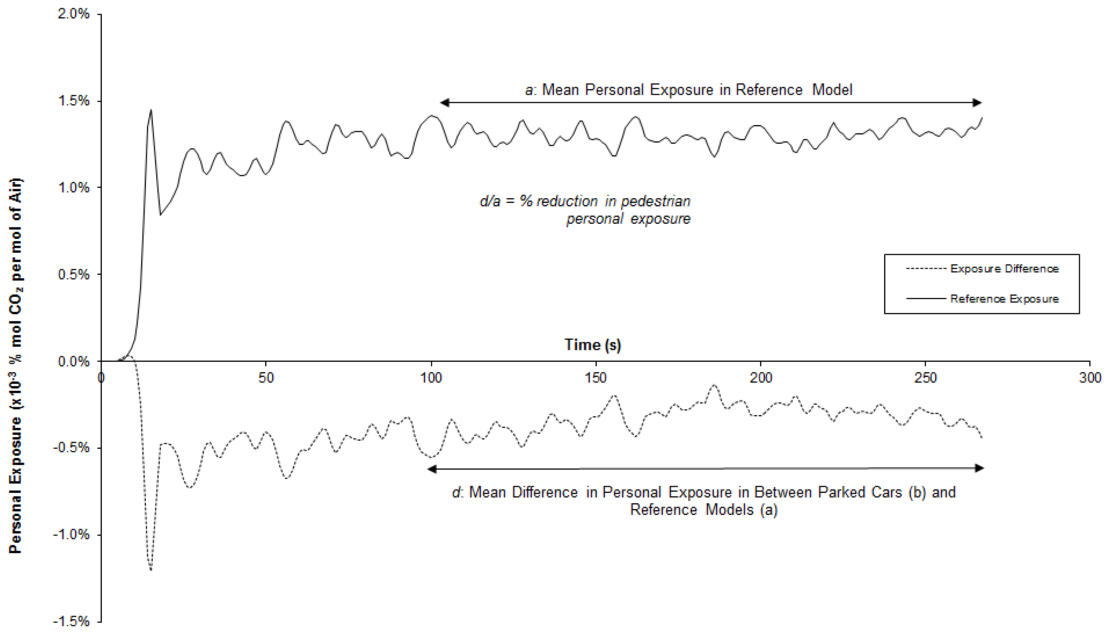

Total Width (Wt)
Total Height (Ht)
Canyon Width (Wc)
Building
Building Height (Hb)
(a)
3m Footpath
Parking Bay (Pw)
Trace Gas Emissions
Parking Bay (Pw)
3m Footpath
Building
8m Road

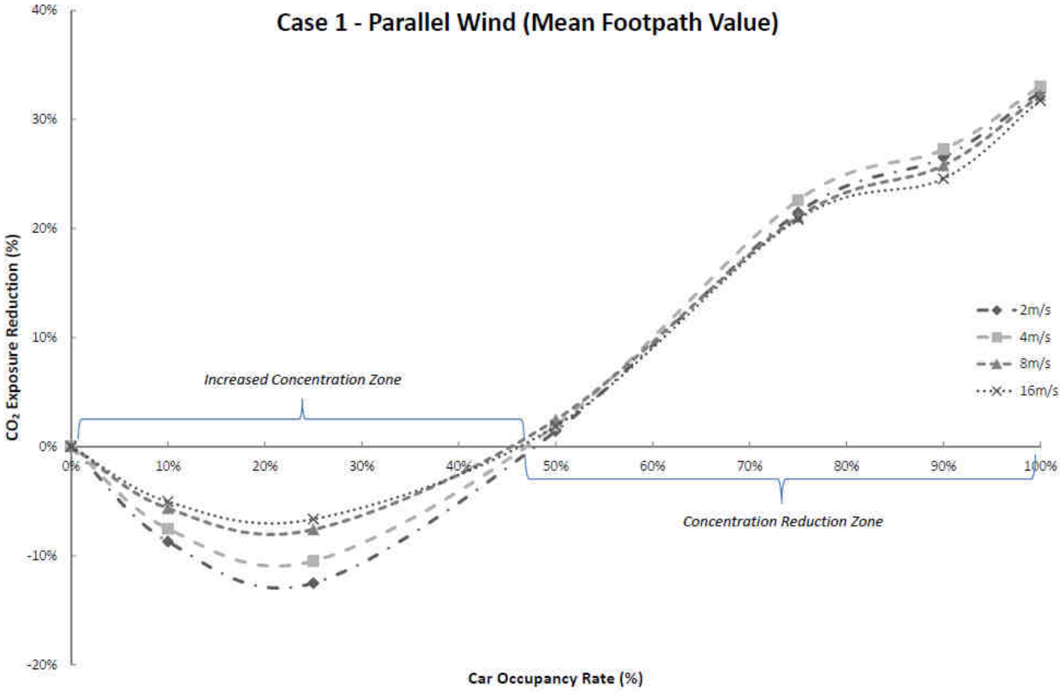


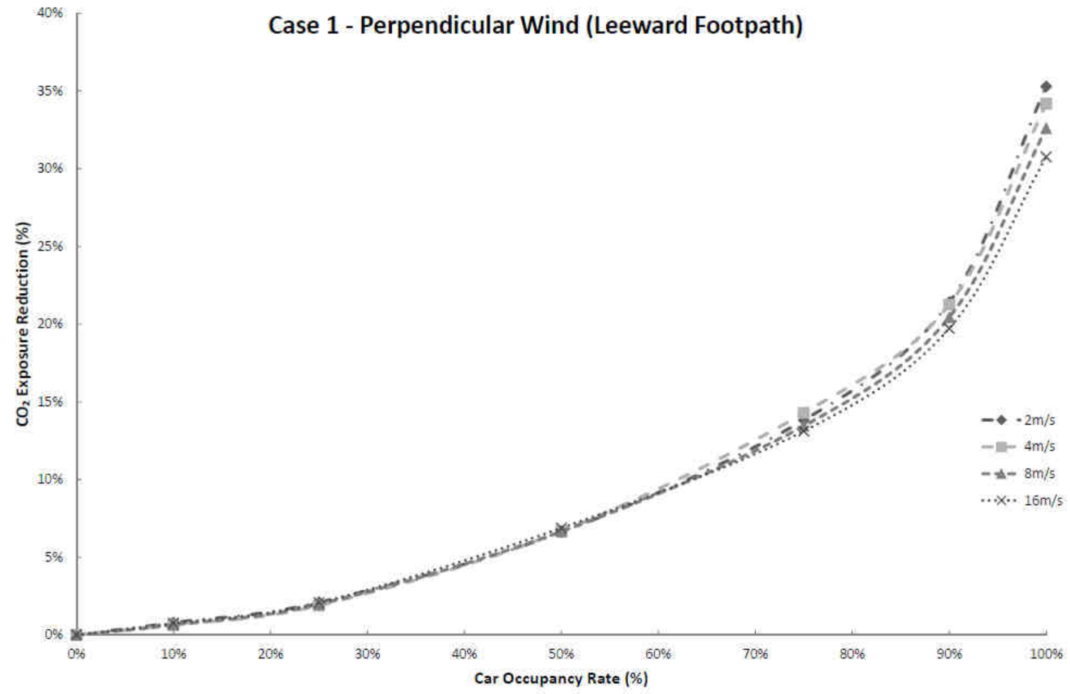
(I) Case 1
Parallel Parking

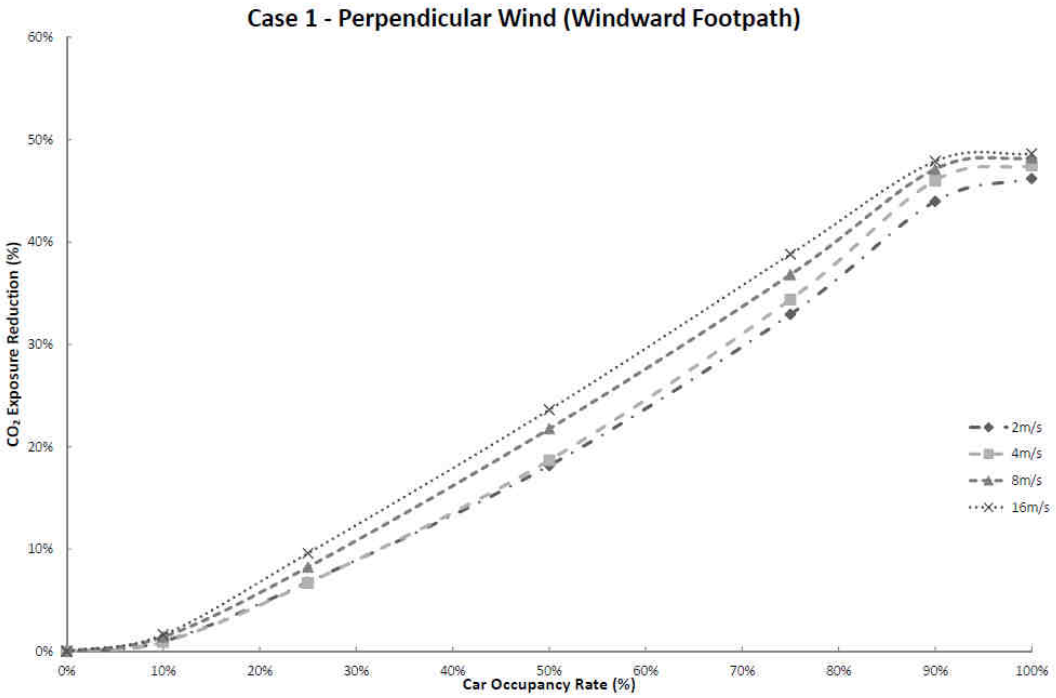
(II) Case 2
Perpendicular Parking

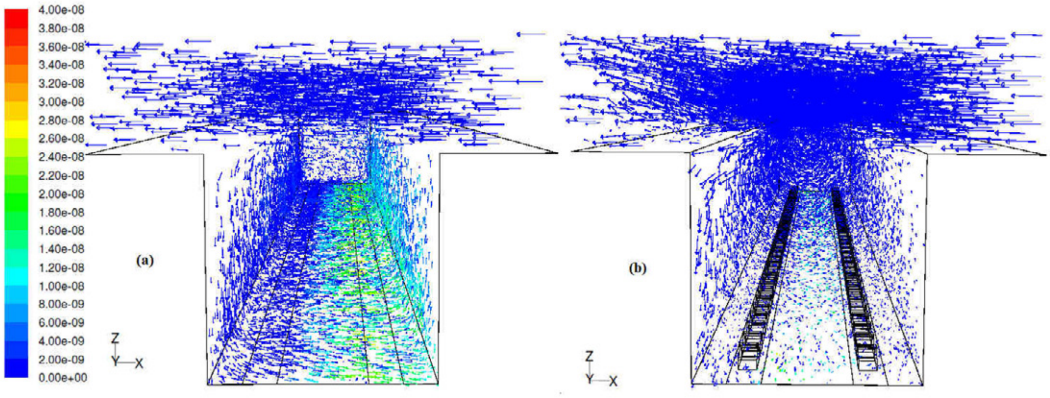
(III) Case 3
45° Parking


a: Mean Personal Exposure in Reference Model
d/a = % reduction in pedestrian personal exposure
Exposure Difference
Reference Exposure
Time (s)
d: Mean Difference in Personal Exposure in Between Parked Cars (b) and Reference Models (a)
Personal Exposure (x10-3 % mol CO2 per mol of Air)
2.0%
1.5%
1.0%
0.5%
0.0%
-0.5%
-1.0%
-1.5%
0
50
100
150
200
250
300


Case 1 - Parallel Wind (Mean Footpath Value)
40%
30%
20%
10%
0%
-10%
-20%
CO₂ Exposure Reduction (%)
Increased Concentration Zone
Concentration Reduction Zone
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Car Occupancy Rate (%)
2m/s
4m/s
8m/s
16m/s


Case 1 - Perpendicular Wind (Leeward Footpath)
40%
35%
30%
25%
20%
15%
10%
5%
0%
CO$_2$ Exposure Reduction (%)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Car Occupancy Rate (%)
2m/s
4m/s
8m/s
16m/s


Case 1 - Perpendicular Wind (Windward Footpath)
CO2 Exposure Reduction (%)
60%
50%
40%
30%
20%
10%
0%
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Car Occupancy Rate (%)
2m/s
4m/s
8m/s
16m/s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1.20e-08
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8.00e-09
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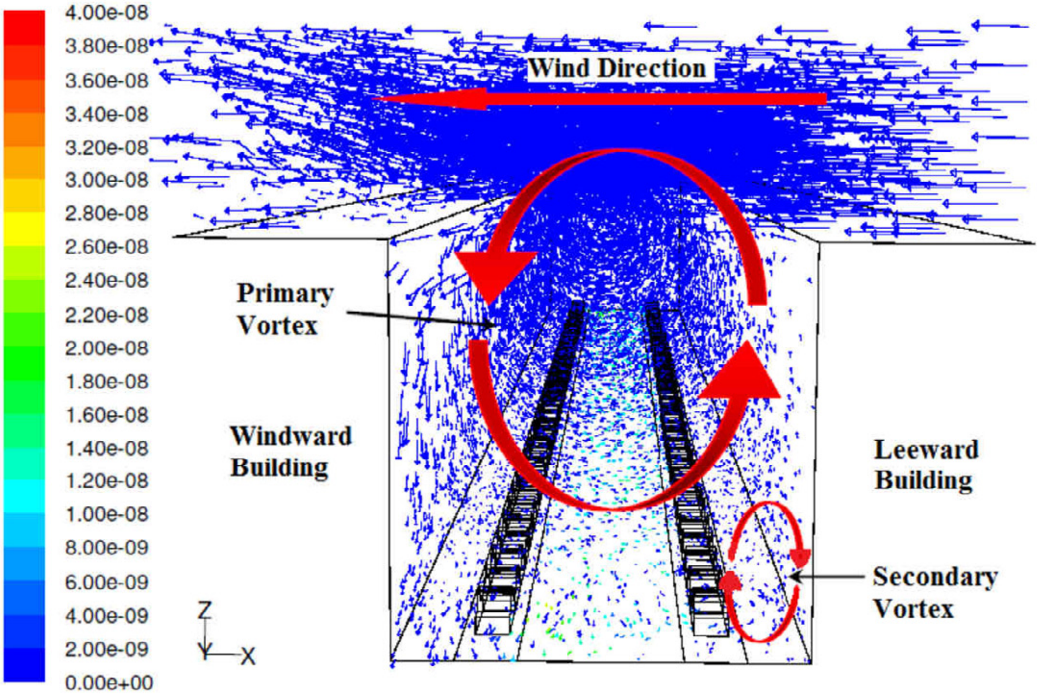
(a)
(b)
Z
Y
X
Z
Y
X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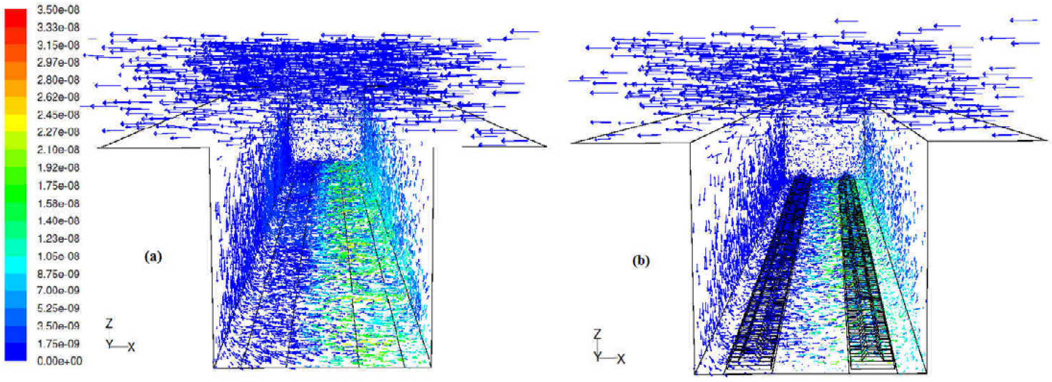
1.00e-08
8.00e-09
6.00e-09
4.00e-09
2.00e-09
0.00e+00
Wind Direction
Primary Vortex
Windward Building
Leeward Building
Secondary Vortex
Z
X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(a)
(b)
Z
Y
X
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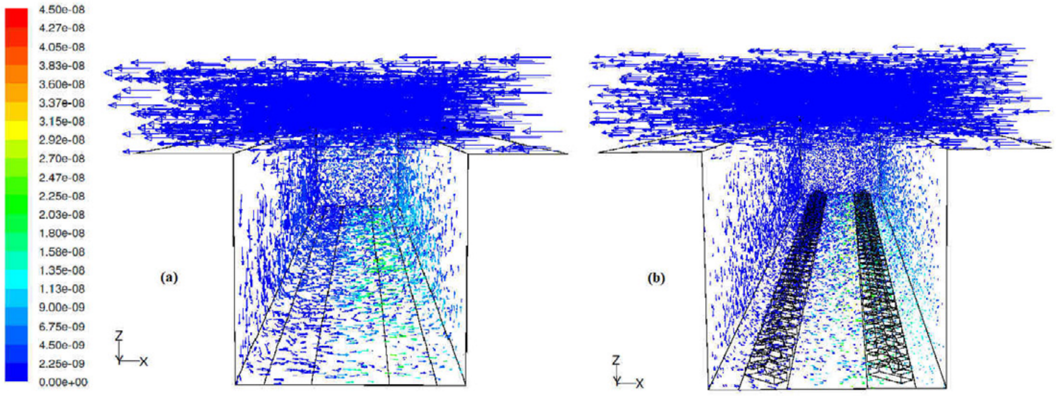
Y
X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(b)
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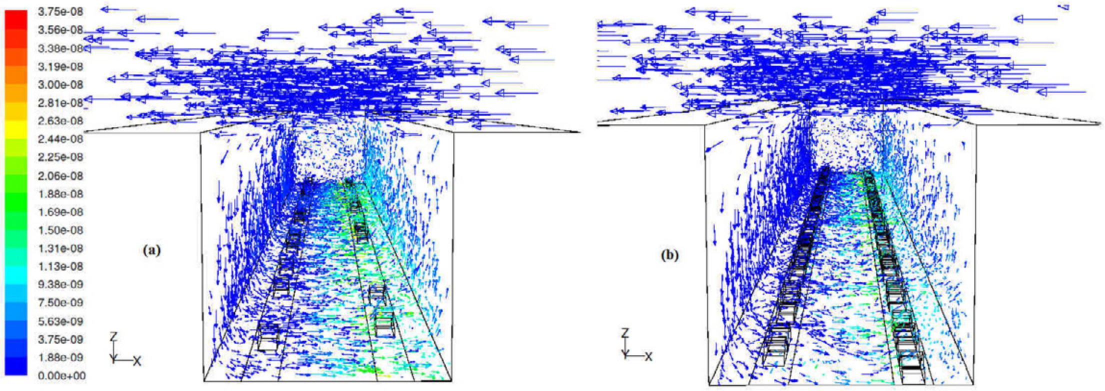
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1.69e-08
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1.31e-08
1.13e-08
9.38e-09
7.50e-09
5.63e-09
3.75e-09
1.88e-09
0.00e+00
(a)
(b)
Z
X
Z
X