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Urban obstacles influence on street canyon ventilation: a brief review †

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Abstract: Many research articles explore new designs and how arrange barriers/obstacles to improve roadside air quality and ventilation within the urban street canyon. These obstacles are generally categorized into porous, non-porous and mixed type. Porous barriers include vegetated shrubs and trees, non-porous barriers include parked cars, low boundary walls, etc, while mixed barriers combine both porous and non-porous barriers. Moreover, new developments can benefit from added design flexibility using lift-up building design and building porosity as a promising way of improving ventilation. This short paper reviews the different research studies conducted on obstacles/barriers in an urban canyon which helps improve air quality and highlight potential future research.

Keywords: urban obstacles; lift-up buildings; ventilation; air quality

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1. Introduction

While there are major sources that contribute towards air pollution – such as road transport, industry, and even households (like fireplaces), vehicle emissions have been considered as major contributors [1–3]. The formation of the street canyon, characterised by open roads/pathways that are surrounding by buildings on either side creates a perfectly hazardous situation that restricts urban wind flow, and traps vehicular pollution in the canyons themselves – thus increasing pollutant concentration levels for the people living in and commuting through these canyons.

A recent review paper by Huang et al. [1] highlighted the various passive mitigation strategies that have been studied in recent research. These mitigation strategies include both traffic interventions (such as low emission zones, congestion charges, etc) and city planning (building geometry, canyon height to width ratio, etc). City planning guidelines can further be subdivided into general design guidelines (such as the consideration of low canyon ratio, alignment of the street with prevailing wind directions, building heights and set-back conditions) that may be encompassed for new developments, while the modification of in-street barriers/ obstacles (such as parked cars, roadside hedges, low boundary walls (LBWs), etc) are more applicable for existing street canyons that are more obdurate to the whims of urban planners.

Further, as some recent research suggests, the use of lift-up buildings – where the first floor/s of a building are left void – creates a setting that is conducive for ventilation flow and potentially the reduction of air pollution concentrations in urban canyons [4–6]

Research for these obstacles have shown that they tend to have various effects on the mitigation of air pollution in cities. The three distinct methods are through dispersion, deposition, and chemical reactions. Dispersion effects are typical for all the types of obstacles. Deposition and chemical effects usually take place in the case of porous vegetated barriers. While all effects are necessarily positive in the context of urban air pollution, certain effects are more predominant than others [7,8].

This paper seeks to underline as well as expand on the definitions of obstacles in urban canyons and discussing about the potential of obstacles in existing as well as new urban street canyons. This paper will expand on the literature review by Gallagher et al. [2], covering research papers since 2015 until the present.

1.1 Search protocol and structure of the review

The review was performed by searching articles using Google Scholar, Scopus, Web of Science and Science Direct in addition to those known to authors, and the approach followed was that of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA).

As per the PRISMA guidelines, "Updates and, sometimes, expansions of an existing systematic review allow for the consideration of new evidence to bring previously published systematic reviews up to date"[9]. This review paper aims for this, by working as an update/expansion to the review paper by Gallagher et al. [2]. The search was conducted in February 2021, and only papers from 2015 onwards were considered. On one hand, all papers that were 'cited by' each paper referred by Gallagher et al. [2] were checked in Google Scholar (which has such a feature). In addition to this, the following keywords were searched: urban, air pollution, ventilation, dispersion, air quality, obstacles, barriers, street canyons, lift-up, etc. Relevant papers were first manually screened by title and imported to the Mendeley Reference Manager; further manual screening of each paper was done by checking abstract, methodology and conclusions and those fitting to the topic of the paper (proposal and/or application) were selected.

Screening between the selected studies and taking into consideration some examples (a comprehensive review will be presented in a full paper later), each of the following sections categorises the studies based on the type of urban obstacle (porous, non-porous, etc) with a broad based definition for each category, in line with the categories presented by Gallagher et al. [2]. Newer studies that also appear to fit the topic (such as lift-up buildings, wind-catchers, etc), have been classified separately.

1.2. Urban Obstacles in Street Canyons

The review by Gallagher et al. [2] highlights urban obstacles can be divided into porous and solid types. Porous barriers include vegetation such as trees and shrubs, while non-porous barriers include LBWs, parked cars and noise barriers (NB).

The grouping as porous or solid barriers depends primarily on its ability to act as either a partial or a fully baffled mechanism between the pollutant source and the receptor/s. However, the grouping is assigned based on individual structure, and not the arrangement of the individual structures; for instance, although parked cars are non-porous, there are instances when the arrangement of parked cars leaves gaps in between (empty parking spaces). Although this may appear to give a degree of porosity to the whole structure, it is not considered as a porous but rather as a non-porous structure based on its individual characteristics. Further, mixed barriers are those which combine both porous and solid barriers, such as in the case of LBWs installed with green hedges.

Some examples of each type are shown in (Figure 1).

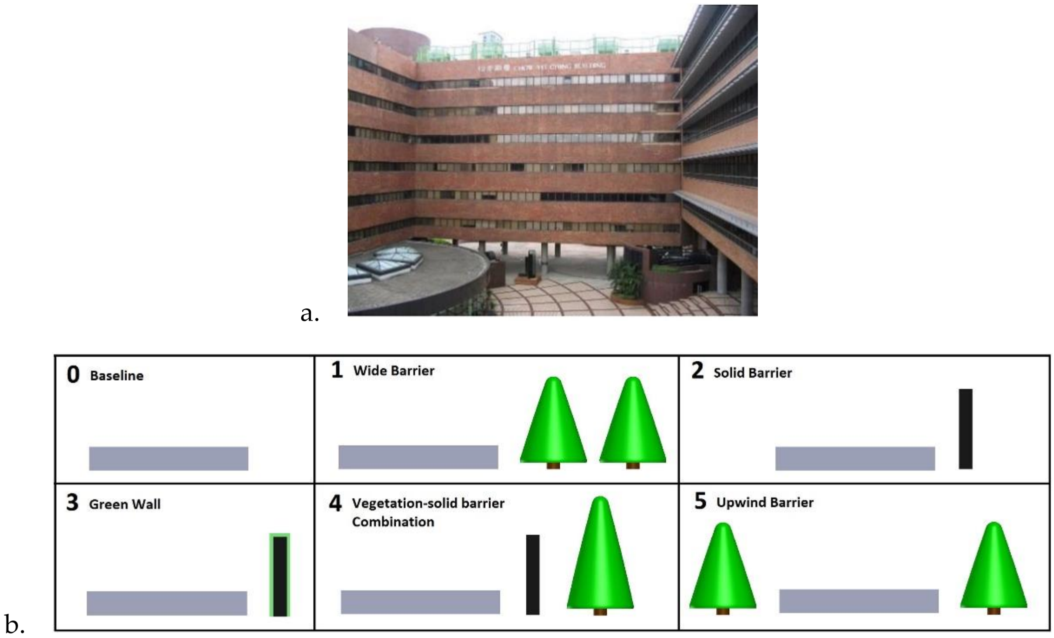

Figure 1. a. Lift-up building [5] (reproduced with the permission © 2017 Elsevier); b. Schematic of different roadside barriers such as solid noise barriers, trees, green walls, etc. [10] (reproduced with the permission © 2016 Elsevier)

2. Porous Obstacles

Green infrastructure/vegetation acts as a porous media between pollutant source and receptor. In addition, Gallagher et al. [2] observed the micro scale impacts of green infrastructure – such as avenue trees or hedgerows, and suggested that in the case of dispersion effects, green infrastructure seems to observe similar characteristics to solid infrastructure. A combination of trees and other solid barriers (like parked cars) seems to offer better impacts than either vegetation or solid barriers alone. In addition, the effect of trees to filter our pollutants through deposition effects was also present. The paper concluded that there was a lack of conclusive guidelines to promote the optimum selection, design, and layout of avenue trees of roadside vegetation. However in general it was seen through later reviews of green infrastructure that for urban street canyons, high level vegetation (trees) led to a deterioration in air quality while low-level infrastructure (hedges) improved air quality conditions [11]. Image of porous obstalces like trees and green walls are shown in Figure 2

2.1. Hedgerows

Further studies on hedgerows shows some similarities with LBW, in terms of its arrangement. Since the dispersion effects of dense vegetation tends to reflect solid barriers, Gromke et al. [12] note that a centrally located hedgerow (running in the middle of the street) seems to offer better concentration reductions and dispersion effects, as opposed to two sideways/ eccentric hedgerows. Santiago et al. [13] found that vegetation barriers composed by a combination of trees and hedgerows were more effective than barriers with only hedgerows.

2.2. Trees

For trees in urban canyons, it was observed that although trees in general tend to worsen the air exchange at pedestrian level, the tree planting pattern and trunk height significantly affect the flow and traffic pollutant dispersion within an urban canyon (aside from the deposition effects already mentioned earlier) [14]. One study showed that the air exchange rate decreased when the tree trunk was much lower than the height of the adjacent buildings (H). However, once the trunk height approached the height of the building

(7H/9 to 10H/9), the ACH dramatically improved within the canyon. Such an arrangement may be feasible for certain trees that are able to reach tall heights that equal the buildings heights in street canyons, especially trees that have an umbrella type geometrical structure – with a tall trunk length and a wide crown that starts at the upper heights. One the other hand, a study by Santiago et al. [15] showed that trees at such a height actually reduced the dispersive flux, and hence resulted in elevated concentrations within the canopy. Hence such an arrangement must be approached with caution, as more studies are necessary to point out what other factors could either assist or hamper the dispersion of pollutants within the canyon.

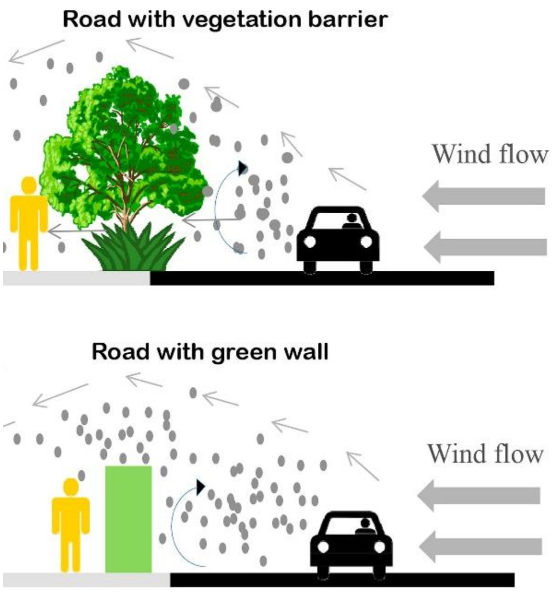

Figure 2. Image showing multiple obstacles – tall green hedges acting as obstacles between cyclists and vehicles, with trees on either side of the road further acting as barriers [11].

2.3 Green Walls

Further studies in green infrastructure also discussed the effects of green walls - which include all forms of vegetated wall surfaces [11,16]. Mostly, the benefits of a green wall pertain to the deposition effect it offers for pollutant reduction [17]. However green walls are also feasible in areas that have limitation on planting trees and hedges inside canyons, due to subsurface infrastructure, poor soil conditions, lack of sunlight, etc [16]. In such cases, combining green walls with already available solid structures offers a host of benefits without occupying extra space; this also includes the concept of vertical green-screens – which is a simple metal/plastic mesh structure with green vertical climbers, and can be more easy and less expensive than green walls to install [16]. The dispersion effects due to green screens may be less pronounced than that of dense green walls or other non-porous barriers, however further research shall be necessary to draw clarity in this regard.

3. Non-Porous Obstacles – Urban Planner Scope

Gallagher et al. [2] recorded several non-porous barriers that have the potential to passively improve air quality. These include parked cars, noise barriers and low boundary walls.

3.1. Parked Cars

Parked cars appear to provide best overall simulated results for air quality in a parallel arrangement, while, perpendicular or central parking bays provided either improvements or deterioration in air quality under different circumstances [2]. Parallel parking arrangement also offered better impacts in combination with trees. However parked cars do always not provide a static or complete barrier, while its generic design allows for limited variability in an urban canyon. However, it has been highlighted that it is still a low-cost method of reducing pollutant concentrations for pedestrians in an urban canyon.

A more recent study in the effects of parked cars in urban canyons show that the resolution of parked cars model is very important when making decisions for on-street parking design [18]. The study demonstrated that an increased resolution of the car design actually presented a larger CO concentration increase for the leeward footpath, as opposed to a reduction in the concentrations in the case of the low-resolution parked car models (generic car and rectangular block scenarios) [18]. This difference shows that potential benefits of parked cars as passive barriers could be overestimated in simple CFD model designs, and such factors must be taken into consideration in policy decisions. Image of a parking bay typical in a street canyon is shown in Figure 3.

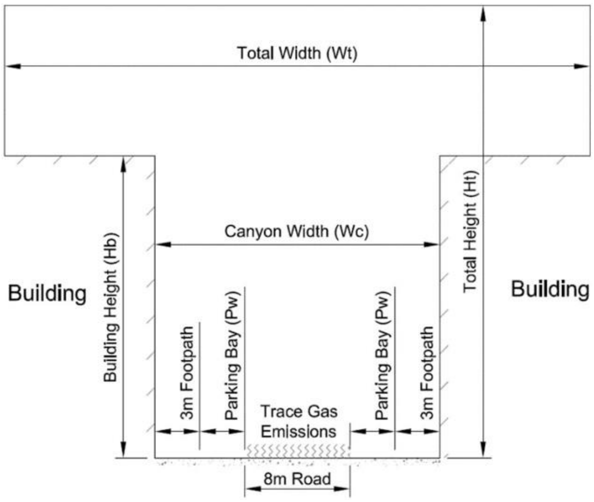

Figure 3: A schematic of an urban canyon with a parking bay. The cars parked in the bay would alter the flow of pollutants towards the footpath on either side [18] (reproduced with the permission © 2019 Elsevier).

3.2 Noise Barriers (NB)

Noise barriers are more commonly placed on high speed highways to reduce noise pollution for surrounding areas [2]. In some instances, NBs are also installed for viaduct that alleviate traffic congestion in an urban canyon [19]. Very rarely are noise barriers seen for a canyon at ground level, as the multi-use nature of many canyons must allow passage for both pedestrians as well as vehicles, as well as visibility. Gallagher et al. [2] traced multiple research studies for noise barriers as compared to LBWs or parked cars.

It was observed that these noise barriers tend to produce lower pollutant concentrations downwind, and greater pollutant reductions the higher the barrier. On the flip side, higher concentrations were noted upwind of the barrier due to recirculation of the pollutants in front of the barrier [2]. Some studies do note higher pollutant concentrations downwind of the barrier, but it was suggested that this was due to the plume reattachment. Despite differences in various factors, it was observed the geometry (such as height) and layout of the barrier played a significant role in affecting the local air flow regimes and turbulent conditions.

Further research has shown that NBs can be optimized with air pollutant sinks placed appropriately above the NB [20]. Although the research gives one example of this 'sink' as an electrostatic precipitator (which is like an active method), it also highlights that artificial pollutant sinks could also be porous vegetation (passive); the position of such a 'sink' over a shorter NB appeared more effective than over a taller NB, and also a small gap between the NB and the sink leads to better aerodynamic performance [20].

Pollutant sampling studies of noise barriers showed that highest metal pollutant accumulation occurred in the lowest part of the noise barriers (0-0.5 m) [21]. Such studies are helpful in the feasibility assessment of noise barriers based on the expected source pollutants. Another study showed that in the presence of a perpendicular wind flow to a highway, the position of an upwind NB creates a recirculation zone above the highway – which could even extend the entire width of the highway depending on the height of the noise barrier (Figure 4) [22]. Such an upwind barrier appears to be better than no barrier at all, and in some circumstances almost as effective as a downwind barrier. This is feasible in cases where installing a downwind barrier may not be suitable, however its applicability in an urban canyon may be limited as it may be more suited to wide open canyon areas or urban-rural transitions. Representative image of a different shape of noise barrier is shown in Figure 5.

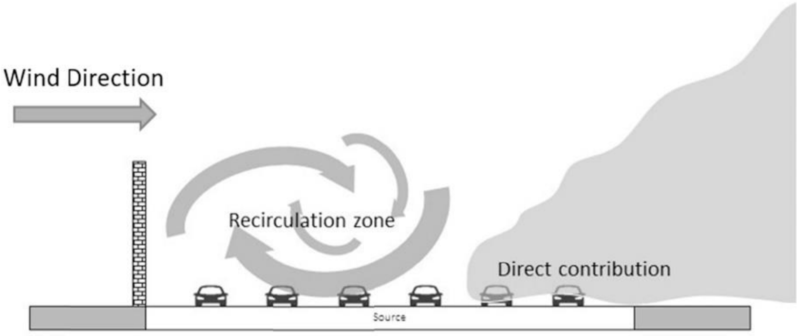

Figure 4: Upwind noise barrier that could potentially create a recirculation zone above the highway [22] (reproduced with the permission © 2017 Elsevier).

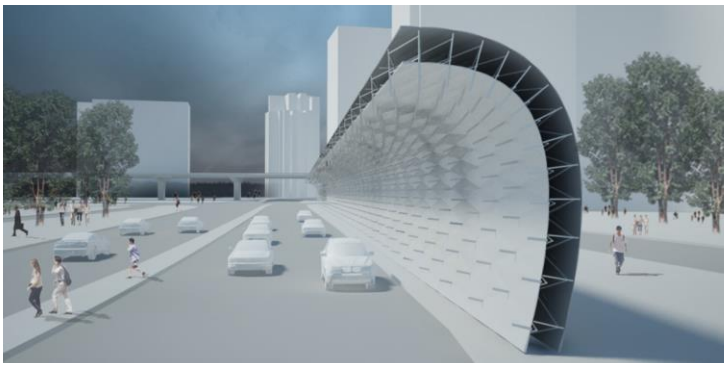

Figure 5: Representative image of a noise barrier separating pedestrian areas from vehicle lanes, which will also reduce the pollutant transfer (Hong Kong Noise Barrier by OFL Architecture/Francesco Lipari - https://www.oflarchitecture.com/hknb).

3.3. Low Boundary Wall (LBW)

Low boundary walls appear to act as a scaled down version of noise barriers, acting as baffles between pollutant source and receptor. For instance, the performance of an LBW between a boardwalk and an adjacent footpath showed significant pollutant reductions for pedestrians walking on the boardwalk (between 35% and 57%) as opposed to the adjacent footpath [2]. Even in instances when boardwalk provision was not possible, studies observed that under perpendicular wind conditions, the central LBW showed better pollutant reductions on both footpaths while the footpath LBW models showed an increase and decrease in concentrations on either footpath; under parallel wind conditions, both appear to offer some advantages [2]. Newer studies post 2015 also show similar results when a single wall running along the central median of a street creates significant reduction in pollutant exposure relative to a canyon with no wall - also in cases where a dense green hedge was substituted for a solid LBW [12,23] (Figure 6). Despite the alterations in local dispersions in street canyons, Gallagher et al. [2] suggested that more studies would be necessary to understand the performance of LBWs under different canyon ratios and vehicular turbulence conditions, while not worsening concentration levels for vehicle users and cyclists.

However, it was also noted that shape of an LBW plays a significant role in the dispersion effect of pollutants from roadways. Studies showed that a T-Shaped or even Y-Shaped barriers showed better pollutant reductions for adjacent pedestrian pathways and recreational spaces [24,25].

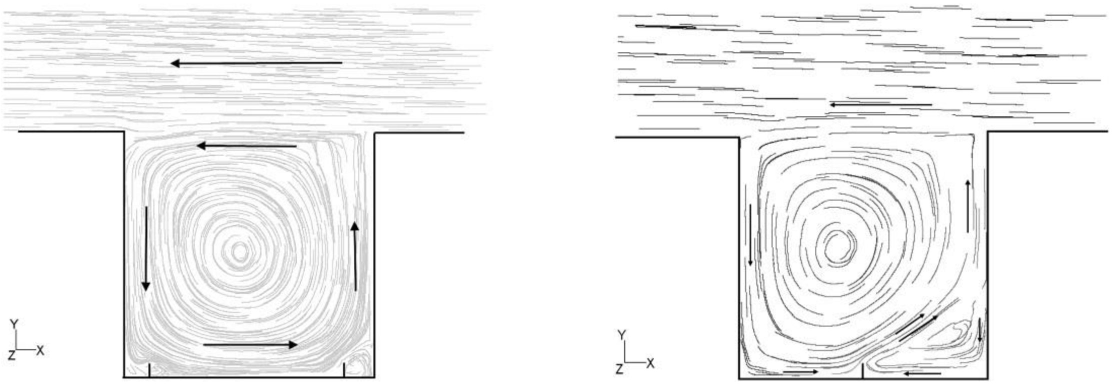

Figure 6. Dispersion profile of perpendicular wind flow in an urban canyon; Left image is with 2 boundary LBWs, Right image is with a central LBW [26] (reproduced with the permission © 2009 Elsevier).

3.4. Viaduct Structures

More recent studies also illustrate the potential of viaduct structures to reduce pollutant concentrations for pedestrians. These viaduct structures are usually discussed in the form of elevated expressways with vehicular movement distributed between the upper (viaduct) and the lower roads, while the pedestrians use the road below Figure 7. In some rare cases it considers vehicular movement only restricted to the viaduct, or strictly as an elevated pedestrian walkway. However, most studies generally consider a distributed vehicular movement unless explicitly mentioned.

Most studies concluded that the presence of a viaduct increases the concentration of particulate matter in the street canyon by greatly affecting the airflow field [27]. However Ding et al. [28] showed that the flow characteristics of viaduct structures not only affects the pollutant dispersion within the canyon, but also changes based on the roof structure. The study assessed the effect of a viaduct in a canyon between flat roof and triangle roof like structure, and observed that at a certain viaduct height there would be a flow reversal within the canyon – except that the flow reversal for the flat/ rectangular roofs will reduce the airflow velocity and deteriorate air quality within the canyon, while the flow reversal in the triangular roof case would enhance flow and potentially reduce air pollution within the canyon [28].

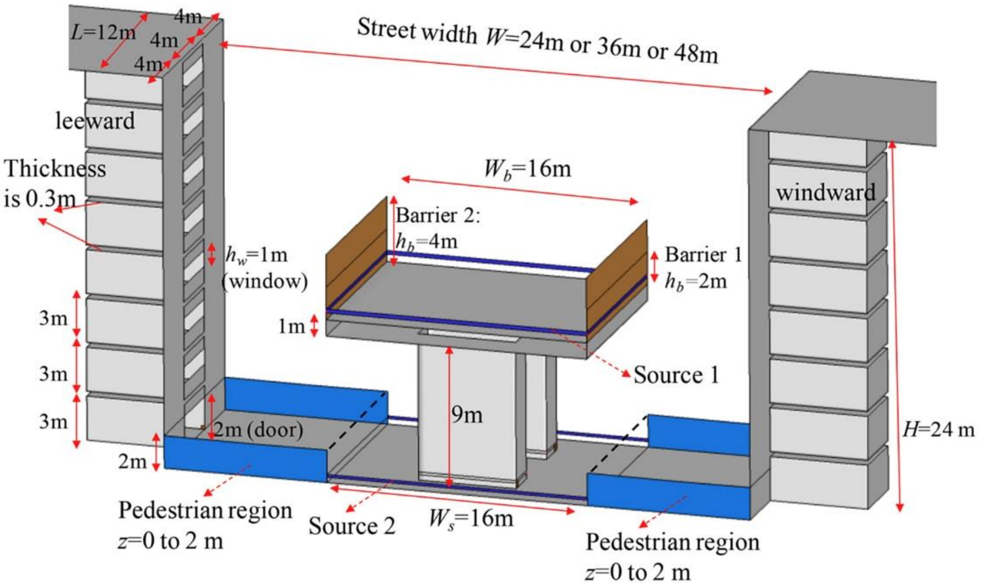

Figure 7. Representative CFD modelling image of an elevated expressway (viaduct structure) with sources of emission (vehicles) moving on the surface (ground) and upper levels; upper level also has noise barriers installed [29] (reproduced with the permission © 2017 Elsevier).

A study by Hang et al. [30] showed that pollutant levels could decrease for viaducts if the pollutant source (vehicles) is fixed to the elevated expressways only. Meanwhile lower concentrations were generally found for larger wind velocity, while in the case of low wind velocity the effect of thermal buoyancy could play a large role in reducing concentrations [30]. Also the presence of a noise barrier combined with the viaduct can prevent some particles from reaching the street beneath the canyon [27].

The presence of a viaduct complicates the flow in the street canyon in different ways. This will further change depending the presence of other obstacles like balconies and noise barriers [27]. While it could reduce pollutant concentrations at the ground level, it could also increase concentrations for residents living in spaces adjacent to the viaduct structure on both the windward and leeward side [27]. Hence these studies seem to provide a reference for future studies, but not necessarily for urban planners on how to use viaduct structures to reduce pedestrian pollutant exposure. These studies point towards factors that could reduce pollutant concentrations for existing viaduct structures, or for cases where viaduct structures are necessary to reduce pollutant hotspots arising due to traffic congestion.

4. Non-Porous Obstacles – Building Policy Guidelines

4.1 Wind Catchers

Wind catchers have been used to improve indoor air quality, however some recent studies show that wind catchers can be effectively employed to improve outdoor air quality as well [31,32]. Located at the roof of certain buildings facing the main street, wind catchers offer a passive method of diluting the pollutant concentrations and increasing wind speed for targeted areas within urban street canyons. An experimental setup of a wind catcher for urban canyons has been shown in Figure 8.

Employment of wind catcher appears to reduce concentrations levels by up to 37% in some pedestrian level areas, by modifying the air entrainment in the street canyons resulting in a more efficient dilution process [31]. The benefits of wind catchers are that they can be targeted for specific buildings, while not taking up space within the urban canyon at street levels. However, the CFD studies may be oversimplified, and more research may be necessary to develop realistic measures with wind-catchers.

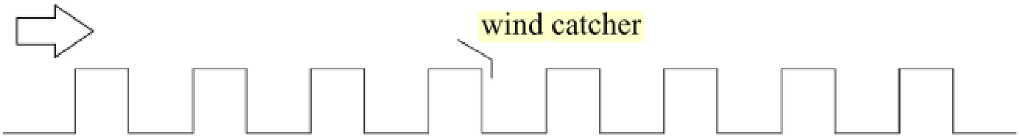

Figure 8. Experimental setup of a wind catcher for an urban canyon [32].

4.2. Lift-up Buildings and Building permeability

For the context of this paper, ‘lift-up’ buildings are defined as an elevated building structure that creates a complete hollow space between floors – typically at the ground, first or second levels. Building ‘permeability’ on the other hand generally considers void like features that do not extend horizontally through the entire building, but rather only creates partial void pockets.

Some studies have assessed the performance of lift-up buildings to improve the wind flow conditions at the pedestrian level to reduce air pollution concentrations as well as improving thermal comfort levels, while not creating too uncomfortable environment due to high wind speeds. Some studies have shown that lift-up building design can actually provide a comfortable microclimate in summer conditions, while not causing a strong cold stress in the winter [33]. Although the study characterised different building shapes – such as the ‘L’, ‘U’, ‘I’ and the ‘□’ shaped buildings in different orientations (Figure 9), the wind flow (at the pedestrian level) seems to be more altered due to the shape and arrangement of the core and column-supports rather than the shape of the building itself [34].

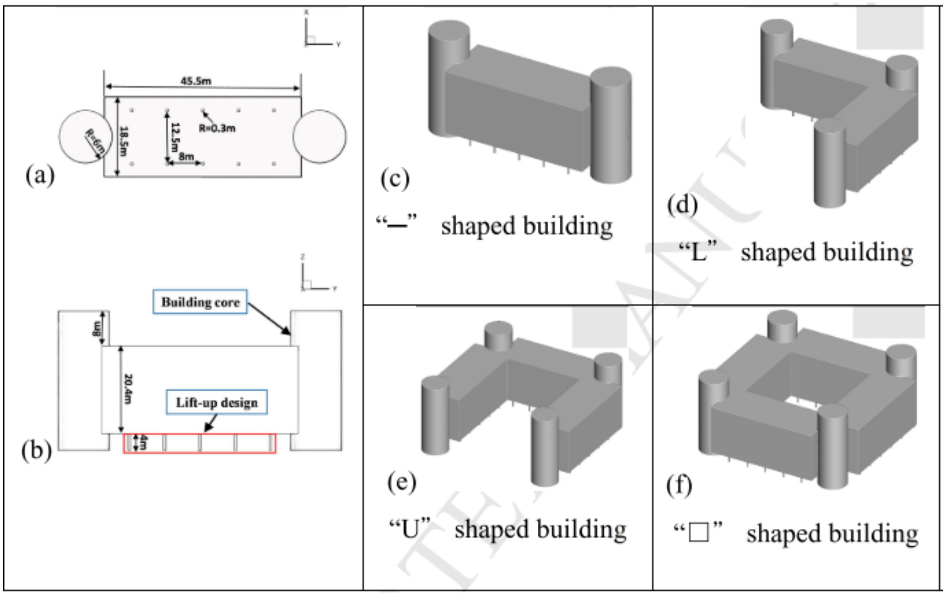

Figure 9. Lift-up buildings analysed for different building shapes [34] (reproduced with the permission © 2017 Elsevier).

This was similarly observed in a parametric study of 9 lift-up building models with different core heights and width, where although the lift-up core height seemed to be the most influential parameter, even the size (width) of the core played a significant role in the wind flow around the building [5]. These results of the arrangement of the supporting columns/core arrangement can also be similar to the discussions around tree height and spacing as well as stand density, all of which would affect the wind flow in different ways [2].

In addition, Sha et al. [4] studied that the ventilation effects (and hence lower pollutant concentrations) were most pronounced for lift-up buildings at the ground level (34-50%), followed by lift-up at the first level (29-38%), while lift-up at the second level produces least amount of difference (6-25%) [4]. Hence although ground level lift-up would be the ideal, the economic incentives for the ground level may make it more feasible to alternatively provide a first level lift-up [4].

5. Discussion and Conclusions

Studies shown above have adopted either a numerical (CFD modelling) or an experimental approach (wind tunnel/ real environment study). However, most studies use a CFD approach, which may not truly represent the best passive methods that can be adopted under real conditions in an urban canyon. Certain measures such as a central hedgerow, lift-up buildings or wind catchers seem to offer more promising results in general. But these results also vary under different geometric and meteorological conditions, as this is what affects localised dispersion and turbulence in the built environment[2]. Moreover, the effect of certain measures like lift-up buildings may allow for ventilating a certain urban canyon but could increase pollution levels in an adjacent street, as the effects of dispersion should be to increase the air exchange with the urban canopy layer above.

From these studies, it is evident that more research should be done to prior to prescribing any design guidelines for an urban canyon. More experimental validation studies would be necessary, while also considering a mix of various obstacles and their combined effect on pollution reduction.

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