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Ranking current and prospective NO_2 pollution mitigation strategies: An environmental and economic modelling investigation in Oxford Street, London☆

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ABSTRACT

Air pollution continues to be a problem in the urban environment. A range of different pollutant mitigation strategies that promote dispersion and deposition exist, but there is little evidence with respect to their comparative performance from both an environmental and economic perspective. This paper focuses on examining different NO_2 mitigation strategies such as trees, buildings facades coated with photocatalytic paint and solid barriers in Oxford Street in London. The case study findings will support ranking the environmental and economic impacts of these different strategies to improve personal exposure conditions on the footpath and on the road in a real urban street canyon. CFD simulations of airflow and NO_2 dispersion in Oxford Street in London were undertaken using the OpenFOAM software platform with the k-ε model, taking into account local prevailing wind conditions. Trees are shown to be the most cost-effective strategy, with a small reduction in NO_2 concentrations of up to 0.7% on the road. However, solid barriers with and without the application of photocatalytic paint and an innovative material (20 times more expensive than trees) can improve air quality on the footpaths more substantially, up to 7.4%, yet this has a significant detrimental impact on NO_2 concentrations ($\leq$23.8%) on the road. Photocatalytic paint on building surfaces presented a minimal environmental reductions (1.2%) and economic (>100 times more expensive than trees) mitigation strategy. The findings recognised the differences between footpath and road concentrations occurred and that a focused examination of three pollution hotspots can provide more cost effective pollution mitigation. This study considers how a number of pollutant mitigation measures can be applied in a single street canyon and demonstrates the strengths and weaknesses of these strategies from economic and environmental perspectives. Further research is required to extrapolate the findings presented here to different street geometries.

1. Introduction

Road traffic emissions are the largest contributors of NO_x emissions in the urban environment (Mattai et al., 2008). They account for 40% of the total European NO_x emissions (Sundvor et al., 2012) and contribute between 47% and 53% of emissions in London (TFL, 2012; Mattai et al., 2008). Epidemiological studies have provided evidence of the adverse health effects of outdoor air pollution (WHO, 2013), linking it to various cardiovascular and respiratory hospital admissions in London (Samoli et al., 2016). The specified European directives on NO_2 concentrations give a limit value with an annual mean value of 40 μg m^{-3} and an hourly value of 200 μg m^{-3} with 18 permitted exceedances each year. However, these limit values are regularly exceeded throughout Europe (Guerreiro et al., 2012) and in London the hourly limit value was exceeded 60 times in the Marylebone area in 2013 (DEFRA, 2015). Personal exposure to NO_2 pollution in London is greatest at peak traffic times, which typically coincides with peak pedestrian and cyclist commuter times (Kaur et al., 2007). Therefore, mitigating air pollution to reduce personal exposure for urban populations is an important consideration for authorities.

A number of pollution mitigation strategies exist to control air pollution in the urban environment. McNabola et al. (2013) defines

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these options as; (i) controlling the quantity of pollution (g) e.g. congestion charging (Kelly et al., 2011), (ii) controlling the emission intensity (g km^{-1}) e.g. carbon tax (Galinato and Yoder, 2010) and (iii) controlling source-receptor pathways (g m^{-3}) e.g. passive control measures (McNabola, 2010). Each control mechanism provides its own benefits and challenges with respect to improving air quality in the urban environment.

Focusing on controlling source-receptor pathways in the urban environment, current techniques for reducing NO_2 rely on improving the aerodynamic dispersion of traffic emissions (Jeanjean et al., 2015, 2016), depositing NO_2 on a surface (Morakinyo and Lam, 2016; Janhäll, 2015) or a combination of these two methods.

Improving aerodynamic dispersion can be achieved by altering street geometry, for example roof shapes (Xie et al., 2005; Yang et al., 2016) or street canyon aspect ratios (Oke, 1988). However, modifying building geometry can be highly expensive and a detailed understanding of local meteorological conditions are required. Alternatively, Gallagher et al. (2015) suggested introducing solid and porous barriers to enhance pollution dispersion at street level in urban street canyons. These barriers range from trees (Gromke and Ruck, 2007; Amorim et al., 2013), hedgerows (Gromke et al., 2016), green roofs and facades (Speak et al., 2012; Perini et al., 2011; Pugh et al., 2012), solid barrier such as low boundary walls (McNabola et al., 2008; Gallagher et al., 2012), noise barriers (Baldauf et al., 2008; Finn et al., 2010) and parked cars (Abhijith and Gokhale, 2015; Gallagher et al., 2011).

Measures to promote pollutant deposition are offered by green infrastructure or the application of photocatalytic paint on building and road surfaces (Janhäll, 2015; Rondón et al., 1993). Both these methods can enhance deposition and reduce NO_2 concentrations. Vegetation is known to reduce NO_2 concentrations via deposition (Smith et al., 2000), with deposition velocity rates ranging from 0.007 to 0.042 cm s^{-1} (Breuninger et al., 2013), to 0.12 cm s^{-1} (Hereid and Monson, 2001) and 0.18–0.21 cm s^{-1} (Rondón et al., 1993). Photocatalytic paint has also been shown to decrease NO_2 concentrations via deposition (Lasek et al., 2013), with literature suggesting the use of titanium dioxide (TiO_2) as a photocatalyst to promote a deposition velocity of 0.002–0.02 cm s^{-1} (Palacios et al., 2015) to 0.027–0.041 cm s^{-1} (Boonen and Beeldens, 2014) and 0.24 cm s^{-1} (DEFRA, 2016b).

The focus of this study is to compare different NO_2 mitigation strategies which promote dispersion and deposition in the urban environment. A number of street canyon modelling studies of individual mitigation strategies have previously been performed, but there are limited findings that directly compare their impact under the same conditions, like in this case study of Oxford Street in London (UK). The different mitigation strategies examined include trees, photocatalytic paint and the introduction of solid barriers, some of which have not been compared in terms of their performance to disperse and deposit air pollutants in a real street canyon. The performance of each strategy will also be evaluated and ranked based on its economic performance (i.e. the associated costs of their implementation and maintenance over a 10-year period). Furthermore, an assessment for improving air quality in hotspot zones is undertaken. Previous research of pollution mitigation has been based on potential, this study delivers results based on environmental and economic performance which is important in translating impact to deliver better air quality.

2. Methods

2.1. Case study: Oxford Street, London

Oxford Street is located in central London within the City of Westminster which extends between the two tube stations of Oxford Circus Station and the Marble Arch Station (see Supplementary Material Fig. S1). Oxford Street, with numerous shopping centres and food-halls is one of the busiest shopping street in Europe with around half a million daily visitors.

2.1.1. Street layout

Buildings data were sourced from Ordnance Survey. The average building height for the modelled scene was calculated to be 15 m and ranked between a few meters up to 59 m. Oxford Street is 1.2 km in length and approximately 20 m in width, with an average height to width ratio (H/W) near unity, which corresponds to expected air flow patterns between skimming flow and wake interference flow (Oke, 1988). The National Tree Map^{TM} (NTM) Crown Polygon produced by Bluesky Ltd was used to represent individual trees or closely grouped tree crowns. Trees and bushes over 3 m in height were included in the database. An overview of the study area with trees can be seen in Supplementary Material Fig. S1. The NTM^{TM} provided a canopy top height but did not provide the canopy base height. A canopy base height of 1/3 of the canopy depth was assumed, which is similar to previous studies (Gromke et al., 2008; Gromke and Blocken, 2015a,b).

2.1.2. NO_x emission

The traffic in Oxford Street mainly consists of taxis and buses, with more than 10 buses routes running along the street each day. According to automatic traffic counts provided by the UK Department for Transport (DFT, 2016), over 5000 buses and more than 6000 taxis travel through Oxford Street each day. For the purpose of this study average daily traffic counts from Oxford St were taken to estimate an average NO_x road emissions of 280 μg m^{-1} s^{-1} using the Emissions Factors Toolkit (EFT, version 6.0.2) from the Department for Environment, Food & Rural Affairs (DEFRA, 2016a). The use of a NO_x to NO_2 calculator (DEFRA, 2016c) taking into account background concentrations of NO_2, O_3, London traffic mix and a reference year of 2014 specifically for Oxford St suggested that a linear relation could be assumed between annual mean NO_2 concentrations and modelled annual mean NO_x concentrations. All simulations were performed with an average NO_2 road emission of 81.2 μg m^{-1} s^{-1} and a NO_2 background concentrations of 33.8 μg m^{-3} (see SI section S.2.1.2). A recent study by Santiago et al. (2017) noted out that assuming non-reactive NO_2 did not affect significantly the spatial distribution and the errors were less than 15% in winter conditions in the City of Madrid (Santiago et al., 2017).

2.1.3. Local meteorological conditions

In order to integrate local meteorological conditions in the modelling results, 30-min average wind data from central London (London City airport) for 2014 was used to determine the prevailing wind directions and the annual average wind speed for London. London City airport is located closely to Central London, being less than 15 km away from Oxford Street. To take into account the spread in wind directions, the performance of each mitigation measure was examined in eight different wind directions at an average wind speed of 4.3 m s^{-1} and weighted according to their probability (see Supplementary Material Fig. S3). Thermal effects can affect gas dispersion, especially for large temperature gradients and low wind speeds. For wind speeds greater than 2 m/s, previous studies have noted that wind dynamics are predominant over thermal effects which can then be neglected (Parra et al., 2010; Santiago et al., 2017). In this study, a wind speed of 4.3 m/s was used which justifies the assumption taken of an isothermal flow.

2.1.4. Modelling outputs

The results from the models will consider the average NO_2 concentrations at adult (1.5 m) height on the footpaths and on the

road. Providing separate results for footpath and road concentrations allows for a clear understanding of the impact of each mitigation measure on pollutant dispersion and deposition effects in the street. In most cases, the results will be presented as relative differences between the reference and mitigation measure scenarios to demonstrate and compare the impact of each strategy on air quality in Oxford Street.

2.2. CFD modelling

2.2.1. Computational grid

Best practice guidelines were followed to build the computational domain (Franke et al., 2007). The maximum reported height in the domain is a building height (H) of 59 m. The computational domain was built with its boundaries placed more than 15 H away from the modelled area (Supplementary Material Fig. S4). The top of the computational domain was set to 500 m, which corresponds to 7.5 H above the highest building. A maximum expansion ratio between two consecutive cells was kept below 1.3. With an average building height of 15 m across the modelled area, the overall blocking ratio was kept below 1.2% inclination (below the 3% recommended threshold). A hexahedral mesh of 3.0 million cells was used. A mesh resolution of 0.5 m in the vertical direction close to the bottom of the computational domain was chosen (<1 m) to ensure proper flow modelling at pedestrian height (Blocken, 2015). A cell size of 1.2 m along the X and Y axis was applied for the buildings, trees and roads. This resolution allows more than 10 cells to be present across the main street canyon to ensure proper flow modelling (see Supplementary Material Fig. S5). The mesh resolution was increased around barriers with a resolution of 0.5 m in the horizontal axis and 0.25 m vertically.

To assess the independence of the simulated wind speed and concentrations from the computational grid inside Oxford Street canyon, a grid sensitivity analysis was performed. Wind speed and NO_2 concentrations were compared between three different grids: a fine grid with a maximum cell resolution in the X-Y-Z directions of 0.8 × 0.8 × 0.3 m (6 million cells); an intermediate grid (1.2 × 1.2 × 0.5 m, 3 million cells); and a coarse grid (2.4 × 2.4 × 1 m, 0.16 million cells). The agreement between the intermediate and fine grid show that the simulated wind speeds and NO_2 concentrations are independent from the grid used, although a few deviation are observed for some points at high NO_2 concentrations (Supplementary Material Fig. S6). More differences are observed between the intermediate and the coarse grid, which can be explained by the fact that the coarse grid is not compliant with the COST guidelines (not enough cells in the centre of the canyon to ensure a proper flow vorticity). As the coarse grid would be too inaccurate to use, the simulations were performed on the intermediate grid.

2.2.2. Flow calculation

The wind flow calculations were performed under the open source OpenFOAM software platform. The simpleFOAM steady-state solver utility of OpenFOAM for incompressible, isothermal and turbulent flow was used. This solver is based on the Reynolds-Averaged Navier Stokes (RANS) with the standard k-ε closure model (Launder and Spalding, 1974). Second-order upwind schemes were used. The present study is based on the OpenFOAM-RANS standard k-ε model, which is supported by recent studies where pollutant dispersion and flow distribution for an idealised street canyon were successfully evaluated against wind tunnel experiments (Jeanjean et al., 2015; Vranckx et al., 2015). Further evaluation work was carried out against monitored NO_x and $PM_{2.5}$ concentrations in Marylebone Rd (London) where seasonal accuracy were found to be between 20 and 40% (Jeanjean et al., 2017), which are similar to the model accuracy of 30–40% when compared to wind tunnel measurements (Jeanjean et al., 2015).

Several turbulence models exist to simulate flow and pollutant dispersion in idealised and real scenarios. Large Eddy Simulations (LES) perform better in predicting turbulence than RANS approaches (Blocken, 2015; Lateb et al., 2016), however difficulties still arise in its application to specify appropriate time-dependent inlet and wall boundary conditions, as well as longer computational times. Alternative RANS k−ε turbulence models have reproduced reliable spatial distributions of mean velocity and concentration fields in and around buildings (e.g. Hang et al., 2015; Lateb et al., 2013; Santiago et al., 2016). As the main focus of this study was gaseous concentrations, the standard k-ε model was chosen as previous extensive evaluation work were already carried out for this model (Vranckx et al., 2015; Jeanjean et al., 2015). The boundary conditions were chosen to reflect an atmospheric boundary layer. Single inlet and outlet were used for Northern, Eastern, Southern and Western winds using the 4 sides of the computational domain. For the other wind directions, two sides of the domain were defined as inlets and two as outlets to model the change in wind direction. Following a parameterisation for a neutral atmospheric boundary layer as per Hargreaves and Wright (2007), the mean velocity boundary flow and the turbulent dissipation were set up to follow a logarithmic law using the ABLInletVelocity (Eq. (1)) and ABLInletEpsilon (Eq. (2)) utilities in OpenFOAM such that:

$$U = \frac{U^*}{K} ln\left(\frac{z + z_0}{z_0}\right) \quad (1)$$

$$\varepsilon = \frac{U^{*3}}{K \times z}\left(1 - \frac{z}{\delta}\right) \quad (2)$$

where K is the Karman's constant, z is the height coordinate (m), z_0 is the roughness length (m), δ is the boundary layer depth (m) and U^* the frictional velocity. The turbulent kinetic energy was setup as follow:

$$k = \frac{U^{*2}}{\sqrt{C_\mu}} \quad (3)$$

where $C_\mu = 0.09$ is a k- constant. As recommended, the top of the domain was set as a symmetry plane (Franke et al., 2007). A surface roughness of $z_0 = 2.0$ m was set for the ground, which corresponds to high rise buildings (WMO, 2008). For the wind flow calculation, a residual convergence of at least 10^{-4} was reached for all field variables.

2.2.3. Gaseous dispersion calculation

To model the NO_2 dispersion emitted from Oxford Street road, the transport equation scalarTransportFoam of OpenFoam was modified to take into account the turbulent diffusivity as:

$$\frac{\partial C}{\partial t} + \Delta(U \cdot C) = \Delta^2((D + K_e) \cdot C) \quad (4)$$

where C is the transported scalar, U is the fluid velocity, D is the diffusion coefficient ($m^2\ s^{-1}$) and K_e is the eddy diffusion coefficient ($m^2\ s^{-1}$). The eddy diffusion coefficient can be expressed as: $K_e = \mu_t / Sc_t$ where μ_t is the eddy viscosity or turbulent viscosity ($m^2\ s^{-1}$) and Sc_t is the turbulent Schmidt number. The wide majority of London taxi and bus fleets can be considered to have exhaust pipes close to the ground level, which led to select grid cells on the road up to 1 m in height for emissions (see Supplementary Material Fig. S4). A surface emissions source was adopted for this study to simulate traffic in the street.

2.2.4. Trees and deposition modelling

Trees were treated as a porous media by adding a momentum source (S) variable to the cells occupied by the tree canopy such that:

$$S = -\lambda(\rho|U|U) \quad (5)$$

where S is the momentum source loss (Pa m^{-1}), λ is the inertial resistance factor or pressure loss coefficient (m^{-1}), ρ is the fluid density (kg m^{-3}) and U the fluid velocity (m s^{-1}). The pressure loss coefficient λ (m^{-1}) induced by trees is expressed as $\lambda = Cd \cdot LAD$ where Cd is the drag coefficient induced by trees and LAD is the Leaf Area Index (m^2 m^{-3}). With the assumption of a homogeneous spread of tree species across South East England and London, it can be estimated that London has 80.3% deciduous trees and 19.7% coniferous trees (Forestry-Commission, 2013). Only deciduous trees were considered in this study as they are predominant in London, which is as well the case of Oxford Street. The LAD through the canopy of deciduous trees can be approximated to range up to 1.06 and 2.18 m^2 m^{-3} (Lalic and Mihailovic, 2004). The drag coefficient can be estimated to range between $0.1 \leq Cd \leq 0.3$ for most types of vegetation (Katul et al., 2004). Here a height-independent leaf area density of 1 m^2 m^{-3} was assumed across the canopy and a drag coefficient Cd = 0.2 were used, which are the same values as used in Gromke and Blocken (2015a). The final pressure loss coefficient λ was therefore equal to 0.2 m^{-1}.

The model was enhanced with additional sink terms which take into account the deposition of NO_2 on trees, buildings and walls using the same implementation method as per Vranckx et al. (2015). The deposition inside the tree crown cells was parameterised as:

$$\Delta C/\Delta t = C_0 \times LAD \times Vd, \quad (6)$$

where ΔC is the change in particles concentration via deposition (g m^{-3}), C_0 is the initial particles concentration (g m^{-3}), LAD is the Leaf Area Density and Vd is the deposition velocity (m s^{-1}). Deposition on buildings and walls differ from trees as they are represented as surfaces. The change in NO_2 concentration via deposition on building and wall surfaces was expressed as:

$$\Delta C/\Delta t = C_0 \times Vd \times S/V, \quad (7)$$

where C_0 is the concentration of NO_2 (μg m^{-3}), S is the surface of buildings or walls (m^2) and V the volume of these cells (m^3).

2.2.5. Model limitations

A RANS CFD model provides a steady state view of the reality, which corresponds to a fixed picture of the wind flow and pollutant concentrations. In real life, the wind is oscillating in strength and directions and pollutant concentrations are highly variable following wind and traffic presence. Traffic turbulence will also affect the way pollutants are dispersed within a street canyon. NO_2 is a reactive gas in a constant cycle of reactions with NO and O_3 (Barker, 1995), in this study the levels of NO_2 were supposed to be constant in the street canyon and kept as an average concentrations, without chemical reaction taken into account. This study accounts for a calculated annual mean background concentration for NO_2 and the use of this estimation introduces limitations in term of temporal variation. For the purposes of determining the impact of background concentrations on quantifying the mitigation potential of the strategies examined, the results with the exclusion of background concentrations are included in supplementary material (Table S2), and is discussed in Section 4.5. The location of pollution hotspots might therefore be affected the spread of traffic as suggested by Borge et al. (2016). The modelled NO_2 concentrations are also likely to be more important during peak-times which would involve greater exposures for pedestrians and road users. Despite these limitations, CFD dispersion models are currently one of the most advanced tools available for researchers to understand what are the drivers affecting pollutants dispersion within street canyons.

2.3. Pollution mitigation strategies

In total, six different mitigation measures (scenarios) were modelled and compared to a reference scenario (see Fig. 1). Scenario 1 corresponds to simulation of an empty street canyon for Oxford Street. This scenario is taken as a reference to which each of the following scenarios will be compared to measure the change in NO_2 concentrations.

Scenarios 2 and 3 focuses on the integration of real porous trees inside the street canyon. Scenario 2 includes existing trees in the street as specified by the National Tree Map™. Scenario 3 considers the effect of narrower crowns (reducing crown diameter by almost half) at these existing tree locations, as they have been suggested to be more effective that thick trees in improving local air quality (Janhäll, 2015). Both aerodynamics and deposition effects were modelled in these scenarios. The upper limit of deposition velocity (Vd) of 0.21 cm s^{-1} was used (Rondón et al., 1993), to see the maximum potential to which the trees could reduce NO_2 concentrations.

Scenario 4 applies photocatalytic paint on building facades on each side of the street. The upper limit of deposition velocity (Vd) of 0.24 cm s^{-1} was used (DEFRA, 2016b), to determine the potential of photocatalytic paint in reducing NO_2 concentrations. The paint was applied to all building surfaces in the model. To take into account the presence of doors and windows in the street, the simulation results were halved based on an assumption that 50% of building facades non-paintable surfaces.

Scenario 5 introduced a solid barrier in the form of a low boundary wall on each side of the street. The wall dimensions were 0.5 m wide by 1 m high and were based on previous studies examining wall height suitability as a passive control strategy (Gallagher et al., 2012; McNabola et al., 2009).

Scenario 6 combines the solid barrier with the photocatalytic paint from the previous two scenarios, where only the barrier is coated in the paint (deposition velocity (Vd) of 0.24 cm s^{-1} (DEFRA, 2016b)).

Lastly, in scenario 7 the solid barriers are coated with an innovative material with an enhanced deposition velocity of 1.0 cm s^{-1} for NO_2. The material used to coat the solid barrier corresponds to deposition capabilities offered by the A9 material, an innovative material which can be used as an alternative technology to photocatalytic paint. The A9 materials will act as facade covering of the solid barrier and will allow for the deposition of NO_2 on the surfaces of the wall. In addition, the wall will continue to promote dispersion.

2.4. Economic assessment of mitigation strategies

In addition to the potential for these measures to mitigate pollution in the urban environment, the likelihood of their implementation is dependent on their economic costs. Therefore, a life cycle cost analysis is undertaken to compare both the environmental and economic performance of each strategy to mitigate NO_2 concentrations.

A similar approach to that used by Churchill and Panesar (2013), to quantify the life cycle costs of using photocatalytic material on highway noise barriers to reduce pollutant concentrations, was

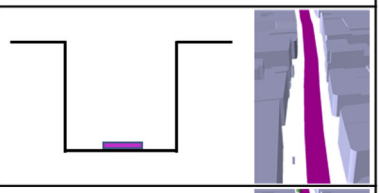
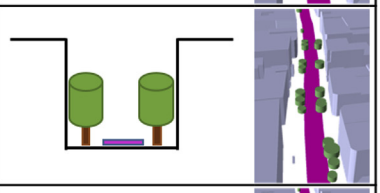
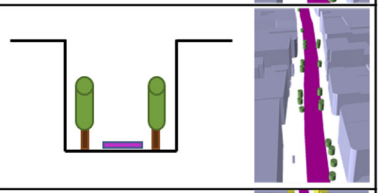
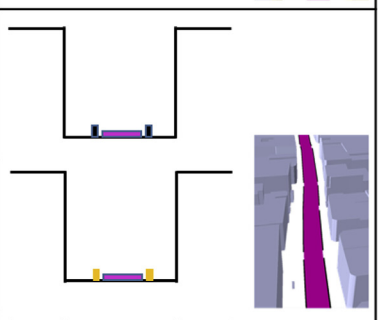
Scenario	Description	
1. Reference	Empty street canyon of Oxford St	
2. Existing tree	Tree using NTM^{TM} specification (total of 50 trees) - on average 5.7 m wide x 5 m tall - total volume occupied by trees = 4000 m^3 2.1: Aerodynamics case (Vd = 0 cm s^{-1}) 2.2: Deposition case (Vd = 0.21 cm s^{-1})	
3. Narrow tree	Same tree height (as NTM^{TM}) but narrower width based on Janhäll (2015) suggestion - 3 m wide x 5 m tall - Total volume occupied by trees = 1000 m^3 3.1: Aerodynamics case (Vd = 0 cm s^{-1}) 3.2: Deposition case (Vd = 0.21 cm s^{-1})	
4. Painted buildings	Photocatalytic paint (pp) coated facades on each side of the street - 60 000 m^2 of painted wall (halved to 30 000 m^2 in results section to consider non-paintable door and window surfaces) 4.1: Deposition case (Vd = 0.24 cm s^{-1})	
5. Solid barrier	Solid barrier on each side of the road - 0.5 m wide x 1 m tall - 5300 m^2 of barrier (2.2 km of barrier) 5.1: Aerodynamics case (Vd = 0 cm s^{-1})	
6. Painted barrier	Same characteristics as solid barrier but painted with photocatalytic paint. 6.1: barrier aerodynamics with photocatalytic paint deposition (Vd = 0.24 cm s^{-1})	
7. Innovative barrier	Same characteristics as solid barrier but coated with innovative material. 7.1: barrier aerodynamics with artificial material deposition (Vd = 1.0 cm s^{-1})	

Fig. 1. List of reference scenario and six mitigation scenarios examined for NO_2 mitigation potential.

adopted in this study. A 10-year period was considered for the economic costing, which included the installation of each measure and its annual maintenance requirements.

However, the disposal stage of the life cycle is excluded as each strategy is considered to last beyond this time-frame. In addition, the embodied burdens associated with each technology is omitted, but it is acknowledged that implementing each measure has an associated environmental impact. Details of the installation and maintenance costs used in the assessment for each measure is presented in the Supplementary Material Table S1.

An inflation rate of 2.5% was applied to annual maintenance costs in the calculation of the total cost of each mitigation measure. The same estimates were used for calculating the economic impact of implementing these mitigation strategies in pollution hotspots in the street canyon.

3. Results

3.1. Environmental performance of pollution mitigation measures

Environmental performance was calculated based on the percentage difference in mean concentrations between the reference scenario and each pollution mitigation measure. The results for the averaged NO_2 concentration on the footpaths and on the road were calculated using the weighted approach for each of the eight wind directions simulated and corresponding to local conditions. The results are presented in Table 1 and Fig. 2.

The overall changes in NO_2 concentrations induced by the existing trees in scenario 2 led to an average reduction of 0.3% in the footpaths zone: 0.1% reduction owing to enhanced dispersion and an additional 0.2% owing to deposition effects. However, the

Table 1
Relative differences in concentrations (%) on footpath and road zones for different NO_2 mitigation strategies (represented as percentage reductions (−) or increases (+) to reference scenario results). Results were taken across Oxford Street on a regular 2 × 2 m grid at adult (1.5 m) height. Absolute concentrations deviation (in μg m^{-3}) are available in SI Table S2.

Scenario	Pedestrian zone			Road zone		
	Dispersion	Deposition	Total	Dispersion	Deposition	Total
2. Existing tree[a]	−0.1	−0.2	−0.3	−0.5	−0.2	−0.7
3. Narrow tree[a]	0.2	−0.1	0.1	0.1	−0.1	0.0
4. Painted buildings[b]	–	−1.2	−1.2	–	−0.6	−0.6
5. Solid barrier	−2.3	–	−2.3	23.8	–	23.8
6. Painted barrier	−2.3	−1.4	−3.7	23.8	−1.8	22.0
7. Innovative barrier	−2.3	−5.1	−7.4	23.8	−6.3	17.5

[a] Trees values halved to consider the yearly effects of deciduous trees (leaf-free season of 6 months).
[b] Deposition values halved to consider half (50%) of the building wall surface non-paintable (doors, windows, etc.).

aerodynamics dispersion effects were greater on the road, with more than double the total average reductions of 0.7%, meaning that tree effects are more effective at reducing the higher concentrations that exist in the road zone. Despite a high deposition velocity value being used in the simulations, the deposition effects had a limited impact in both zones meaning that trees have limited abilities in capturing NO_2.

The overall changes in NO_2 concentrations due to narrow trees (scenario 3) was very different to the existing trees in scenario 2, with an average increase of up to 0.2% and 0.1% in the footpath and road zones respectively, Increased concentrations were due to reduced dispersion when narrow trees are implemented when compared to the reference scenario. The impact of deposition effects were close to be negligible with decreases of 0.1% on both footpath and road zones.

Photocatalytic paint presented small reductions in NO_2 concentrations solely due to pollutant deposition, with average reductions of 0.6% in the road zone and 1.2% in the pedestrian zone.

The solid barrier leads to very different results for footpath and road NO_2 concentrations, with average reductions of 2.3% on the footpath, but a more substantial 23.8% increase in the road zone. This mitigation measure demonstrates the impact of low boundary wall on NO_2 dispersion, however it recognises that it does not promote pollutant deposition in the street.

Coating the low boundary walls with photocatalytic paint in scenario 6 improved the performance of the solid barrier by decreasing NO_2 concentrations by an additional 1.4–1.8% by promoting pollutant deposition. The average reduction in NO_2 concentrations on the footpaths improved to 3.7%, and a notable 22.0% average increase still existed in the road zone despite the additional use of photocatalytic paint.

Lastly, the deployment of a new innovative barrier with a deposition velocity of 1.0 cm s^{-1} presented enhanced deposition effects of 5.1%–6.3%. This was three to four times better than photocatalytic paint. However, the overall results for this mitigation strategy presents a reduction of 7.4% on the footpath zone and a significant increase of 17.5% remains in the road zone.

3.2. Mitigation at pollution hotspots

As the cost of different mitigation strategies can be a driver to their implementation in a street, another approach was considered by focusing on mitigating pollution hotspots. Fig. 3 illustrates the average NO_2 concentrations for the reference scenario and three hotspot locations were identified in Oxford Street. The different mitigation strategies previously used (see Fig. 1) are examined at these hotspots locations, which accounts for 25% of the full length of the street, and the results are presented in Table 2. The effects of existing and narrow trees were not considered as their impact was negligible in the hotspot zones.

The performance for the photocatalytic paint ranged presented reductions of between 0.3% and 1.7% at all hotspot zones for both footpath and road zones. The combined results for aerodynamic dispersion and deposition effects for the solid barrier (scenario 5) ranged from reduction of 9.6%–20.1% on the footpaths, with mixed results on the road zone: increases of 6.0%–6.1% in hotspots 1 and 3,

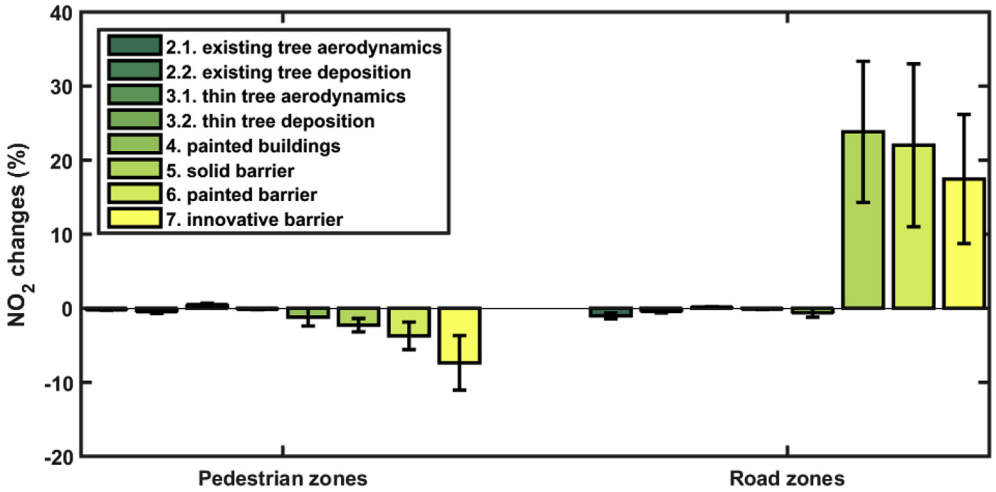


Fig. 2. Relative difference in NO_2 concentrations in comparison to an empty street canyon (scenario 1). Sampled were taken all across Oxford Street on a regular 2 × 2 m grid at adult (1.5 m) height. Error bars correspond to the model accuracy of 40% (see Section 2.2.2).

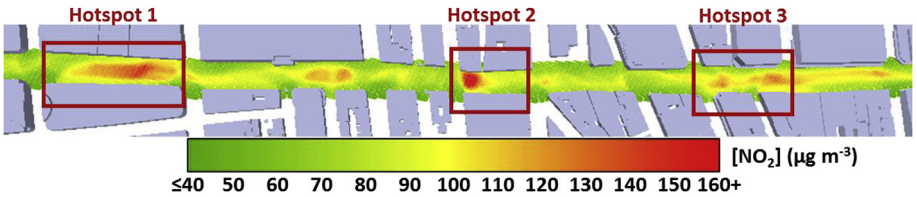


Fig. 3. Hotspots locations in Oxford Street for the reference scenario 1. Wind directions were averaged over the prevailing winds, leading to an average NO_2 canyon concentrations of 80.6 µg m^{-3}.

Table 2
Relative differences in concentrations on footpath and road zones for different NO_2 mitigation strategies at hotspot locations (represented as percentage reductions (−) or increases (+) to reference concentrations). Results were taken across Oxford Street on a regular 2 × 2 m grid at adult (1.5 m) height.

Scenario	Hotspot 1 (H/W of 1.0)		Hotspot 2 (H/W of 0.9)		Hotspot 3 (H/W of 0.8)	
	Footpath	Road	Footpath	Road	Footpath	Road
4. Painted buildings[a]	−1.5	−0.6	−1.7	−0.7	−0.9	−0.3
5. Solid barrier	−20.1	6.0	−16.4	−9.0	−9.6	6.1
6. Painted barrier	−21.4	4.0	−17.6	−10.2	−10.4	4.7
7. Innovative barrier	−24.4	−0.8	−20.7	−13.4	−12.6	1.2

[a] Deposition values halved to consider half of the building wall surface non-paintable (doors, windows, etc.).

while hotspot 2 observed a reduction of 9.0%. The application of photocatalytic paint (scenario 6) improved these results for both footpath and road zones by 0.8–1.3% and 1.2–2.0% respectively. The innovative material used in scenario 7 led to further improvements from the low boundary wall with reductions of 3.0–4.3% on the footpath zone and 4.4–6.8% on the road zone, respectively.

3.3. Economic assessment of pollutant mitigation measures

Based on the estimated costs for the installation and annual maintenance, Fig. 4 presents the economic costs of each pollution mitigation measure for the next ten years.

The findings illustrate the significant differences in initial installation and annual maintenance costs for each pollutant mitigation measure over the 10-year period in Oxford Street. The cost of trees as a pollution mitigation measure was the least expensive of all scenarios, with initial planting and annual maintenance estimated at £10.7 k and £11.7 k depending on tree type. The cost of installing solid barriers with or without the use of an innovative material to enhance NO_2 deposition, were almost 30–40 times more expensive (£192-230 k versus £5-6 k) than planting trees in the street. The costs of annual maintenance were also higher than that for the trees, contributing an additional £4 k for standard wall and £11 k for the other materials, making a total of £236 k to £361 k. The initial application of photocatalytic paint in the street (£95 k) plus the cost of annual cleaning or reapplication (£47.5 k) of paint on building surfaces was estimated £638 k, sixty times more expensive than trees and two to three times more expensive than the solid barriers.

4. Discussion

4.1. Strengths and weaknesses of each pollution mitigation strategy

Each pollution mitigation strategy presented distinctive results based on its impact on NO_2 dispersion and deposition. The results demonstrated that the effect of dispersion lead to the greatest changes on annual average NO_2 concentrations with the introduction of the solid barrier, with the exception of the innovative barrier which had the potential to have a greater impact of pollutant deposition on the footpath zone for adult personal exposure. However unlike dispersion effects, only deposition results were positive in all scenarios as it removed pollution rather

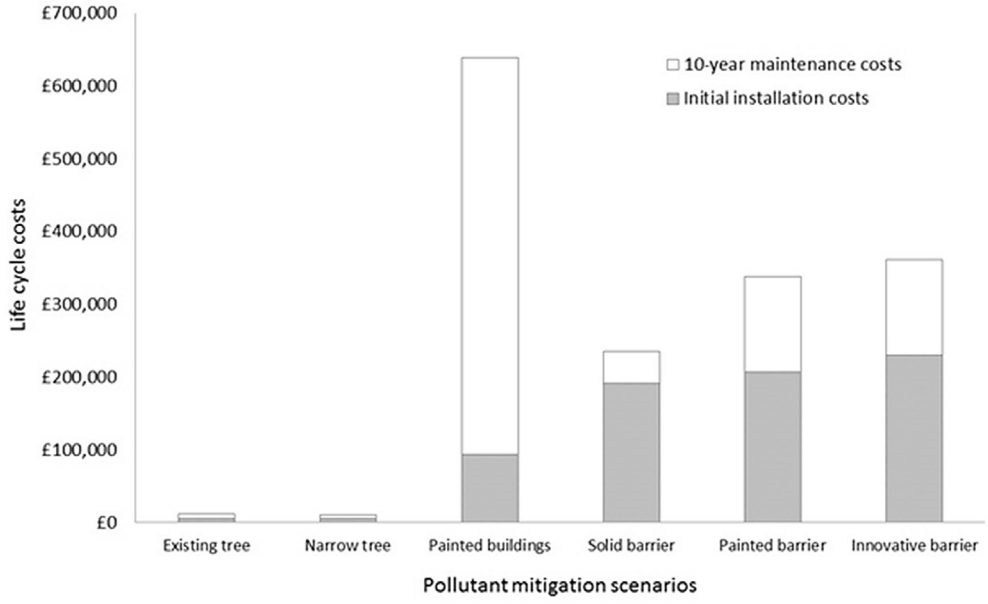


Fig. 4. Economic life cycle costs of different pollution mitigation measures in Oxford Street.

than displacing pollution on the footpath and road zones.

The findings demonstrated that the inclusions of trees in the street had a limited impact. As narrow trees led to a deterioration in air quality as compared to the wider tree crowns, it questions whether narrow trees are better suited in all streets to promote deposition and allow for maximum natural ventilation. The volume of narrow trees (1000 m^3) was one quarter of the existing trees (4000 m^3), yet the results for deposition and dispersion were very different, suggesting that deposition effects are non-linear to the volume of trees in a street canyon. The deposition effects on trees extend to other air pollutants, such as particulate matter, $PM_{2.5}$ (Nowak et al., 2013) and PM_{10} (Nowak et al., 2006). Furthermore, other benefits of urban green infrastructure includes their contribution to the well-being of urban populations (White et al., 2013), for example regulating traffic noise level of busy streets (Kalansuriya et al., 2009).

The results for applying photocatalytic paint was marginal on building surfaces, but demonstrated more of an impact of improving air quality when applied closer to the emissions source where greater NO_2 concentrations were observed. However, in combination with the solid barrier, the deposition effects were outweighed by the dispersion effects of the low boundary wall. Furthermore, the deposition values used were the upper limit values for deposition velocity and therefore the results may be overestimated.

Solid barriers along the edge of both footpaths presented the best and worst results in terms of changes to the average NO_2 concentrations on the footpath and road zones, respectively. The low boundary wall had very positive effects for pedestrians but presented adverse effects for cyclists and drivers as they trap air pollution over road zones. Thus, it is worthwhile improving their performances with paint and with innovative material which will introduce NO_2 reductions via deposition. This suggests that no single mitigation scenario may be used on its own to get the best results for improved air quality through promoting dispersion and deposition. The option of green walls was not explored here, although this would offer deposition capabilities for both NO_2 and PM in the street.

Local meteorological conditions must also be taken into account in the optimisation of all pollution mitigation strategies, as the each measure may require custom layout to ensure reductions in pollutant concentrations and not the creation of new pollution hotspots. This study was limited to the geometrical and meteorological conditions on a single environment, but it demonstrated the differences that a range of pollution mitigation measures can have in comparison to one another.

4.2. Pedestrian vs road zones

If improvements in air quality in pedestrian areas are a priority for city planners, based on the results the most beneficial mitigation strategy would be the installation of solid barriers, as the results were an order of magnitude greater than the tree and photocatalytic scenarios. However, as the results indicated, the low boundary walls only promotes aerodynamic dispersion and did not support deposition. Furthermore, it led to significant increases in NO_2 concentrations on the road, which would be detrimental to exposure of cyclists and drivers (although they are usually in an enclosed vehicle). Deposition to the solid barrier could help decrease NO_2 with an additional 1.4–1.8% added with the use of photocatalytic paint and 5.1–6.3% with the use of innovative material.

When considering road pollution, the most beneficial scenario to decreases NO_2 concentrations on the road and on the footpath are existing trees. Tree presents the interesting trade-off of being beneficial to pedestrians as well. In addition, there is the potential to increase the number of trees in Oxford Street. However, there is a limit to the potential of additional trees that can maximise pollutant deposition without causing the canopy effect and lead to trapping pollutants at street level. Further research is required to fully maximise this opportunity.

4.3. Full street vs hotspots

Limited available financial resources will be one of the main challenges faced by city planners wanting to improve air pollution within busy streets. Therefore, applying a mitigation strategy only within hotspots reduces the price of photocatalytic paint and solid barriers by a factor of 4 (25% of the street length).

The results for the hotspots in Oxford Street were relatively similar to the results obtained in the case of a full street mitigation in most cases, however a number of differences were noted. Firstly, the impact of the photocatalytic paint on building surfaces had a greater impact on reducing footpath pollution in the hotspots zones, with reduction of up to 1.7% compared to an average reduction of 1.2% across the fully mitigated street. Similarly, the impact of the solid barrier improved air quality at the hotspot locations by 9.6%–20.1% compared to the average 2.3% across the entire street. Similar improvements were noted using the photocatalytic paint and innovative materials for footpath and on-road NO_2 concentrations. As the results had previously shown that the low boundary wall increased NO_2 concentrations on the road in the full street, hotspot 2 uniquely presented an improvement in the road of 9.0%. This suggests that a well-designed solid barrier may help improve air quality on both the footpaths and on the road in some cases.

Consequently, mitigating hotspots where the pollution levels are the greatest provides a cost-effective alternative to reducing personal exposure. It should be noted that the application of mitigation strategies may create new hotspots, such as increased concentrations over road zones in the case of solid barriers.

4.4. Ranking mitigation strategies

To compare each mitigation strategy in terms of environmental and economic performance, the ranking of the mitigation strategy are shown in Table 3.

The overall results demonstrate the differences between the environmental and economic results for a range of different pollution mitigation strategies in the same street canyon. From an economic standpoint, the existing trees performed the best overall and improved air quality in both the footpath and road zones. However, the environmental performance places this measure as the least effective when considering footpath air quality. Therefore, it is suggested that planting trees should be carefully considered in cities as a cost-effective pollution mitigation strategy, taking into account local meteorological and geometrical conditions. Photocatalytic paint was identified as the most expensive mitigation strategy with a limited environmental performances. Owing to their enhanced deposition performance, the solid barriers coated with innovative material and photocatalytic paint presented the best pollutant mitigation measures, despite the high initial cost of the barrier itself.

4.5. Importance of incorporating pollution background concentrations

Despite the perception that local pollutant emission sources plays the most significant role on nearby personal exposure, background concentrations can still contribute to air pollution in

Table 3
Ranking of mitigation strategies based on both their environmental and economic performance to decreasing NO_2 concentrations (over pedestrian zone at 1.5 m height). If a mitigation strategy was shown to increase concentrations, no final rank (–) was attributed.

Scenario	Environmental performance	Economic performance (per 1% reduction)
2. Existing tree	5	1
3. Narrow tree	–	–
4. Painted buildings	4	5
5. Solid barrier	3	4
6. Painted barrier	2	3
7. Innovative barrier	1	2

urban street canyons. Comparing the results in Table 1 to the findings in Supplementary Material Table S2 provide evidence in relation to the impact of background concentrations on the calculated performance of each mitigation strategy.

The dispersion results were significantly different for each mitigation strategy when background concentrations were not included in the calculations: the impact of these measures were overestimated by factors of between 1.9-3.0 and 1.4–2.0 in the footpath and road zones, respectively. This means that the addition of a background significantly decreases the aerodynamic dispersive abilities of the studied mitigation strategies.

Changes in the deposition results ranged from fully underestimating the removal of NO_2 for narrow trees and a 30% underestimation for the photocatalytic coating on the building to a 30–50% overestimation for the painted and innovative barriers.

In summary, the omission of background concentrations overestimated the dispersion and deposition performance of almost all mitigation strategies examined, with the exceptions of underestimating removal performance for narrow trees and photocatalytic paint deposition.

5. Conclusions

A number of different pollution mitigation measures were compared in this case study of Oxford Street in London, and the environmental and economic performance tell different stories for implementing these strategies.

Trees could be a cost-effective strategy to promote deposition and enhance aerodynamic dispersion of NO_2 concentrations in a street canyon. However the shape of trees placed in a street canyon, as demonstrated by the narrow trees examined in this paper, may impact air quality both positively and negatively. Solid barriers can improve air quality solely through dispersion for pedestrians on the footpaths, but are expensive to construct. In addition, low boundary walls have detrimental effects of NO_2 concentrations in road zones, which may affect personal exposure of cyclists and drivers. Performance improvements to a solid barrier may be made with the application of photocatalytic paint or innovative materials to promote deposition on surfaces. Photocatalytic paint on building surfaces presented minimal improvements to overall air quality and was significantly more expensive that alternative strategies.

Differences exist when considering the impact of a range of pollutant mitigation strategies on personal exposure for people in both the pedestrian and road zones i.e. as pedestrian and cyclists. For example, the solid barrier demonstrated improvements on the footpaths but a deterioration in air quality on the road. Furthermore, specific zones in the street may be impacted differently as the comparison of hotspots showed less predictable results in some cases with the implementation of each mitigation strategy e.g. improvement on the footpath and on the road with the introduction of a solid barrier at one of the hotspots.

A detailed understanding of site specific conditions are required to maximise the potential of different pollution mitigation strategies in a street canyon environment. A range of pollutant mitigation strategies exist that can promote aerodynamic dispersion and deposition, and this study demonstrates how they perform differently when compared to one another from an environmental and an economic perspective.

The results provide an indication of the environmental and economic performance of these pollution mitigation strategies, however further assessment of diurnal traffic and background NO_2 concentrations is necessary to quantify the temporal variability in the results. A further breakdown of wind conditions i.e. considering laminar and turbulent flow conditions would also improve our understanding of the potential of these mitigation measures in the urban environment. Modelling gaseous pollution emission such as NO_2 is a complex problem and needs further examination, as the presence of other pollutant such as ozone can lead to reactions taking place in urban street canyons. Lastly, the simulation of the effect of trees remains an area that requires further research, as the tree species and factors such as leaf area density (LAD) can play a significant role in the impact of such pollution mitigation strategies.

Despite combined dispersion and deposition reductions, the findings of this study suggest that mitigation strategies do not remove the problem of pollution. The urban background was found to be a large contributor of air pollution even within busy roads such as Oxford St, which decreases the aerodynamic dispersive effects of some of the mitigation strategies presented here.

6. Extrapolation of research findings

The results presented in this study were highly dependent on street canyon geometry (aspect ratio), as demonstrated by the differences in results from the hotspot analysis. Local meteorological conditions, specifically the wind direction in the street canyon was also found to have a significant impact on the modelling results (see Supplementary Material Fig. S7), where the aerodynamic effects of each mitigation strategy may differ depending on the orientation of the wind towards the street canyon. However, deposition reductions associated with the impact of photocatalytic paint or trees were stable across the range of modelled wind directions.

In modern cities with similar grid street patterns, these modelling results could potentially be extrapolated to assess the impact of a mitigation strategy over the entire city. However, as street geometry is variable within the neighbourhoods in London and other typical European cities, further research is required to extrapolate these results.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.03.027.

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