Passive methods for improving air quality in the built environment: A review of porous and solid barriers

John Gallagher a, *, Richard Baldauf b, Christina H. Fuller c, Prashant Kumar d, e, Laurence W. Gill f, Aonghus McNabola f

a School of Environment, Natural Resources & Geography, Bangor University, United Kingdom
b U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC 27711, USA
c Georgia State University, School of Public Health, P.O. Box 3995, Atlanta, GA 30302-3995, USA
d Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences (FEPS), University of Surrey, Guildford GU2 7XH, Surrey, United Kingdom
e Environmental Flow Research Centre, FEPS, University of Surrey, Guildford GU2 7XH, Surrey, United Kingdom
f Department of Civil, Structural & Environmental Engineering, Trinity College Dublin, Ireland

HIGHLIGHTS
- Porous and solid barriers can act as passive methods for improving air quality.
- Experimental or modelling studies don’t capture all complexities of dispersion.
- Passive barriers offer other benefits (shading, noise reduction, aesthetics, eco-system service).
- These passive barriers can be implemented as new or retrofitted from existing systems.
- Developing design guidelines is required before it is adopted by urban planners.

ARTICLE INFO
Article history:
Received 27 March 2015
Received in revised form 24 August 2015
Accepted 25 August 2015
Available online 29 August 2015

Keywords:
Passive methods
Pollutant dispersion
Barriers
Air quality
Urban planning
Policy

ABSTRACT
Protecting the health of growing urban populations from air pollution remains a challenge for planners and requires detailed understanding of air flow and pollutant transport in the built environment. In recent years, the work undertaken on passive methods of reducing air pollution has been examined to address the question: “how can the built environment work to alter natural dispersion patterns to improve air quality for nearby populations?” This review brings together a collective of methods that have demonstrated an ability to influence air flow patterns to reduce personal exposure in the built environment. A number of passive methods exists but, in the context of this paper, are split into two distinct categories: porous and solid barriers. These methods include trees and vegetation (porous) as well as noise barriers, low boundary walls and parked cars (solid); all of which have gained different levels of research momentum over the past decade. Experimental and modelling studies have provided an understanding of the potential for these barriers to improve air quality under varying urban geometrical and meteorological conditions. However, differences in results between these studies and real-world measurements demonstrate the challenges and complexities of simulating pollutant transport in urban areas. These methods provide additional benefits to improving air quality through altering dispersion patterns; avenue trees and vegetation are aesthetically pleasing and provides cooling and shade from direct sunlight. Additionally, real-world case studies are considered an important direction for further verification of these methods in the built environment. Developing design guidelines is an important next stage in promoting passive methods for reducing air pollution and ensuring their integration into future urban planning strategies. In addition, developing channels of communication with urban planners will enhance the development and uptake of design guidelines to improve air quality in the built environment.

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1. Introduction

Vehicular emissions are the predominant source of air pollution in the majority of urban environments throughout the world (Kumar et al., 2013; Wang et al., 2008). Personal exposure to a large fraction of these pollutants occurs during individual commuting (Goel and Kumar, 2014, 2015; Knibbs et al., 2011), which is associated with adverse health impacts for both urban inhabitants (Pupe et al., 2009) and built infrastructure (Kumar and Imam, 2013; Tiwary and Kumar, 2014). Airborne particulate matter (PM), including very small ultrafine particles (UFP, <1 μm) are such pollutants sourced from vehicles' exhaust emissions (Kumar et al., 2010), and has made the issue of air pollution exposure in cities worldwide even more challenging (Kumar et al., 2014). To improve air quality in the built environment, three approaches outlined by McNabola et al. (2013) may be considered: (i) controlling the quantity of pollution (g), (ii) controlling the emission intensity (g km⁻¹), and (iii) controlling source-receptor pathways (g m⁻³). Each method provides its own benefits for improving air quality. The combination of these strategies requires a framework to ensure their successful implementation (Roumboutsos and Kapros, 2008).

As urban populations continue to grow, and the majority of people now live in urban areas (United Nations, 2009), methods to improve air quality in the built environment have become more important than ever before. The implementation of emission standards to reduce urban pollution will take years to achieve desired results. Removing vehicles from urban areas to create zero pollutant emission zones is also not an easy option for most urban areas. Therefore, alternative solutions such as implementing passive methods for improving air quality and reducing personal exposure must be considered (McNabola, 2010).

In the case of vehicle emissions, altering the pathway between the pollutant source and receptor can reduce the concentration of personal exposure for pedestrians (Garcia et al., 2014). Pollutants emitted from a vehicle can behave differently in the atmosphere and therefore different processes exist for each pollutant (De Nevers, 2000). For example, De Nevers (2000) discusses the behaviour of some primary pollutants that react with other gases to create secondary pollutants, while others remain in an inert state and are dispersed by local meteorological conditions. In an urban context, increasing the distance between the source and receptor can reduce personal exposure to vehicular emissions, where transport emissions is considered the predominant source of pollution in the built environment (Kaur et al., 2005; King et al., 2009; Zhao et al., 2004). Segregating vehicles and pedestrians by increasing the number of pedestrianised streets is another solution (Briggs et al., 2008), yet this is a solution that requires substantial planning and can lead to new pollutant hotspots. More recently, McNabola (2010) reported that literature in the area of the passive methods for reducing personal exposure and presented evidence for research opportunities to improve air quality through altering local dispersion patterns.

A significant amount of research has taken place in the past decade on passive methods that can improve urban air quality, with each method presenting a unique solution to the challenge. These methods have included forms of porous (trees and vegetation) and solid (noise barriers, low boundary walls, and parked cars) barriers (McNabola, 2010). Considering this relatively new area of research, this review article outlines the future potential for these methods for improving urban air quality and suggests how they can be incorporated in future urban planning strategies. In addition to methods for controlling the quantity or intensity of emissions, passive methods to improve urban air quality offer a potential long-term solution to urban air quality. As most of these barriers are existing components in the built environment, implementing or retrofitting these systems presents a potentially low cost option compared to other methods. This paper examines the effectiveness and suitability of these methods to optimise local dispersion patterns and provide potential solutions for reducing personal exposure.

2. Passive methods for improving air quality

A range of passive methods have been identified to reduce personal exposure to primary pollutant concentrations in the built environment (Table 1).

These mechanisms can improve air quality and provide healthier conditions for urban dwellers (Amorim et al., 2013a; McNabola, 2010). This study focused on relevant publications from the least ten years, specifically dealing with the impact of passive methods that impact specifically on pollutant dispersion to potentially improve air quality in the built environment.

These passive methods are grouped either as a porous or solid barrier, based on its ability to either partially or fully act as a baffle between a pollutant source and individual or a group of receptors (McNabola, 2010). The passive barriers can protect human health by influencing localised dispersion. Reducing pollutant concentrations is dependent on local meteorological conditions and the geometry of the built environment. The findings from this review presents comparative and contrasting results that provide an evidence base for the true effectiveness of passive methods to improve urban air quality.

3. Porous barriers

Green infrastructure offers a porous media that can provide a barrier between traffic emissions and nearby populations, potentially benefiting urban air quality by influencing localised turbulence and altering natural dispersion patterns. In addition, these porous barriers promote filtration and deposition of pollutants, particularly different sizes of airborne particulates, thus affecting local pollutant concentration in a different manner to gaseous pollutants (Janhäll, 2015). They also provide an aesthetically pleasing component amidst the colder building facades.

3.1. Trees and vegetation

Trees and vegetation affect localised pollutant deposition and offer additional benefits of filtering out particulate pollutants (Fig. 1). Previous investigations have explored and quantified the macro-scale impacts of trees and vegetation on air pollution in the built environment (Janhäll, 2015; Nowak et al., 2006; Setälä et al., 2013; Tallis et al., 2011; Vos et al., 2013). Janhäll (2015) recently reviewed the literature on vegetation effects on urban and local-scale for a range of particulate concentrations, noting the ability for vegetation to remove PM pollutants through dispersion and deposition. This paper focuses primarily on micro-scale impacts of urban green infrastructure, either as avenue trees or hedgerows in a street canyon or arterial roads or highways with mixed roadside vegetation.

Janhäll (2015) reviewed multiple studies that measured changes in pollutant concentrations in the presence of vegetation at both urban and local scales: eleven modelling investigations, six wind tunnel experiment studies, six sets of field experiments, with several studies adopting a combination of modelling and field measurements. These studies examined a range of particulate and gaseous pollutants and details relating to the details focused upon if each study is outlined in Table 2.
Furthermore, Janhäll (2015) also noted that these wind tunnel and dispersion modelling studies do not account for the effect of heat flux and buoyancy on the dispersion of air pollutants in the presence of vegetation.

Most recently, a modelling study by Abhijith and Gokhale (2015) examined the combined effect of porous and solid (parallel parked cars) barriers by considering the dispersion of a tracer gas in a street canyon. The results showed that improvements of up to 19% on the windward footpath in parallel winds in the street, yet substantial deteriorations in air quality of 105% in perpendicular wind conditions. The study presented a combination of low-stand, high porosity trees as a porous barrier in combination with a solid barrier (parallel parked cars) as the best solution for enhancing the dispersion of gaseous pollutants in the built environment.

3.1.1. Strengths and limitations of trees and vegetation

Findings of previous studies present mixed results of improvements and deteriorations in urban air quality. Focusing on the dispersion effects of trees and vegetation on pollutants, findings have suggested that vegetation presents similar characteristics to a solid barrier. This related to tree parameters, specifically crown size, porosity and leaf density, tree height and spacing. Notably, the impact of trees and vegetation on air quality is predominantly influenced by street geometry or highway layout and local meteorological and vegetation stand conditions. Furthermore, preliminary research suggests that the potential to combining these porous barriers with solid barriers may provide the best solution to improving air quality.

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**Table 1**

Research studies undertaken for different passive methods for improving air quality.

<table>
<thead>
<tr>
<th>Passive method</th>
<th>Study type</th>
<th>Pollutant$^a$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier type</td>
<td>Method</td>
<td>Measurement</td>
<td>Modelling</td>
</tr>
<tr>
<td>Porous</td>
<td>Trees and vegetation</td>
<td>✓✓✓✓✓✓✓✓</td>
<td>(Abhijith and Gokhale, 2015; Al-Dabbous and Kumar, 2014; Amorim et al., 2013a; Amorim et al., 2013b; Baldauf et al., 2008; Brantley et al., 2014; Buccolieri et al., 2009; Buccolieri et al., 2011; Gromke, 2011; Gromke et al., 2008; Gromke and Ruck, 2007, 2012; Hagler et al., 2012; Mao et al., 2013; Ng and Chau, 2012; Salmond et al., 2013; Steffens et al., 2012; Wania et al., 2012)</td>
</tr>
<tr>
<td>Solid</td>
<td>Noise barrier</td>
<td>✓✓✓✓✓✓✓ ✓</td>
<td>(Baldauf et al., 2008; Bowker et al., 2007; Finn et al., 2010; Hagler et al., 2012; Hagler et al., 2011; Jeong, 2014; Ning et al., 2010; Schulte et al., 2014; Steffens et al., 2014; Steffens et al., 2013)</td>
</tr>
<tr>
<td>Low boundary wall</td>
<td>✓✓✓✓✓✓✓ ✓</td>
<td>(Gallagher et al., 2012, 2013; King et al., 2009; McNabola et al., 2008, 2009)</td>
<td></td>
</tr>
<tr>
<td>Parked cars</td>
<td>✓✓✓✓✓✓✓ ✓</td>
<td>(Abhijith and Gokhale, 2015; Gallagher et al., 2011, 2013)</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Particulate matter (PM) – PM$_{2.5}$, PM$_{10}$, UFP and heavy metals; CO; NO$_x$; VOCs including benzene.

$^b$ Includes other inert tracer gas studies (e.g. SF$_6$).

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Fig. 1. (a) tree experiment in wind tunnel, (b) real-world assessment of vegetation barrier, (c) tree crown cross section and (d) model of street canyon with trees (Buccolieri et al., 2009; Gromke et al., 2008; Gromke and Ruck, 2007; Steffens et al., 2012).
4. Solid barriers

A number of solid barriers have also been identified and investigated as potential passive methods to improve air quality. Noise barriers, low boundary walls (LBWs) and parked cars present distinct solid barriers in the built environment that can influence air flow and pollutant dispersion in different ways. The primary differences between a noise barrier and the other solid barriers are: (i) height difference: a noise barrier is typically in excess of 4–5 m tall, compared to a LBW or parked car of 1–2 m or less in height, respectively, and (ii) LBWs and parked cars are often adjacent to low speed roadways while noise barriers are often located along high speed highways. Parked cars present a non-continuous and temporary barrier in comparison to the other solid barriers examined in this study.

4.1. Noise barriers

Noise barriers are commonly placed on major high-speed highways to reduce noise pollution for populated areas, but these barriers can also influence localised dispersion and have been shown to improve downwind air quality (Fig. 2). The investigations examined in this section adopted either one or multiple methods of assessment: five undertook field measurement studies, five used modelling (three CFD models and two empirical studies) and one study included wind tunnel experiments. Most research papers considered only one pollutant, with only two publications examining multiple pollutants. The majority (five) of studies used a tracer gas (either SF6 or ethane, C2H6), which mimic the behaviour of gases like CO (which was examined in two additional investigations). Three particulate studies (two measuring PM number and one PM mass concentrations, one measuring black carbon, and two collecting UFP concentrations) and one investigation measured NO2, which is highly reactive in comparison to the other pollutants examined.

The influence of a noise barrier on air quality and pollutant dispersion was investigated in the U.S. as part of a modelling and measurement study of different roadside barriers (Bowker et al., 2007). This study considered the impacts of a barrier on UFP concentrations along a busy highway (Fig. 2a) and allowed for the assessment of a barrier versus no barrier in a real-world environment. The measurements reported by (Baldauf et al., 2008) for PM and CO demonstrated that the introduction of a noise barrier reduced pollutant concentrations behind the barrier by approximately 15% but at times reached 50%. With the inclusion of a barrier, the modelling results suggested that a reduction in pollutant concentrations would be achieved further downwind (Bowker et al., 2007). These results performed well against decay rate measurements, noting minor differences for initial concentrations in the mixing zones.

The work by Ning et al. (2010) measured the size distribution of particulate concentrations and several other pollutants in two case studies of urban freeways. Very similar results were noted in this study for PM number concentrations, with reductions in the 45–50% range downwind of the barrier. Tracer pollutant investigations reported by Finn et al. (2010) demonstrated the potential for noise barriers (Fig. 2b) to improve air quality by over 50% downwind of the barrier during certain meteorological conditions such as stable atmospheres. The results of another tracer (C2H6) modelling investigation by Hagler et al. (2011) ranging from 15 to 61% and dependent on the height of the barrier (higher the barrier, the greater the downwind pollutant reduction).

A number of the studies have shown how a noise barrier traps pollutants on the upwind side of the structure and this may lead to higher concentrations in this location (Bowker et al., 2007; Finn et al., 2010; Ning et al., 2010; Steffens et al., 2014). In particular, Finn et al. (2010) noted this occurrence in a tracer study in low wind speeds. Based on the tracer gas modelling study results from Hagler et al. (2011), the on-road pollutant concentrations increased by a factor of 1.1–2.3, increasing as the barrier height increased. The study by Ning et al. (2010) concluded that the barrier creates an impact zone for traffic emissions. A modelling investigation by Steffens et al. (2013) identified a recirculation zone in the wake of the barrier, which impacted on pollutant transport in the road area. These results suggest that pollutant concentrations from upwind sources may lead to higher pollutant concentrations, although...
questions still remain on whether turbulence created by traffic on the roadway may limit these effects for the on-road environment.

Evidence of potentially higher pollutant concentrations further downwind of the barrier (approximately 150 m) was noted by Ning et al. (2010) compared with the situation of no barrier present. The modelling results found by Bowker et al. (2007) suggested that this was due to the re-attachment of the plume downwind of the barrier. Bowker et al. (2007) noted that concentrations at 150 m from the road were approximately 35% higher than with no barrier; although they also noted that these concentrations were significantly lower at this distance, both with and without the barrier, compared to the high concentrations closer to the highway with no barrier present. However, no other controlled wind tunnel studies or tracer gas experiments have identified this plume re-attachment phenomena.

The potential of noise barriers to affect pollutant transport and dispersion is influenced by the size and layout of the barrier, wind direction and turbulence conditions (Finn et al., 2010; Hagler et al., 2011; Jeong, 2014; Schulte et al., 2014; Steffens et al., 2014, 2013). As previously noted, results measured by Hagler et al. (2011) showed reductions in pollutant concentrations of up to 61%, with improved air quality conditions associated with an increase in the barrier height. The impact of wall height on both noise and air quality was noted by King et al. (2009) and Steffens et al. (2014) who considered a number of road and barrier configurations. The barrier height was shown to have the greatest influence on pollutant concentrations near the barrier and on atmospheric stability downwind of the barrier (Schulte et al., 2014). The study by Finn et al. (2010) recorded detailed measurements of barrier-induced turbulence and pollutant concentrations around the barrier, identifying significantly more lateral dispersion in the barrier region. Different flow conditions were modelled by Schulte et al. (2014), but found that overestimations of pollutant concentrations were made in unstable, turbulent conditions. Wind speed and direction were identified as factors that influence air pollutant concentrations in the barrier region (Baldauf et al., 2008). The modelling of noise barriers with different flow regimes by Jeong (2014) demonstrated how wind conditions significantly impact the influence of noise barriers on air quality. Both lateral dispersion and increasing vertical mixing occurred due to the noise barrier, altering natural air flow patterns and the direction of pollutant transport (Jeong, 2014; Steffens et al., 2014). Furthermore, Baldauf et al. (2008) and Bowker et al. (2007) included scenarios which combined a porous and solid barrier i.e. a noise barrier and vegetation, which further enhanced dispersion to improve air quality.

A study by Ning et al. (2010) identified the need to consider their findings in other exposure research. Measurement studies have demonstrated the potential of noise barriers and their impact on air quality for different pollutants (Baldauf et al., 2008; Bowker et al., 2007; Finn et al., 2010; Ning et al., 2010). This has been complemented by more recent modelling investigations (Hagler et al., 2011; Steffens et al., 2014, 2013), which has provided a better understanding of pollutant dispersion for different barrier configurations and in a range of flow conditions.

4.1.1. Strengths and limitations of noise barriers

The potential for solid noise barriers to influence pollutant dispersion was found to be impacted by the geometry and layout of the noise barrier, and its influence on local air flow regimes and turbulence conditions. Thus, local meteorological conditions and highway layout play a significant part in quantifying the impact of noise barriers on local air quality conditions. The findings demonstrate that a reduction in pollutant concentrations occurs downwind of the barrier. In some cases, this downwind location may be a densely populated area, therefore implementing this type of barrier may help improve air quality conditions for urban inhabitants. Studies have also demonstrated the potential negative impact of increased concentrations of pollutant on the roadside of the barrier if vehicle turbulence does not increase mixing and dilution. Noise barriers can reduce downwind pollutant concentrations and further investigations can provide transferable results to ensure these solid barriers provide simultaneous air and noise quality benefits.

4.2. Low boundary wall

A LBW is presented as a scaled down alternative to a noise barrier in an urban street canyon setting, which influences local dispersion and can improve air quality (Fig. 3). Unlike previously discussed passive methods of pollution reduction, LBWs are currently not as prevalent in the built environment. Five studies examining LBWs adopted computational modelling, with two undertaking field measurements. Only one pollutant was considered in four of the five investigations, with three studies considering benzene and the additional studies adopting either CO, PM$_{2.5}$ or NO$_x$ to quantify the impact of LBWs on air quality in urban street canyons.

Initial studies on LBWs were carried out along a boardwalk in Dublin, Ireland (King et al., 2009; McNabola et al., 2008). The investigations examined the influence of a boundary wall constructed between a boardwalk and an adjacent road with three lanes of one-directional traffic. McNabola et al. (2008) found that an LBW acted as a baffle, which when located along the outer edge of footpaths or in the centre of the canyon, promoted pollutant dispersion in a street canyon. A subsequent investigation by King et al. (2009) noted the clear benefits of the boardwalk on air and noise pollution as the segregation of human and vehicular traffic increased the distance between the source and the receptor.
The results from the air quality sampling study by McNabola et al. (2008) measured reductions of between 35% and 57% in personal pollutant exposure for pedestrians walking along the boardwalk as opposed to the adjacent footpath. A generic computational modelling investigation by McNabola et al. (2009) calculated reductions in personal pollutant exposure of up to 40% and 75% in perpendicular and parallel wind conditions, respectively. A subsequent study by Gallagher et al. (2012) found that footpath LBWs (i.e. a low wall on the outer edge of the footpath) models ranged from a 19% increase to a 30% reduction on the leeward footpath and reductions of 26%–50% on the windward footpath. Following this, Gallagher et al. (2013) assessed LBWs in a real-world investigation and found reductions in pollutant concentrations of up to 35% to a maximum increase of 25% on the footpaths in varying wind conditions.

King et al. (2009) found that the height of the LBW impacted the effectiveness of the barrier on air flow and pollutant concentrations on the footpath. In addition, McNabola et al. (2009) considered two footpath LBWs and a central LBW (i.e. a wall in the middle of the street), and found that the location of the LBWs impacted the results for pollutant concentrations. This was due to the development of different shaped vortices in the street canyon: a singular primary vortex developed in the footpath LBWs model compared to two primary vortices in the central LBW model. The central LBW models demonstrated similar results for perpendicular wind conditions, but significant variances in parallel wind scenarios. The generic street layout, limited wind conditions and omission of vehicular turbulence were noted to provide inaccuracies in the results compared to real-world conditions (McNabola et al., 2009). The error due to the simplified emissions model was considered to be more influential in model results for low wind speeds in the street canyon (Gallagher et al., 2012). The most recent study by Gallagher et al. (2013) adopted a semi-empirical equation for a real-world investigation to calibrate the models and account for factors such as vehicular turbulence, in addition to the fleet composition in the street canyon. The study recognised that the omission of vehicular turbulence reduced street level dispersion, thus over-estimating the potential of LBWs to reduce pollutant concentrations and provide the sole method of enhancing dispersion in a street canyon.

The turbulence effects of LBWs is dependent on site specific characteristics: street geometry, wind conditions and vehicular turbulence (et al. (2013), McNabola et al. (2008)) found that the H/W ratio impacted air flow patterns in the canyon. The study also determined that the location of the emissions source affected the fraction of pollutants transported and re-circulated to the footpaths (McNabola et al., 2009). A more extensive investigation by Gallagher et al. (2012) examined the influence of LBWs in a range of asymmetric canyon scenarios (H/W ratio of 0.5–1.5 in 0.1 intervals, where H1 and H2 were height of adjacent buildings). The study demonstrated both potential improvements and deteriorations in air quality at street level in varying geometry and meteorological conditions (Gallagher et al., 2012). Furthermore, the non-continuous nature of the LBW (due to gaps required at junctions) was found to alter the development of the vortices in the canyon and thus impact pollutant concentrations on the footpaths (Gallagher et al., 2013).

In perpendicular wind conditions, reductions and increases in pollutant concentrations were evident in the footpaths LBW models, with reductions noted on both footpaths for all central LBW models (McNabola et al., 2009). The footpath LBWs provided the best results in parallel wind conditions, however improvements in air quality were found for both LBW configurations. Gallagher et al. (2012) noted that the development and strength of the primary and secondary vortices in the street canyon was dependent on wind speed. This was reinforced by the findings from Gallagher et al. (2013) as limited vortex development was recognised in the street canyon due to low wind speeds.

4.2.1. Strengths and limitations of LBWs

LBWs act as a baffle and alter air flow patterns at street level. The research on LBWs has been limited to date, however, the results show that LBWs have the potential of enhancing local dispersion in the built environment. The height of the LBW, its location in the street and whether spaces exist in the barrier was found to influence air flow in street canyons. Similar to noise barriers, the findings suggested that their effectiveness is dependent on varying street canyon geometry, barrier configuration, wind conditions and vehicular turbulence. Previous research provides an understanding of the impact of LBWs in generic and real-world settings. However, further studies are required to allow for the extrapolation of findings in other cities. This requires an examination of LBWs in a broader range of climatic conditions and high rise street canyons. Furthermore, a confined street canyon study needs to be expanded to a city-scale, as the frequency and variation of road characteristics...
and intersections are not considered in the LBW studies to date. Similar to noise barriers, there is some evidence that LBWs could cause deteriorations in air quality for vehicular users and, in particular, pedestrians and cyclists. However, the influence of vehicle-induced turbulence in modelling studies may lead to overestimations of some results. LBWs can provide a solution to enhancing dispersion and improving air quality in distinct street canyons settings. However, further work is required to ensure their implementation in the built environment has a positive impact on air quality.

4.3. Parked cars

Parking bays are a common feature in the built environment. Parked cars can be considered as obstacles to the natural air flow patterns in a typical street canyon. Three modelling studies have been carried out on parked cars to date (Fig. 4), with one study also undertaking air quality field measurements. These investigations considered CO, NOx, and SF6 as a pollutant to help calculate the impact of parked cars on air quality in an urban street canyon.

Parked cars present a transient passive method of pollution reduction, as they move in and out of parking bays at irregular times each day. They are located directly adjacent to vehicle lanes (Fig. 4) and thus provide a barrier between the pollutant source and human receptors on the footpaths (Gallagher et al., 2011, 2013). An initial generic modelling investigation of a symmetrical street canyon \( H/W = 1 \) by Gallagher et al. (2011) assessed three common parking bay configurations, while a subsequent investigation by Gallagher et al. (2013) examined a real-world scenario with parallel parked cars in a street canyon in Dublin, Ireland. Parked cars impact pollutant dispersion and influence the development of vortices in the street canyon. However, it was recognised that some configurations could be detrimental to air quality on adjacent footpaths in certain wind conditions (Gallagher et al., 2011).

Parallel parking demonstrated the best overall simulated results in air quality, with an average modelled reduction in pollutant concentrations between 31% and 49% on both footpaths for varying wind conditions (Gallagher et al., 2011). A subsequent study by Abhijith and Gokhale (2015) expanded upon this work for a wider street canyon \( H/W = 0.5 \) and found maximum improvements of up to 28%. Gallagher et al. (2013) compared previous results from a generic modelling study to a real-world scenario and the results only showed an improvement in air quality of up to 15% when the parking bays were fully occupied. However, this was due to (i) the parking bays not taking up the full length of the street, and (ii) the parking bays only existing on one side of the street. Based on the occupancy rate of parked cars along the street canyon, similarities were noted between the results from both studies.

Perpendicular and central parking bays demonstrated improvements and deteriorations in air quality for different wind conditions unlike parallel parking (Abhijith and Gokhale, 2015; Gallagher et al., 2011). The spacing between vehicles and the occupancy rate of the parking bays influenced air quality on the footpaths and the development of the vortex in the street (Gallagher et al., 2011). Furthermore, the results from a combined assessment of cars and trees suggested that parallel parked cars had the greatest impact as a passive barrier in perpendicular winds (Abhijith and Gokhale, 2015). The investigation by Gallagher et al. (2013) examined the effects of complex canyon geometry and included local traffic and meteorological conditions through the models and a semi-empirical equation to calibrate the model. Similar to other methods, street geometry (i.e. aspect ratio) and meteorological (i.e. wind) conditions were predominant factors on the ability to alter localised dispersion patterns and improve air quality (Abhijith and Gokhale, 2015; Gallagher et al., 2011, 2013). However the semi-empirical model accounted for factors such as vehicular turbulence, which helped improve the accuracy of results in comparison to the previous studies.

4.3.1. Strengths and limitations of parked cars

Unlike the other passive method of pollution reduction, parked cars do not present a static barrier in the built environment. However, as only a limited number of investigations are available, further research is required to provide more conclusive evidence of their potential in a range of settings. In addition, the use of a generic car design is restrictive to the reality of variability in shapes and sizes of vehicles. As barrier height has been found to impact its effect on air quality and dispersion, parked cars can provide a taller boundary than a LBW, yet not to the extent of a noise barrier. The temporary, non-continuous and variable shape or parked cars could be considered as less effective than a narrower and shorter LBW. However, parked cars are likely to continue as a common visual element of the built environment. They present a low cost method of pollution concentration reductions that can be implemented through the simple re-design of parking bays, converting streets with the best layout based on local meteorological conditions.

Fig. 4. (a) Parked cars demonstrating its influence on air flow in generic street canyon model and (b) parked cars layout in model of Pearse Street, Dublin, Ireland (Gallagher et al., 2011, 2013).
5. Summary

The assessment of each passive method for improving air quality presents their own unique findings, yet similarities have been identified on how the methods influence air flow and pollutant dispersion. The findings are summarised by the adopted methodologies, quality and quantity of results, and commonalities or differences for each method.

- **Trees and vegetation** present a common and aesthetically pleasant element that can impact pollutant dispersion in the built environment. A recent review by Janhäll (2015) provides a detailed overview on the impacts of green infrastructure on dispersion in the urban environment. Summarising the findings of a range of measurement, modelling and experimental studies in relation to pollutant dispersion in the built environment: tree parameters (crown height, leaf density tree height and spacing) have been found to impact air quality; street canyon or highway geometry (e.g. narrow street layout) and meteorological conditions (e.g. low wind speeds and wind direction) impacted poor natural ventilation; and despite their porous nature, avenue trees have been reported to act more like a solid barrier. In addition, a combination of trees and other solid barriers (e.g. parked cars) can have combined benefits on local air quality.

Trees and vegetation offer many benefits to the urban environment, however as Janhäll (2015) states that urban planner need to account for the impact of trees and vegetation on pollutant dispersion. However, a lack of conclusive guidelines limits the translation of these findings to urban planners for providing the optimum selection, design and layout of avenue trees or roadside vegetation in the built environment.

- **Noise barriers** can be found alongside busy arterials and high-speed, high-traffic highways in most cities as solid high walls, complemented in some cases by roadside vegetation. Measurement studies and modelling investigations have found relatively consistent reductions in pollutant concentrations downwind of the barriers. However, similar to the roadside vegetation studies, an increase in upwind concentrations has been identified due to the recirculation of pollutants in the zone in front of the structure. In addition, a couple studies suggest that the reattachment of a plume downwind of a barrier could lead to higher concentrations further downwind of the barrier compared to no barrier under some settings. The height and layout of the noise barrier (i.e. continuous barrier or the combination of the barrier and vegetation) presented the greatest influence on the dispersion of pollutants along the highway. Wind conditions also presented a significant contributor to the impact that noise barriers have on pollutant transport and air quality along arterials and highways. The research undertaken for noise barriers has focused on real-world experiments, and the complementary modelling investigations provide an understanding of their potential to affect localised dispersion and air quality. Noise barriers are a feasible passive method of pollution reduction and present less variable factors in their effectiveness than porous barriers. Generating guidelines for urban planners is therefore considered less complex as the results to date have been relatively complementary; however the relationship between vegetation and the noise barriers present the most complex factor for developing future design guidelines. In addition, guidelines require development that can respect the dual function of such barriers and thus the studies must examine the impact of noise barrier design on both noise levels and air pollution.

- **LBWs** can improve urban air quality by enhancing pollutant dispersion in street canyons. They act as a baffle at street level and increase the distance between the pollutant source and human receptor. A number of modelling investigations of LBWs have shown how different configurations alter the natural air flow patterns in an urban street canyon and lead to the development of distinct vortex structures. The modelling and measurement results present LBWs as an effective barrier and reductions in pollutant concentrations have been found on the footpaths in most wind conditions. Low wind speeds and wall and canyon geometry impact on the effectiveness of the LBWs to promote dispersion and the development of vortices in street canyons, which transports pollutants to roof level. Deteriorations in air quality were measured on the leeward footpath from model simulations for perpendicular wind conditions. However, the majority of these generic street canyon modelling studies present non-realistic settings, typically overestimating the improvements in air quality compared to real world measurements. The development of guidelines to provide practical instructions for implementing LBWs in a street canyon environment still requires further research as current findings are limited. Similar to noise barriers, there is some evidence of increased concentrations in the road. However, there is evidence that LBWs present a method of altering localised dispersion patterns and improving air quality at street level, which can provide an alternative to pedestrianised streets and improve conditions for our urban populations.

- **Parked cars** are presented as a higher and wider barrier than a LBW, yet gaps between cars and the presence of empty spaces allows the direct transport of pollutants between the roadway and footpaths. Modelling investigations of different parking configurations demonstrated the impact of the parking bay layout and occupancy rate of the parking bays on the pollutant dispersion as a consequence of the development of the street canyon vortices. As parallel parked cars provided improvements in air quality in all wind conditions, a subsequent real world investigation showed similar improvements. However, varying street geometry and the non-continuous nature of the parking bay prevented the occurrence of strong vortices which enhanced dispersion at street level. Due to the spacing between vehicles, parked cars impact air flow differently to the other barrier types. Despite this, fully occupied parking bays typically followed the same pattern of controlling pollution on the footpaths. Guidelines to promote the retrofitting of parking bay designs in street canyons presents the greatest potential to ensure parked cars can promote dispersion where they exist and improve local air quality.

6. Conclusions and future directions

Studies examining passive methods of reducing air pollution concentrations have adopted different measurement or modelling approaches in their investigations. They have explored the impact of these passive methods for a range of pollutants and for different urban zones in the built environment. Generic wind-tunnel and modelling results provide a suitable context for the effectiveness of the different passive methods. However, the need for more real-world studies is envisioned to validate these findings and aid the development of unambiguous guidelines for the implementation of these pollution reduction strategies. The results from each of the barrier studies provide an evidence base that they have the potential to alter pollutant transport and dispersion patterns and improve air quality in the built environment. Yet, it has to be recognised that their effectiveness is dependent on local geometrical and meteorological conditions, as this is what affects localised dispersion and turbulence in the built environment (Kumar et al.,


