Guidelines for passive control of traffic-related air pollution in street canyons : an overview for urban planning

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Abstract

Recent studies indicate the necessity of addressing traffic-related air pollution in urban environments, as street canyons are known for their lack of natural ventilation and increased pollution levels. To address this issue, numerous studies have been conducted on different aspects (e.g. aspect ratio, orientation and height variation) and their impact on ventilation and pollution dispersion/dilution performance in street canyons. Despite the numerous studies, the information remains fragmented and the results and applications are fairly unknown in urban planning. Broad review studies on numerous street canyon aspects are also quite scarce. In this study, over 200 studies were collected and reviewed across various parameters and on different configuration levels (street canyon configuration / building configuration / in-canyon configuration). Hereby, the study aims to give a comprehensive overview and to formulate spatial guidelines to improve the application of the reviewed studies for the purpose of urban planning. In total, 19 general guidelines were formulated, and an implementation strategy for the purpose of urban planning was developed. Despite the usability of these guidelines for urban planning, a high number of limitations and variabilities were detected. The broad literature review also revealed knowledge gaps, indicating the potentials for further research.

Keywords

Urban design; Air pollution; Street canyon; CFD modelling

Nomenclature

ACH	air exchange rate	LEZ	low emission zones
AR	aspect ratio	PNC	particle number concentration
BHR	building height ratio	P_{vol}	pore volume
CFD	computational fluid dynamics	*Re*	Reynolds number
C_x	pressure loss coefficient	SF	skimming flow
H_d	building height of the downwind building	TMS	traffic management strategies
H_t	trunk height	V_d	deposition velocity
H_u	building height of the upwind building	V_{inlet}	inlet wind velocity
IRF	isolated roughness flow	WIR	wake interference flow
LAD	leaf area density	WOP	window opening percentage
LAR	lateral aspect ratio	Z_h	roof height
LBW	low Boundary Wall		

1. Introduction

According to the European Commission (2017) air pollution poses the second biggest environmental concern for Europe after climate change. In urban environments, air pollution poses a high risk since pollutants get trapped in the urban canopy layer (the layer of air extending from the ground surface up to the level of the buildings) where human exposure to these pollutants is high. Vehicular emissions are the predominant source of air pollution in the majority of urban environments (Gallagher et al., 2015). In most urban environments, the urban canopy layer is defined by a high number of street canyons (narrow inner urban roads, flanked by a continuous row of (high) buildings on both sides), which promote the accumulations of traffic-induced pollution. Recent air quality mappings in Europe (Paris (AIRPARIF, 2010), London (Environmental Research Group of Kings College London, 2015) and Antwerp (Vito, 2019)) showed that the levels of air pollution (NO_2) in street canyons are nearly as high as on highways and ring roads, although traffic intensity is lower. This indicates that the lack of sufficient natural ventilation in street canyons plays an important role in the accumulation of air pollution.

2. Problem statement

Since air pollution is recognized as an environmental threat, the EU has been working for decades on the development of the EU's clean air policy, which is strongly focused on the reduction of pollutant emissions. In most local policies, the actions are narrowed down to the reduction of the impact of traffic on air quality by using traffic management strategies (TMS). As a result, air quality action plans are applied with a strong emphasis on traffic regulations and policies that reduce private car usage, stimulate public transport, traffic flow improvement, speed limit reduction, the implementation of low emission zones (LEZs) and mobility plans (Panteliadis et al., 2014). Scientific reviews in the last couple years on the efficiency of LEZs (Boogaard et al., 2012; Panteliadis et al., 2014; Ezeah et al., 2015; Holman et al., 2015; Ku et al., 2020) all conclude uncertain results. Boogaard et al. (2012) and Ku et al. (2020) indicate that local traffic policies, including LEZs, are too modest to produce significant decreases in traffic-related air pollution.

Since the overall evidence of the effectiveness of TMS is weak (Bigazzi and Rouleau, 2017) the improvement of air quality by implementing passive measures starts to gain more interest. Passive control measures are mostly used to manipulate the natural ventilation patterns and hereby enhance pollutant dispersion and reduce pedestrian exposure to air pollutants (Galagher et al., 2011). This review study focusses mainly on spatial interventions which promote in-canyon ventilation and thereby also promote pollutant dispersion. On a city-wide scale, numerous urban morphology indices, such as gross floor area ratio, plan area density and frontal area density (summarized in Badach et al., 2020) can be used to determine and improve the ventilation capacity of a city region.

However, on a local scale such as in street canyons, possible measures and their effect on air quality are relatively unknown for urban planners. A high number of studies on different small-scale measures to improve air quality in street canyons have been conducted, especially in the field of engineering and bio-engineering. Moreover, this information remains fragmented, mostly specified on one specific aspect and rather technical, which reduces the applicability for urban planning. In order to support urban planners, this article aims to enumerate a number of potential measures to improve air quality on a street canyon scale, supported by evidence (strong or weak) from numerous studies. It should be stressed that, although a wide range of urban design measures can be found, this research is narrowed down to the measures applicable to the small scale of the street canyon which promote in-canyon ventilation and the dispersion of local traffic-related air pollutants, since measures on this level are relatively unknown for urban planners.

3. Method

The method described is this article is derived from a method presented by Bigazzi and Rouleau (2017), who performed a broad literature search to investigate the evidence on the effectiveness of TMS. First, a number of design parameters were defined by using preliminary research on the topic of urban design and the improvement of air quality on a local scale. These fundamental preliminary works include researches conducted by Spirn (1986), Oke (1988), Theurer (1999), Chan et al. (2001, 2003), Ng (2009, 2010), Garcia et al. (2013), Pijpers-van Esch (2015), Krautheim et al. (2014), Yazid et al. (2014), Yuan et al. (2014), Lenzholzer (2015), Abhijith et al. (2017) and Yang and Fu (2019). The selection of the first parameters were altered/extended during the research process. In total, 12 parameters were selected, divided in tree types of configuration:
Street canyon configuration with parameters:

- street canyon orientation
- aspect ratio
- street canyon depth
- street canyon length

Building configuration with parameters:

- building height variation
- building setback
- roof shape
- building permeability

In-canyon configuration with parameters

- semi-open settings
- trees
- hedges, low boundary walls and parked cars
- lane position

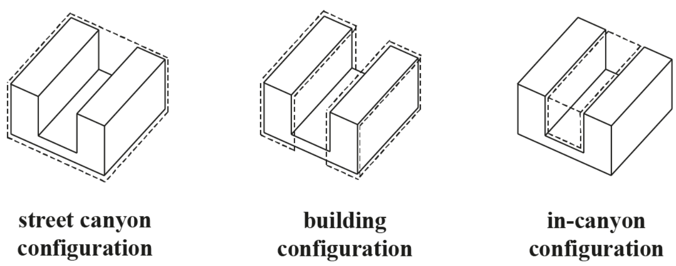


Figure 1. Overview of the reported configuration levels.

All parameters were submitted to the method of a scoping review (Xiao and Watson, 2017), which aims to broadly and systematically search literature on every parameter. The information extracted from the papers was compiled with the ambition to formulate overall conclusions for the purpose of urban planning.
The scoping review was conducted using the EBSCO Discovery Service Database and Google Scholar (http://scholar.google.com/). Based on the guidelines by Xiao and Watson (2017), search strings with Boolean operators ("AND" and "OR") were entered in the search engines. For each

parameter, a new search string was formulated with different synonyms. An example of such a search string in case of the parameter "aspect ratio" is: "street canyon" AND ("aspect ratio" OR "Height/Width ratio" OR "geometry") AND ("air pollution" OR "flow regime" OR "pollutant dispersion"). The first and last term were kept the same for all parameters and the middle term was changed corresponding to the parameter. In case of a high number of relevant hits, the 20 most relevant studies were selected (first 20 hits of the database/search engine when ranked by relevance). However, for some parameters, the number of relevant studies did not exceed 20 or was fairly limited. An overview of all reviewed studies is represented in Table 1 and a more extensive overview incorporating the employed methods can be found in the **Appendix**. For each parameter, the main findings were summarized, and afterwards translated into specific guidelines for the purpose of urban planning and policy making. During the review process, a high number of variabilities and uncertainties (e.g. influence of surrounding urban morphology, impact of transboundary pollutants and other sources, impact of solar radiation and wall heating and chemical reactions between pollutants) were detected. These uncertainties are summarized in Section 5.2.

Table 1. Overview of the reviewed studies for every parameter.

Parameter	Number of studies reviewed	References
Street canyon orientation	20	Dabberdt and Hoydysh (1991), Oke (1997), Becker et al. (2002), Kim and Baik (2004), Brown et al. (2004), Pospisil et al. (2005), Voigtländer et al. (2006), Klein and Clark (2007), Soulhac et al. (2008), Xie et al. (2009), Hang et al. (2009), Soulhac and Salizzoni (2010), Afiq et al. (2012), Gromke and Ruck (2012), Yassin, M.F. (2013), Arkon and Özkol (2014), Zhang et al. (2016), Kwak et al. (2016), Niu et al. (2018), Huang et al. (2019a)
Aspect ratio	20	Hussain and Lee (1980), DePaul and Sheih (1985), Oke (1988), Hunter et al. (1992), Sini et al. (1996), Huang et al. (2000), Chan et al. (2001), Chan et al. (2002), Kovar-Panskus et al. (2002), Liu and Barth (2002), Walton and Cheng (2002), Caton et al. (2003), So et al. (2005), Bady et al. (2008), Wang and Mu (2010), Chung and Liu (2013), Yassin and Ohba (2013), Ngan and Lo (2016), Oke et al. (2017), Di Bernardino et al. (2018)
Street canyon depth	20	Lee and Park (1994), Sini et al. (1996), Baik et al. (1999), Chan et al. (2002), Kovar-Panskus et al. (2002), Liu et al. (2004), Li et al. (2008), Murena et al. (2008), Li et al. (2009), Wang and Mu (2010), Murena et al. (2011), Zhang et al. (2011), Murena (2012), Allegrini et al. (2013), Zhong et al. (2015), He et al., (2017), Zhong et al. (2017), Chew et al. (2018), Zhang et al. (2019), Zhang et al. (2020)
Street canyon length	15	Oke (1988), Hunter et al. (1990/1991), Hunter et al. (1992), Johnson and Hunter (1995), Kastner-Klein and Plate (1999), Chan et al. (2001), Chan et al. (2003), Kastner-Klein et al. (2004), Georgakis and Santamouris (2005), Hang et al. (2009), Ng (2010), Michioka et al. (2014), Yuan et al. (2014), Wang et al. (2017a), An et al. (2019)
Building height variation	20	Hoydysh and Dabberdt (1988), Baik et al. (1999), Gerdes and Olivari (1999), Sagrado et al. (2002), Assimakopoulos et al. (2003), Brown (2004), Xie et al. (2005), Xiamin et al. (2006), Gu et al. (2011), Zajic et al. (2011) Hang et al. (2012), Addepalli and Pardyjak (2013), Garcia et al. (2013), Miao et al. (2014), Nosek et al. (2016), Chen et al. (2017), Ming et al. (2018), Zhang et al. (2019), Park et al. (2020), Reiminger et al. (2020)
Building setback	8	Lne (2009), Ng and Chau (2014), Kanakiya et al. (2015), Huang et al. (2016b), Lau et al. (2017), Wen et al. (2017), Llaguna-Munitxa and Bou-Zeid (2018), Hassan et al. (2020)
Roof shape	20	Rafailidis and Schatzmann (1996), Rafailidis (1997), Louka et al. (1998), Kastner-Klein and Plate (1999), Theodoridis and Moussiopoulos (2000), Vlachogiannis et al. (2002), Xie et al. (2005), Huang et al. (2007), Huang et al. (2009), Yassin (2011), Kellnerova et al. (2012), Takano and Moonen (2013), Huang et al. (2015), King et al. (2015), Huang et al. (2016a), Llaguno-Munitxa et al. (2017), Llaguno-Munitxa and Bou-Zeid (2018), Wen and Malki-Epshtein (2018), Klukova et al. (2019), Nguyen et al. (2019)
Building permeability	20	Ng et al. (2006), Wong and Ng (2009), Ng and Chau (2011), Yuan et al. (2014), Ai and Mak (2015), Yang et al. (2015), Yang et al. (2016), Zhu (2016), Fan et al. (2017), Peng et al. (2017), Baghlad et al. (2018), Chew and Norford (2018), An et al. (2019), Gronemeier and Sühring (2019), van Druenen et al. (2019), Yang and Fu (2019), Zhang et al. (2019), Wong et al. (2020), Yang et al. (2020), Zhang et al. (2020)
Semi-open settings	20	Gerhardt and Kramer (1990), Hall et al. (2010), Kim et al. (2010), Hiyama et al. (2011), Hang et al. (2013), Hiyama et al. (2013),

		Montazeri and Blocken (2013), Lim et al. (2015), Marini et al. (2015), Sato et al. (2015), Murena and Mele (2016), Sahanavin et al. (2016), Suebyat and Pochai (2017), Hang et al., (2018), Llaguno-Munitxa and Bou-Zeid (2018), Weissert et al. (2018), Chomcheon et al. (2019), Ding et al. (2019), Pothiphan et al. (2019), Karkoulias et al. (2020)
Trees	20	Gromke and Ruck (2007), Buccolieri et al. (2009), Gromke and Ruck (2009), Buccolieri et al. (2011), Salim et al. (2011), Gromke and Ruck (2012), Ng and Chau (2012), Wania et al. (2012), Amorim et al. (2013), Li et al. (2013), Salmond et al. (2013), Abhijith and Gokhale (2015); Di Sabatino et al. (2015), Janhäll (2015), Jeanjean et al. (2016), Abhijith et al. (2017), Xue and Li (2017), Buccolieri et al. (2018), Huang et al. (2019b), Karttunen et al. (2020)
Hedges, low boundary walls and parked cars	18	McNabola et al. (2009), Keuken and Van Der Valk (2010), Gallagher et al. (2011), Wania et al. (2012), Vos et al. (2013), Abhijith and Gokhale (2015), Chen et al. (2015), Gallagher et al. (2015), Gromke et al. (2016), Lazzari et al. (2016), Li et al. (2016), Abhijith et al. (2017), Wang et al. (2017b), Kristof and Papp (2018), Baghlad et al. (2018), Kumar et al. (2019), Gallagher and Lago (2019), Ottosen and Kumar (2020)
Source position	6	Kastner-Klein and Plate (1999), Jicha et al. (2000), Chan et al. (2001), Liu and Barth (2002), Huang et al. (2015), Tan et al. (2019).

4. Results

The findings of the reviewed studies are hereafter described and summarized. In most studies, wind/water tunnel modelling and CFD (computational fluid dynamics) have been used for analyzing idealized street canyon configurations. It is important to bear in mind that the result of these studies are abstractions from reality that merely aim to describe general effects of urban form on airflow and pollution dilution and dispersion. They are intuitive 'models' helping researchers to consider practical implications of different parameters. In some cases, simulations have been supported with field studies, making the results more reliable. In general, it should still be stressed that most results are strongly determined by site-specific arrangements, and a high number of variables should be taken into account.

4.1 Street canyon configuration

Following aspects will be addressed within the scope of the street canyon configuration: street canyon orientations (Section 4.1.1), aspect ratio (Section 4.1.2), street canyon depth (Section 4.1.3) and street canyon length (Section 4.1.4). The main findings of every section are summarized in Fig. 2.

4.1.1 Street Canyon orientation

Despite the fact that in most cases street canyon orientation is fixed, it is important to understand the correlation between the wind direction and its impact on natural ventilation and pollutant accumulation. Based on the orientation of a street canyon, three flow patterns can be distinguished: parallel, perpendicular or at an angle to the canyon's axis (Afiq et al., 2012). A comprehensive overview is illustrated in a recent study by Huang et al. (2019a), where a CFD study of an idealized street canyon with L/H = 10 and W/H = 1 was subjected to seven different wind directions (Θ = 0°, 15°, 30°, 45°, 60°, 75° and 90°). For parallel or nearly parallel wind directions (Θ = 0°, 15°) the model showed that the flow is mainly governed by a street-axis flow. When the angle increased to 30° and 45°, a corkscrew like flow appeared and for Θ = 60° and 75° a corkscrew like flow appeared in the upwind part of the street canyon while the downstream part was characterized by a clockwise vortex structure. Once Θ=90° (perpendicular), the clockwise vortex structure was developed in the entire street canyon. The same wind patterns were found in earlier studies by Oke (1997), Soulhac et al. (2008) and Pospisil et al. (2005). A CFD study by Hang et al. (2009), which assumed parallel wind directions, indicates that at a distance of about 6H (for a canyon with W/H = 1, W = width and H = height) the velocity becomes nearly constant and does therefore not increase or decrease further. The higher the W/H ratio, the further into the street canyon this fully developed flow starts.

Regarding pollutant dispersion patterns, studies by Dabberdt and Hoydysh (1991), Xie et al. (2009), Yassin (2013), Zhang et al. (2016), Huang et al. (2019a) and field studies by Voigtländer et al. (2006), Arkon and Özkol (2014) and Kwak et al. (2016) all conclude that the highest concentration occurs at the leeward oriented wall in case of oblique or perpendicular wind directions. However, the difference in concentration levels between both sides of the street canyons does not hold in case of parallel winds ($\Theta = 0°$). Regarding longitudinal and lateral pollutant dispersion, a wind tunnel study by Gromke and Ruck (2012) and a CFD study by Huang et al. (2019a) showed that for perpendicular winds (lateral dispersion), a decrease in pollutant levels near the wall ends was found, whereas for oblique and parallel winds (longitudinal dispersion) the pollutant levels increased towards the downwind street canyon end. The same peak at the street canyon end in case of parallel winds was found in a field study by Niu et al. (2018). The main findings of previously indicated studies are summarized in Fig. 2. It should be stressed that these findings do not hold for every situation. In some cases, concentration levels in case of parallel winds (due to the mean advection along its axis) or oblique winds (due complex urban configurations or the presence of trees) can exceed the pollution levels compared to perpendicular winds (Soulhac and Salizzoni, 2010; Niu et al., 2018; Gromke and Ruck, 2012). Conclusion from the Joint Urban 2003 Tracer Experiment (Brown et al., 2004 and Klein and Clark, 2007) and an early field study by Johnson and Hunter (1999) also showed that small variations of wind direction can significantly change in-canyon flow properties and in-canyon wind direction can rapidly shift by 120-180°. Brown et al. (2004) found typical along-canyon flow motions, even for wind directions perpendicular to the street canyons. Detailed flow studies by Becker et al. (2002) and Kim and Baik (2004) also observed far more complex 3D flow fields (Fig. 7) than those represented in Fig. 2.

Regarding urban planning, it can be concluded that street canyons are preferably oriented parallel to the prevailing wind direction, provided that their length stays limited (LAR < 12, see Section 4.1.4). However, the orientation of a street canyon is not adjustable in an existing urban fabric. Still, the knowledge on street canyon orientation helps understanding the potentials of street canyons with an orientation parallel to the prevailing wind direction, since they have the ability to supply fresh air deep into the urban fabric when obstacles are limited (Ng, 2010; Quintiens, 2017).

4.1.2 Aspect ratio

Numerous studies have been conducted on the relationship between the ratio of the building height to the street width (H/W ratio), also known as the aspect ratio (AR), and the impact on the flow field and pollution dispersion. Early research by Hussain and Lee (1980), DePaul and Sheih (1985), Oke (1988) and Sini et al. (1996) gives fundamental insight on the development of three typical flow regimes and their threshold AR values for street canyons subjected to the boundary condition of perpendicular approach flows: (1) an isolated roughness flow (IRF) appears when buildings are widely spaced (AR < 0.35), (2) a wake interference flow (WIF) arises when the 0.35 < AR < 0.65 and (3) a skimming flow (SF) appears when AR > 0.65. Oke (1988) describes that the transition between the three regimes is defined by the critical combination of the AR and the L/H ratio (where L is the length of the continuous facade of the street canyon) or lateral aspect ratio (LAR). When the LAR increases, skimming flow can occur with lower ARs. Corresponding results were found by Chan et al. (2002), Kovar-Panskus et al. (2002) and Ngan and Lo (2016). An early study by Hunter et al. (1992) also indicated the presence of corner eddies (recirculation zones) near the corners of the leeward facade of the street canyon, changing the flow regimes. In this case, the transition to WIF will only occur for canyons sufficiently wide so that the corner recirculation zones fully formed. However, a field study by Johnson and Hunter (1999) showed that in a street canyon with AR = 0.4, where a WIF or IRF is expected, a SF was present. The study therefore suggests that factors additional to relative canyon geometry are relevant in determining flow regimes.

Caton et al. (2003) and So et al. (2005) stress the impact of the incoming flow characteristics. They conclude that the development of a specific flow regime is closely related to the turbulence of the incoming flow, defined by the Reynolds number (*Re*). In most reduced scale studies (wind and water tunnel or CFD), *Re* varies between 400 (So et al., 2005) and 2.1 x 10^6 (Yassin and Ohba, 2013) and in case of full-scale studies (mostly CFD) *Re* varies between 1.10 x 10^5 (Chung and Liu, 2013) and 5.0 x 10^7 (He et al., ,2017). A full list of the retrieved *Re* values for the reviewed studies can be found in the **Appendix.** In reality, atmospheric flows tend to be highly turbulent, and a large *Re* (an order of magnitude up to 10^6) should be taken into account (Lee and Park, 1994; Zajic et al., 2011; Zhang et al., 2011; He et al., 2017; Zhang et al., 2020). Chew et al. (2018) found that depending on the aspect ratio, the development of the different flow regimes requires different limit Reynolds numbers to be exceeded.

The levels of air pollution are closely related to the flow regimes. Numerous studies (Huang et al., 2000; Chan et al., 2001; Liu and Barth,2002; Bady et al., 2008; Wang and Mu, 2010, Yassin and Ohba, 2013 and Di Bernardino et al., 2018) show lower pollution levels in wide street canyons (IRF, WIF) compared to narrow street canyons (SF). These studies suggest that canyon geometry should be restricted to threshold values for SF. Chung and Liu (2013) indicate AR = 0.5 as a threshold value for pollutant removal and indicate a sharp reduction of the pollutant exchange rate once AR > 0.5. When considering in-canyon pollutant dispersion in case of a SF and perpendicular wind, numerous studies (Huang et al., 2000; Chan et al., 2001; Walton and Cheng: 2002; Wang and Lu, 2010, Yassin and Ohba, 2013, Di Bernardino et al., 2018) indicate increase pollution levels (2-3 times higher) on the leeward facade.

Previously described studies have the potential to support the formulation of guidelines for urban planning, such as the restriction of the AR to the threshold values for SF (AR < 0.65 (Oke, 1988) or AR < 0.5 (Chung and Liu, 2013)). However, as Oke (2017) already states, most studies merely represent an abstraction from reality. Numerous impact factors should be taken into account such as wind turbulence (Caton et al., 2003 and So et al., 2005), background pollution and pollution source strength. A field study by Miao et al. (2020), for example, showed lower pollution concentrations in narrow street canyons compared to wide street canyons, likely related to the lower amounts of traffic in the narrow street canyons. Brown (2004) indicates that it may also be hard the find a case where these simple vortex flows exist, since the flow field will most likely be a complex combination of 2D and 3D vortices and channelized flow.

4.1.3 Street Canyon depth

The canyon depth is closely related to the aspect ratio (AR). A street canyon is defined as deep once AR > 1.5-2.0 (Murena et al., 2008; Vardoulakis et al., 2003). In this case, deviating flow patterns and enhanced pollutant concentrations can be expected (Vardoulakis et al., 2003). In most studies, deep street canyons promote the development of two counter-rotating vortices, with the bottom vortex weaker than the upper one (Murena, 2012). However, the threshold AR values for the development of the two vortices vary in different studies. Studies by Sini et al.(1996), Baik et al. (1999), Kovar-Panskus et al. (2002) and Chan et al. (2002) show two in-canyon vortices once AR > 1.43-1.65. Additional studies by Murena (2012) and Li et al. (2008) even report 3 vortices once AR > 3.0 (also found by Sini et al., 1996). In very deep street canyons with AR=10, 8 vortices were reported by Li et al. (2009).

When comparing different studies, it can be concluded that the appearance of these flow regimes strongly depends on two main aspects: wind speed and turbulence levels. In case of lower wind speeds (V_{inlet} = 2-3 m s^{-1}) or lower turbulence values (*Re* < 2.5x10^6 in case of full-scale studies), a double vortex was reported for AR = 1-2.7 (Lee and Park, 1994; Chang et al., 2002; Allegrini et al., 2013; Zhang et al., 2019). In case of higher wind speeds (15 m s^{-1}) or higher *Re* values ($\approx$5x10^6 in case of full-scale studies) no double vortex structure was found for AR = 1 – 4 (Chang et al., 2002; Zhang et al., 2011, 2019, 2020). Only when AR > 5, a double vortex was developed. A field campaign by Eliasson et al. (2006) in a street canyon with AR ≈ 2,1 also reported that no evidence could be found for the existence of a double staggered vortex in case of perpendicular winds.

Once a secondary vortex is formed, pollution levels are strongly enhanced and the highest pollution level shifts to the windward facade instead of the leeward facade (Liu et al., 2004; Zhong et al., 2015; Zhong et al., 2017; Zhang et al., 2019; Zhang et al., 2020). The sharp increase in pollutant levels can be explained by the strongly reduced wind speed (Kovar-Panskus et al., 2002), low mass transfer velocity (Murena et al., 2011) and high retention value (Wang and Mu, 2010) when a secondary vortex is formed. Due the low wind speed, the difference in pollution levels between the windward and leeward facade is also less distinguished than in case of a single vortex (Murena et al., 2008; Li et al., 2009).

Related to urban design it can be concluded that the potential development of a secondary vortex should be avoided. First of all, AR = 5 should be respected as an upper bound for a street canyon AR (Li et al., 2009). For street canyons with an AR ranging from 1-5, wind speed and turbulence should be taken into account to predict the development of a secondary vortex. Zhang et al. (2020) investigated the impact of wind catchers and concluded that wind catchers have the potential to destroy multi-vortex flow patterns, produce single-vortex structures and hereby enhance street ventilation capacity, which could lead to a significant pollutant reduction by an order of magnitude up to two. However, it should be born in mind that the actual vortex formation in deep street canyons is still largely unpredictable.

4.1.4 Street Canyon length

As described in section 4.1.2, Oke (1988) introduced the importance of the length of the street canyon, where the lateral aspect ratio (LAR) influences the appearance of different flow regimes. Only a few years later, Hunter et al. (1990/1991) conducted further research on this matter and classified street canyons with LAR < 3 as short, LAR = 5 as medium and LAR > 7 as long. In accordance to Oke (1988), they concluded that in case of long street canyons, skimming flow could occur in case of lower ARs. In 1992, Hunter et al. investigated the development of corner eddies (also called lateral recirculation zone; Kastner-Klein et al, 2004) near the street canyon's outer ends. An experimental study by Kastner-Klein et al. (2004) and a CFD study by Michioka et al. (2014) show that for short street canyons (LAR < 4) under perpendicular wind conditions, the lateral recirculation zones converge in the center of the street canyon, causing strong vertical motions which promote ventilation and pollutant reduction. When LAR increases (> 4), the impact of the corner recirculation reduces in the middle section of the street canyon, and pollutant accumulation is promoted in this area (Hunter et al., 1992; Johnson and Hunter, 1995; Kastner-Klein and Plate, 1999; Chan et al., 2001; Kastner-Klein, 2004).

In case of parallel winds, long street canyons can operate as air paths, supplying fresh air in the urban fabric (Ng, 2010). A CFD study Hang et al. (2009) shows that the maximum wind speed in a street canyon under parallel wind conditions increases sharply from LAR = 4-12 and then levels off. This indicates that in long street canyons (LAR > 12), wind speed is more likely to decrease resulting in pollutant accumulation at the end of the street canyon.

With regard to urban design, it can be concluded that long street canyons are preferably oriented parallel to the dominant wind direction (Ng, 2010; Wang et al, 2017a). However, channelized winds can be strong and result in an unpleasant pedestrian environment (Lenzholzer, 2015). When oriented perpendicularly, LAR = 4 can be used as a threshold value (Chan et al., 2001; Georgakis and Santamouris, 2005; Michioka et al., 2014). Michioka et al. (2014) indicate that the aforementioned effects only take place in case of simplified models. Once the complexity of the model increases, more complex wind fields occur and irregularities in pollutant dispersion are notable.

Street canyon lengths can be limited by introducing intersections and increasing building permeability. A more complex CFD study by Yuan et al. (2014) showed reductions up to 25 % of the average normalized concentration in the mean street when the overall permeability of the street was increased by ≈ 30 %. Another complex CFD model by An et al. (2019) illustrated that the introduction of a single building separation in the middle of a street canyon could locally decrease air pollution levels by 80 %. Despite the promising results, no field studies were conducted on this matter. Even more, none of these studies considered the impact of intersections on traffic flow and traffic congestions. Therefore, conclusions should be carefully considered. The main findings of the effects of the street canyon configuration (Sections 4.1.1 – 4.1.4) on the in-canyon flow field and pollutant distribution are summarized in Fig. 2.

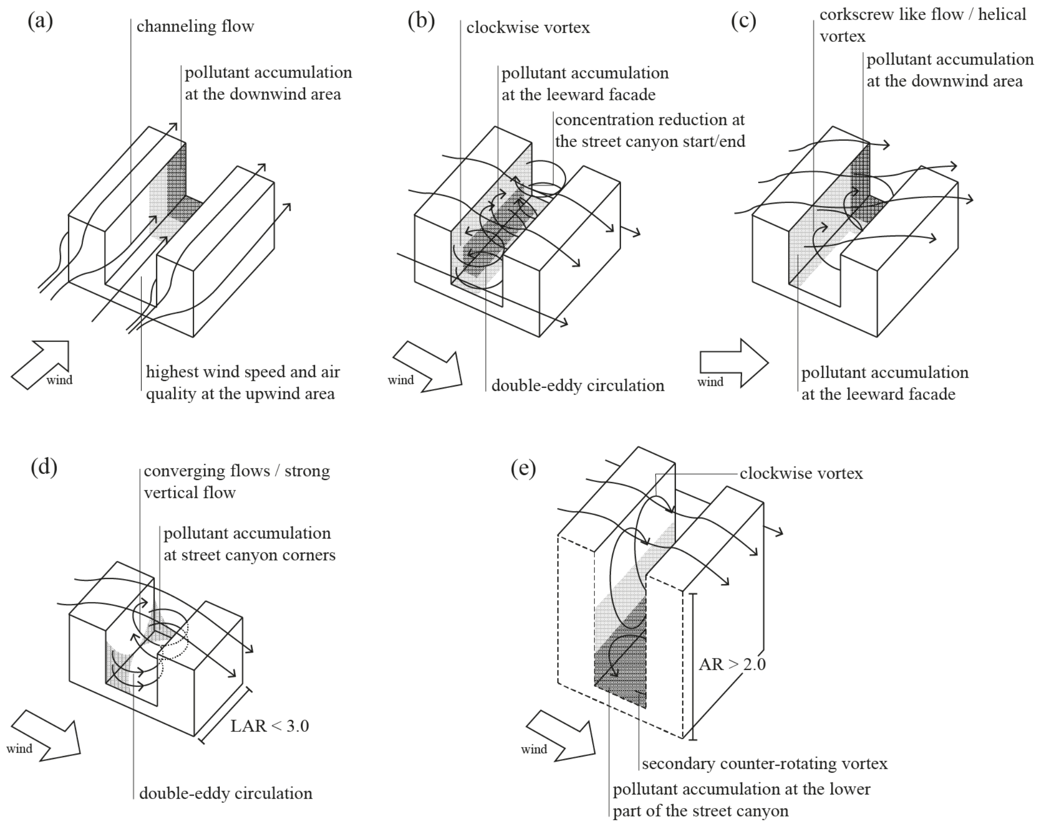


Figure 2. Estimated flow regimes and pollutant distribution for: (a,b,c) different orientations of the street canyon towards the prevailing wind direction, (d) short street canyons (LAR < 3.0) with converging flows and (e) deep street canyons (AR > 2.0) with a double vortex structure. Modified after Johnson and Hunter (1995), Oke (1997), Huang et al. (2019a), Soulhac and Salizzoni (2010), Michioka et al. (2014), Pijpers-van Esch (2015) and Zhang et al. (2019, 2020).

4.2 Building configuration

4.2.1 Building height variation

In general, it is assumed that changes in building height have the potential to enhance or reduce ventilation in street canyons. In most studies, the variance in building height is expressed by the ratio between the height of the upwind building (H_u) and the height of the downwind building (H_d), also called the building height ratio (BHR; Zajic et al., 2011). Street canyons are generally called step-down street canyons when BHR > 1 (upwind building is higher than the downwind building) and step-up canyons when BHR < 1 (upwind building is lower than the downwind building). Based on multiple studies (Hoydysh and Dabberdt, 1988; Gerdes and Olivari, 1998; Sagrado et al., 2002; Assimakopoulos et al., 2003; Xie et al., 2005; Ming et al., 2018) it can be assumed that in most cases, pollution levels tend to be higher in step-down canyons compared to step-up street canyons.

The lower pollutant levels in step-up street canyons can be explained by the so called 'downwash' effect. This phenomenon is caused by the flow blockage in front of the higher downwind building, which enhances the strength of the downdraft flow near the windward facade of the downwind building resulting in divergent flow in the lower part of the street canyon (Miao et al., 2014). These divergent flows enhance pollutant dilution to the leeward facade and due to the low building height of the leeward building, pollutants are transported rapidly to the roof level and afterwards diluted by the wind (Ming et al., 2018). For most idealized cases (with AR≈1, where AR is defined by the ratio between the height of the upwind building (Hu) and the street width) with perpendicular winds, it is assumed that a downwash effect is created once BHR < 0.8 (Xie et al., 2005; Miao et al., 2014; Ming et al., 2018).

In case of step-down street canyons, Assimakopoulos et al. (2003) showed that in an idealized street canyon with AR = 1 and BHR = 2, pollutant levels in the lower corner of the downwind building increase by ≈30 % and in the lower corner of the upwind building by ≈ 300 % compared to the concentration levels in an even street canyon (AR = 1 and BHR = 1). Visualizations by Baik et al. (1999), Xie et al (2005), Xiaomin et al. (2006) and Reiminger et al. (2020) show a single vortex in case of a step-up canyon (AR= 0.5 and AR = 1) and in case of a step-down canyon, the main clockwise vortex shifts above the downwind building roof and a secondary counterclockwise vortex is formed in the lower region of the street canyon (Fig. 3). Therefore, higher pollutant levels are found at the windward facade in case of a step-down configuration (Xie et al., 2005). Despite the overall agreement that step-down street canyons are less favorable in terms of air quality and ventilation, Miao et al. (2014) concluded that a step-down setup can potentially results in improved ventilation due the formation of the large recirculation clockwise vortex at the leeward facade of the higher building and divergent flows in the lower part of the street canyon.

It also seems that in case of longer (L/W-ratio > 3.0) or deeper (AR > 2) street canyons, the effect of the BHR becomes less distinguished (Assimakopoulos et al.,2003; Addepalli and Pardyjak, 2013; Park et al.,2020). A CFD study by Zhang et al. (2019) even indicates that for very deep street canyons (AR = 5), a step-up notch (BHR = 0.83) can potentially create a third rotating vortex, resulting in a decreased pollutant dilution capacity.

It should be noted that in most of the aforementioned studies, the building heights is only changed for the entire length of a building, which in most cases is not a suitable configuration to represent real urban environments. Gu et al. (2011) and Nosek et al. (2016) investigated more complex 3D CFD models with an uneven and non-uniform building layout. Gu et al. (2011) found that pollution levels are in general lower in non-uniform street canyons than in even street canyons, and Nosek et al. (2016) also reported lower pollution levels in averaged step-up canyons but higher pollutant levels in averaged step-down canyons. The study of Gu et al. (2011) also showed that separate or isolated notches have a potentially larger impact on the reduction of in-canyon air pollutants, where adjoining notches have less impact. In most studies, the building height variability is also limited (0.33 < BHR < 2.0). Therefore, the effect of high-rise buildings is not taken into account. On a larger scale, Hang et al. (2012), Garcia et al. (2013), Chen et al. (2017) and Yang and Fu (2019) indicate that selective high-rise buildings might be interesting to improve air quality in street canyons, especially on the downwind side of the street canyon.

Related to urban planning, it can be concluded that building height variation can largely affect in-canyon flow patterns. In general, street canyons with a higher building height variation tend to create more turbulence, resulting in an increased in-canyon ventilation. Therefore, the classic street-canyon configuration with homogeneous building heights should be reconsidered. When introducing building height variations, the orientation towards the main wind direction should be kept in mind, where step-down configurations seem to worsen in-canyon ventilation and step-up configurations tend to improve in-canyon ventilation. However, further research should still be conducted on this matter.

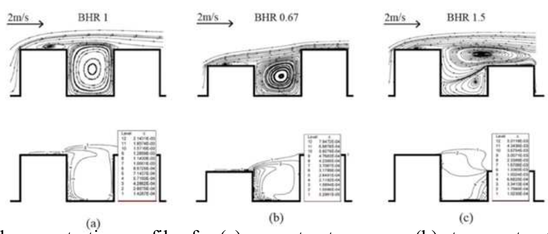


Figure 3. Estimated streamlines and concentration profiles for (a) even street canyons, (b) step-up street canyons and (c) step-down street canyons. Modified after Xie et al. (2005).

4.2.2 Building Setback

Whereas previous indicators are relatively well investigated, the impact of building setbacks has received less attention. Only eight relevant articles/studies could be found within the literature search. Ng and Chau (2014) conducted a broad research on the matter using a CFD simulation with horizontal (full length) and vertical (full height) setback configurations (see Fig 4). According to Ng and Chau (2014) building setbacks can be beneficial for personal exposure to air pollution in case of perpendicular winds. However, their efficiency largely depends on the aspect ratio (AR) of the street canyon. A study by Ng and Chau (2014) showed that in case of regular street canyons (AR<2), a full-height vertical setback could induce higher flow velocities in the upper part of the canyon together with the formation of a large counter-rotating vortex formed in the vertical setback, which reduced in-canyon pollutants and increased the air exchange rate (ACH) at the top of the street canyon. In contrast, horizontal setbacks resulted in a lower flow velocity. On the other hand, full-length horizontal setbacks seemed to disrupt the vortex structure in deep street canyons (AR=4-6), resulting in increased flow velocities at pedestrian levels. In this case, the pollutant levels at pedestrian level are reduced and the ACH at the top of the street canyon increased. The same conclusions for full-length horizontal setbacks were made by Wen et al. (2017). Other studies indicating the potential effect of building setbacks on improving in-canyon ventilation were conducted by Kanakiya et al. (2015), Huang et al. (2016b), Lau et al. (2017) and Hassan et al. (2020) which recommend full-length horizontal setback in case of a deep street canyon under perpendicular winds, and a study by lne (2009) which illustrates the potential of full height vertical setback setback at the downwind side of the street canyon (with a potential reduction of 10 % for PM10 and 25 % for NO_2). A horizontal setback can not only be implemented at ground level, but also at roof level (also called upper void podium; Hassan et al., 2020). Studies by Hassan et al. (2020) and Llaguna-Munitxa and Bou-Zeid (2018) indicate that an upper void setback can also promote the vertical transport of pollutants. However, the results also show that the pollutant reduction at pedestrian level is rather limited, but the overall in-canyon pollutant level can be reduced by almost 50 %. Horizontal setbacks on different heights have not been investigated yet. However, Spirn (1986) and Ng. (2009, 2010) suggest that a stepped street canyon profile improves ventilation and reduces air pollution.

In case of a parallel prevailing wind direction, Spirn (1986) and Ng and Chau (2014) state that it is not recommended to use setbacks as this will possibly result in higher personal exposures compared to street canyons without setback (estimated pollutant increase by 168 % up to 272 %; Ng and Chau, 2014).

Regarding to urban planning it can be concluded that the type of setback should be considered based on the AR and the prevailing wind direction. However, due the lack of sufficient studies (e.g. studies on different wind directions or field studies), the introduction of building setbacks as a potential solution for air pollution should be carefully considered, and location-specific studies should be conducted in advance.

4.2.3 Roof Shape

The impact of different roof shapes (flat, slanted (or pitched or gable), wedged, trapezoidal and vaulted) on flow patterns and pollutant dilution has widely been researched. CFD studies by Theodoridis and Moussiopoulos (2000) and Wen and Malki-Epshtein (2018) indicate that due to the presence of slanted roof, a weak counter-rotating vortex is created in the lower part of the canyon, resulting in a decreased ventilation capacity. On the other hand, multiple other studies by Rafailidis (1997), Louka et al. (1998), Vlachogiannis et al. (2002), Abdulsaheb and Kumar (2010), Kellnerova et al. (2012), King et al. (2015), Garau et al. (2018), Llaguno-Munitxa and Bou-Zeid (2018) indicate improved ventilation and reduced pollutant levels in case of slanted roofs. These studies indicate that pitched roofs improve pollutant dispersal due to the enlargement of the vortices penetrating into the street canyon, aiding the in-canyon ventilation and reducing pollutant accumulation. It is also thought that different non-flat roof typologies increase turbulence, improving pollutant dilution (Llaguno-Munitxa et al., 2017). The discussion of whether non-flat roof typologies increase or decrease urban ventilation can mostly be reduced to whether or not a double or single vortex structure appears. However, the discrepancy between previous studies on this matter suggests the impact of different parameters such as aspect ratio, roof height, roof shape and roof slope.

CFD studies by Huang et al. (2007, 2009, 2015, 2016a), Nguyen et al. (2019) and Yassin (2011) suggest that the appearance of a single or double vortex structure largely depends on the roof shape and the roof height. The results of the more favorable and unfavorable configurations in terms of street canyon ventilation are summarized in figure 4. In general, it is thought that the lowest pollution level occurs in the canyon with the downward wedged roof. However, Takano and Moonen (2013) suggest that the beneficial effect depends on the roof slope, and critical slope of $\approx 18°$ (for a street canyon with AR = 1) was found to be the switching point between double and single vortex structures. Also in case of pitched roofs, roof height seems to have a crucial impact. For street canyons with pitched roofs on both sides and AR = 1, Xie et al. (2005) found a double vortex and strongly reduced ventilation capacity for Zh/H = 1/2 (where Z_h= roof height and H=building height), where Abdulsaheb and Kumar (2010) found a single vortex and induced ventilation capacity for Z_h /H < 1/6. Xie et al. (2005) also illustrated the impact of the AR, whereas for Z_h /H = 1/2, a double vortex structure was present for AR = 1 and a single vortex structure was found for AR = 0.5.

Similarly to the building height variation (Section 4.2.1), it is generally assumed that step-up configurations are more favorable in terms of urban ventilation when compared to even or step-down configurations (Kastner-Klein and Plate, 1999; Huang et al., 2007; Huang et al., 2009). A wind tunnel study by Rafailidis and Schatzmann (1996) also suggests that, when the whole building (including the slanted roof) is confined within the urban canopy of the surrounding buildings, a slanted roof on the upstream building has the potential to increase canyon ventilation, lowering the pollution levels by half compared to a flat-roof scenario. On the other hand, when the slanted roof protrudes above the urban canopy, into the free-stream, upstream slanted roofs tend to reduce urban ventilation, and downstream roofs improve in-canyon ventilation. The study by Rafailidis and Schatzman (1996) therefore stresses the impact of the surrounding buildings on the formation of different in-canyon flow patterns.

When comparing the studies on roof shape it becomes clear that most of these studies are merely 2D simulations, outlying real-world urban configurations. Klukova et al. (2019) used a more complex 3D CFD model with pitched roofs and found higher ventilation levels in non-uniform canyons compared to uniform street canyons. It can also be concluded that in all 20 studies reported in this overview, the street axis was always perpendicular to the main wind direction. Only the study by Louka et al. (1998) used a parallel wind direction, but no conclusions related to roof shape were made. Since the impact of roof shape was not investigated under different wind directions, conclusions should be considered carefully.

Despite the difficulty to formulate guidelines for urban planning, most studies suggest that trapezoidal and upward slanted roofs should be avoided. When simulating in-canyon ventilation and pollution, the aforementioned studies also suggest that roof shape should not be neglected, whereas most idealized simulations reduce the complexity of roof shapes by using flat roofs. They also indicate that in case of new urban developments or building modifications, the impact of the roof shape on in-canyon ventilation should be considered and thoroughly investigated.

4.2.4 Building permeability

For the purpose of this research, building permeability is defined as the extent to which a building allows wind to pass through (based on Handy et al., 2005). Permeability can be created by actual voids in the building, or by open windows (defined by the window opening percentage; WOP). The effect of the WOP has been thoroughly investigated by Ai and Mak (2015), Yang et al. (2015, 2016), Peng et al. (2017) and Yang et al. (2020), but is less related to urban design interventions and therefore not further discussed in this paper. In case of building voids, it is thought that when permeability increases, a greater amount of fresh air enters the street canyon and distorts the main vortex (Yang et al., 2016). In case of deep street canyons, void decks can potentially destroy double vortex structures and therefore improve ventilation at pedestrian level (Zhang et al., 2017).

Void decks do not only result in distorted vortex structures, but also reduce the wind-pressure differences across the top of the street canyon, which induces the air exchange rate between the street canyon and the free surface layer. This leads to less pollutants reentering the street domain and therefore pollutant dilution is improved. Both phenomena (distortion of vortex structure and reduction of wind-pressure difference at the top of the street canyon) potentially result in a pollution level decrease (Yang et al., 2016).

Numerous idealized studies have been conducted on void decks in different configurations (e.g. Yuan et al., 2014; Fan et al., 2017; Zhang et al., 2019; Zhang et al., 2020). In general, it is assumed that street canyons with void decks have better ventilation levels compared to street canyons without void decks. Permeable elements at ground level (Wong and Ng, 2009; Ng and Chau, 2011; Baghlad et al.,2018; Zhang et al., 2019) or at podium level (Fan et al., 2017) were found effective in increasing in-canyon ventilation and a total decrease in pollution levels by a factor up to 5 was found. More complex CFD simulations by Yuan et al. (2014) and An et al. (2019) also show promising results when void decks are introduced in a more complex urban setting.

Despite the promising results of previous studies, numerous 'side effects' of building voids have been detected and should carefully be taken into consideration. Fan et al. (2017) and van Druenen et al. (2019) emphasize the impact of void decks on pedestrian comfort and state that when a certain threshold value for permeability is reached (20% for deep street canyons and 10% for street canyons with AR < 2), air quality improves but pedestrian comfort decreases. *The Guidelines for Sustainable Building Design in Hong Kong* (Yang and Fu, 2019) suggest for example a minimum building permeability of 20 % in dense urban areas. In cases like this, additional guidelines should be formulated to ensure pedestrian comfort. It is also thought that void decks on floor level are less favorable for pedestrian comfort compared to void decks at higher building levels (Chew and Norford, 2018; Druenen et al., 2019). Void decks can also result in increased pollution levels in street canyons or courtyards when stronger pollutant sources are present in adjacent street canyons, especially in cases of AR > 2 (Fan et al., 2017; Gronemeier and Sühring, 2019). Also, single void decks can improve in-canyon ventilation, but Ng et al. (2006), Chew and Norford (2018) and Wong et al. (2020) suggest that void decks are most effective when they are combined as continuous airpath through an entire urban fabric

Similar to previous parameters, orientation to the prevailing wind direction should be considered. Most studies were conducted under perpendicular wind directions, since increasing permeability is assumed most effective in this scenario (Zhu, 2016). Ng and Chau (2011) suggest that in case of parallel winds, building voids interrupt the channeling effect of the street canyon, and pollution levels tend to increase. Therefore, open space may not always favor the pollution removal process. However, in order to draw firm conclusions, the impact of wind direction is still inadequately investigated. An overall lack of field data is also notable in the mentioned studies. Regarding urban planning, it seems legit to state that increased building permeability can be beneficial for in-canyon ventilation, especially when the permeability is improved at ground level. However, especially in deep street canyons, ground-level permeability can result in strongly enhanced wind speed, resulting in an unfeasible pedestrian micro-climate. Therefore, the impact of implementing void decks in a specific situation should be researched in advance and if necessary, measures should be taken to ensure pedestrian comfort.

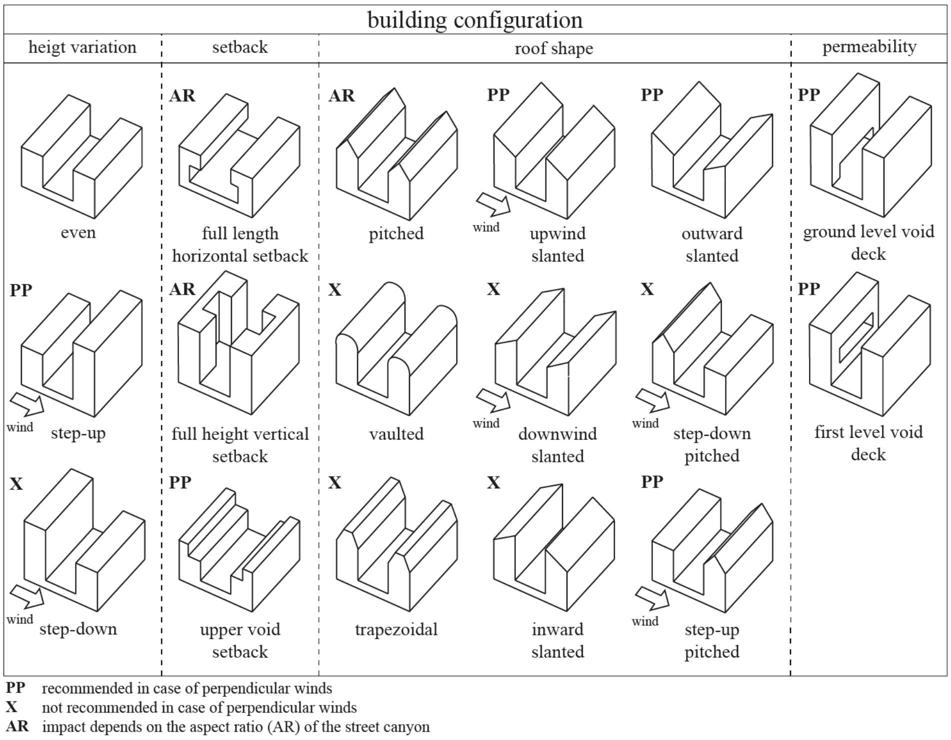


Figure 4. Estimated most favorable building typologies based on a prevailing wind direction perpendicular to the axis of the street canyon.

4.3 In-canyon configuration

4.3.1 Semi-open settings

For the purpose of this research, in-canyon constructions such as eaves (louvers), awnings, overhangs (hanged walls), balconies, arcades, platforms and other elevated structures are assembled under the title 'semi-open settings'. In general, the effect of these structures on the in-canyon airflow and pollutant dispersion has been widely investigated and it can be concluded that for most cases, semi-open structures limit the ventilation efficiency which results in increased pollutant levels. A number of CFD studies has been conducted recently on the presence of balconies in a street canyon (Hall et al., 2010; Montezari and Blocken, 2013; Murena and Mele, 2016; Llaguno-Munitxa and Bou-Zeid, 2018; Karkoulias et al., 2020) and show that in general, the depth of the balconies reduces the space available for flow recirculation. This reduces in-canyon wind speed and the air exchange between the street canyon and the free surface layer. Studies by Hall et al. (2010), Montezari and Blocken (2013) and Murena and Mele (2016) clearly show a significant modification of the flow field inside the street canyon when balconies are present, where several separate vortices and multiple areas of flow separation, recirculation and reattachment are created. This reduces mass transfer to the upper urban canopy layer. It is also thought that balconies have a greater influence on pollution levels near pedestrian height, compared to other in-canyon locations. A study by Llaguno-Munitxa and Bou-Zeid (2018) detected on overall in-canyon pollution increase by ≈10 % when balconies were placed on both sides of a street canyon (AR = 1). Near pedestrian level, a pollutant accumulation was detected under the first-level balconies, resulting of a pollutant increase by ≈80 %. A detailed monitoring campaign by Marini et al. (2015) confirmed these findings, whereas a higher exposure to PNCs (particle number concentrations) was detected near the sidewalks which were partly covered by balconies. However, it should be noted that most of the aforementioned studies only conducted research on balconies attached to the building's facade as overhangs, and not on the arrangement where balconies are incorporated in the building volume (no reduction of the street canyon AR). Further research should be conducted on this matter.

Awnings, eaves, overhangs and platforms are also thought to limit ventilation in a street canyon. In general, these constructions alter the in-canyon flow structures (see Fig. 5) and increase pollution levels (Mohamad et al., 2015, Sato et al., 2015, Chomcheon et al., 2019; Ding et al., 2019; Pothiphan et al., 2019). CFD and wind tunnel studies by Hang et al. (2013, 2018) indicate an increase of air pollutant concentration when the width of overhangs increases. In contrast to open street canyons, it seems that the largest pollutant increase takes place when the wind direction is parallel (0-15°) to the street canyon axis (up to 630%; Hang et al., 2013, 2018; Hiyama et al., 2013). These finding are further supported by field measures by Weissert et al. (2018) and Lim et al. (2015). Other campaigns in Bangkok (Hiyama et al., 2011; Sahanavin et al., 2016) show a large pollution increase when comparing street canyons with and without platforms (up to 172% for PM_{10}) under approximately the same wind and traffic conditions. It should also be noted that in most CFD studies, the support structure of the platform is not taken into account, whereas they potentially increase in-canyon pollution (Suebyat and Pochai, 2017).

When the street canyon is completely covered by overhangs, an arcade is created which reduces wind speed significantly (Gerhardt and Kramer, 1990) and increases in-canyon pollution levels (Hang et al. 2013). However, Kim et al. (2010) showed that the arcade design (e.g. height, roof type, ventilation openings) has a large impact on ventilation efficiency.

For the purpose of urban planning, it can be concluded that all semi-open constructions have the tendency to reduce in-canyon ventilation, from small balconies to large overhangs and platforms. This would suggest that semi-open settings should be avoided in a street-canyon setting. However, in most cases, semi-open settings are constructed to protect pedestrians from specific weather conditions such as heat and heavy rain or wind, which conflicts with previous findings regarding air quality and ventilation. This illustrates the necessity to search for innovative and more flexible solutions (e.g. retractable awnings) in street canyons.

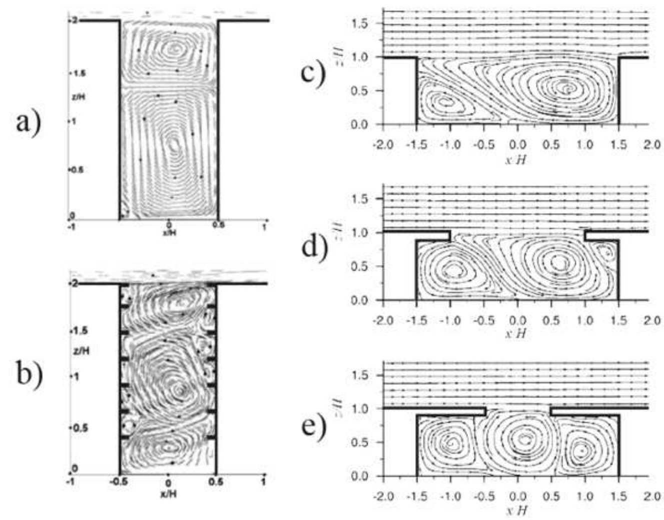


Figure 5. Estimated impact of balconies (b) and overhangs (d,e) on vortex structure in narrow (a,b) and wide (c,d,e) street canyons. With a and b retrieved from Karkoulias et al. (2020) and c, d and e modified after Mohamad et al. (2015).

4.3.2 Trees

Initially it was thought that trees improve air quality due to their capability of deposing particulate pollution ($PM_{2.5}$ and PM_{10}) and decreasing gaseous pollutants such as NO_x and O_3 (Abhijith et al., 2017). However, numerous studies concluded that an increase of pollutant concentration can possibly occur when trees are present in a street canyon configuration as a result of reduced wind speed and air exchange (Buccolieri et al., 2009; Gromke and Ruck, 2007, 2009, 2011; Buccolieri et al., 2011; Salim et al., 2011; Ng and Chau, 2012; Salmond et al., 2013; Di Sabatino et al., 2015; Karttunen et al., 2020). In most wind tunnel and CFD studies, a large increase in air pollution is found near the leeward facade, and a small decrease near the windward facade when perpendicular winds occur. However, field studies (Salmond et al., 2013; Di Sabatino et al., 2015) reported no pollutant decrease at the windward facade, and thus a pollutant increase on both facades of the street canyon. For parallel winds, conflicting results were found in different studies, where some studies indicate increased air pollution on both sides of the street canyon and higher concentration levels towards the outer end of the street canyon (Abhijith and Gokhale, 2015; Buccolieri et al., 2011; Gromke and Ruck, 2012; Wania et al., 2012) and other studies indicate a general decrease in air pollution levels (Amorim et al., 2013; Jeanjean et al., 2016; Buccolieri et al., 2018). Oblique wind directions were reported by Gromcke and Ruck (2012) and Buccolieri et al. (2015) as the worst background conditions, with the highest increase in pollution levels on the leeward and windward facade. In all studies the increase/decrease of air pollutants due to the presence of trees varies widely. Changes in concentration levels on the leeward facade vary for example by -39 % (Xue and Li, 2017) to +164 % (Wang et al., 2018).

The differences in results can be explained by the high number variables which were detected amongst the studies. Besides the impact of wind direction, eight essential variables were found: (1) wind speed and particle size (Janhäll, 2015; Abhijith et al., 2017), (2) the amount of pollution (Li et al., 2013), (3) the AR of the street canyon (Buccolieri et al., 2011; Ng and Chau 2012), (4) the tree planting density (Ng and Chau, 2012), (5) tree crown porosity and (6) leaf area density or LAD (Salmond et al., 2013; Abhijith and Gokhale, 2015; Xue and Li, 2017; Buccolieri et al. , 2018), (7) trunk height and (8) stand density which refers to the actual density of the trunk (Abhijith and Gokhale, 2015; Huang et al., 2019b). In general, it can be concluded that trees with a high tree crown porosity, low LAD, low stand density and low trunk height are preferred in a street canyon configuration (Salmond et al., 2013; Abhijith and Gokhale, 2015; Janhäll, 2015; Xue and Li, 2017; Buccolieri et al., 2018; Huang et al., 2019b). In case of deep street canyons (AR > 2) the change in ventilation performance was indicated to be less sensitive to tree planting (Buccolieri et al., 2011; Ng and Chau, 2012)

Previous variables indicate that the effect of trees on the distribution of air pollutants in street canyons is very specific for different urban environments and tree types. Therefore, decisions in urban planning regarding planting/removing trees in street canyons should be carefully considered and supported by detailed CFD models and field measurements. Nevertheless, the decisions in relation to tree planting in street canyons should also carefully be weighed against other benefits like cooling effects and energy saving (Ng and Chau, 2012).

4.3.3 Hedges, low boundary walls and parked cars

Similar to trees, hedges can be planted in a street canyon configuration. A number of studies have been conducted on this issue (Keuken and Van Der Valk, 2010; Wania et al., 2012; Vos et al., 2013; Chen et al., 2015; Gromke et al., 2016; Lazzari et al., 2016, Li et al., 2016; Ottosen and Kumar, 2020) suggesting that hedges can act as barriers for lateral dispersion of air pollution emitted by road traffic with only limited absorption of air pollutants. Therefore, similar to trees, the aerodynamic effect of hedges is shown to be much stronger than the pollutant removal capacity (Vos et al., 2013). In general, most studies show lower pollution levels (24 % to 61 % lower) behind the hedge (sidewalk) compared to the pollution levels in front of the hedge (roadside) (Li et al., 2016; Abhijith et al., 2017). Field observations by Keuken and Van Der Valk (2010) and Ottosen and Kumar (2020) confirmed these findings, with concentration reductions by 27 % to 52 % behind the hedge compared to the roadside values. These results show that a hedgerow can potentially have a positive effect on the air quality at pedestrian level, however on the roadside, a pollution increase (up to 44%) is likely to occur (Li et al. (2016). The impact of hedgerows is also strongly affected by the porosity of the hedge (Vos et al., 2013; Lazzari et al., 2016), where a pollutant increase was found at pedestrian level for high-porosity hedges and a pollution decrease in case of green barriers (no porosity). Therefore, hedgerows with a low porosity are recommended (Kumar et al., 2019). In general, hedgerows are preferably placed as close as possible to the road, with favorable dimensions of 0.9-2.0 m high and 1.5 m wide (Li et al., 2016; Kumar et al. 2019).

Similar to hedges and green barriers, a number of studies indicate that low boundary walls (LBWs) can have a positive effect on pollution concentrations at the windward and leeward facade and also result in an increased pollution near the road axis (McNabola et al., 2009; Gallagher et al., 2015; Kristof and Papp, 2018; Baghlad et al., 2018). In most studies, two scenarios are investigated: (1) two LBWs on both sides of the road and (2) one central LBW, separating the traffic lanes. Studies by McNabola et al. (2009) and Kristof and Papp (2018) indicate that a central LBW could be most beneficial in case of winds perpendicular to the axis of the street canyon, with potential pollutant reductions up to 40 % at pedestrian height. Due to the presence of the central LBW, the vortex structure is largely altered, improving vertical dilution of air pollutants. In this scenario, a sharp pollution increase is detected near the LBW. In case of parallel winds, McNabola et al. (2009) states that two LBWs on both sides of the road are more effective, resulting in a potential pollutant decrease at pedestrian level up to 75 %. Despite these promising results, a CFD study by Wang et al. (2017b), which incorporated a dynamic wind field (changes in magnitude of the boundary layer inflow) and traffic flow, suggests that for certain wind conditions and traffic intensities LBWs could increase pedestrian exposure to air pollutants by 12-23 %. This mainly happens when wind speeds are low and the LBW weakens the wind speed even further, which results in a gradual accumulation of the in-canyon air pollutants.

Studies by Abhijith and Gokhale (2015), Gallagher et al. (2011) and Gallagher and Lago (2019) indicate that roadside parked or stationary cars can also act as a LBW. However, the effect of parked cars largely depends on the parking arrangement (parallel/perpendicular/oblique parking). Based on Gallagher et al. (2011) and Abhijith and Gokhale (2015) it can be concluded that in case of a street canyon with AR = 1, parallel parking seems generally preferable (potential reduction in pollutant levels by 15 % at the leeward facade and 30 % at the windward facade). However, for an oblique wind direction, every parking arrangement resulted in increased pollution levels at the windward (up to ≈ 10 %) and leeward (up to ≈ 23%) facade. A study by Gallagher and Lago (2019) even reported a pollution increase of 32 %-62 % at the windward facade and a largely variable impact at the leeward facade ranging from -160 % to +62 %. Gallagher and Lago (2019) conclude that under low wind speed conditions, similar to LBWs, pollutant can get trapped at the windward and leeward footpath, resulting in increased pollution levels at pedestrian height.

For the purpose of urban planning it can be concluded that in general, dense hedges, LBWs and parallel parked cars can potentially shield pedestrians from high concentrations of air pollution, but only in case of high wind speeds and parallel or perpendicular wind directions. In case of low wind speeds, deep street canyons or oblique wind directions, an aversive effect could be generated. This indicates the necessity of conducting research on the average effect of these interventions, where varying wind conditions (direction and speed) should be incorporated.

4.3.4 Lane position

In most studies, a street canyon is modelled with a pollution source at the center of the road, representing pollution by traffic. As shown previously, numerous studies have been conducted on changing different variables, but few studies conducted research on the lateral displacement of the pollution source. In general, it is clear that a lateral displacement of the pollutant source does not alter the in-canyon flow structure, but it is assumed that it still can affect the dispersion process substantially (Chan et al., 2001). Studies by Kastner-Klein and Plate (1999), Chan et al. (2001), Liu and Barth (2002) and Huang et al. (2015) found a pollution reduction (by a factor up to 2) at human respiration level near the leeward wall when the traffic lane was laterally repositioned towards the windward wall. In general, the overall pollution retained by the street canyon and the pollution levels near the windward facade seem merely affected by the source position. However, when placed too close to the leeward wall, pollutants can get trapped in the small corner vortex in the lower region of the windward wall, resulting in a steep increase in pollution levels on the windward footpath (Huang et al., 2015). When traffic lanes are placed at the central axis of the street canyon, the number of traffic lanes can possibly still impact pollution dispersion. Kastner-Klein and Plate (1999), Jicha et al. (2000) and Tan et al. (2019) suggest that one central lane with traffic in one direction is more beneficial for air quality compared to two lanes, given the traffic intensity stays the same. It is thought that one central lane promotes equal distribution of pollutants at the windward and leeward side of the street canyon, which reduces pollutant peaks (Tan et al., 2019). It should be noted that the aforementioned studies are all carried out under perpendicular wind direction. Therefore, the effect of lane displacement is still uncertain under varying wind directions.

Regarding urban planning, it can be concluded that the lateral repositioning of traffic lanes can potentially be a useful tool to reduce the pedestrian exposure to air pollutants. Therefore, it seems interesting to reconsider the classic street layout with central car lanes and to introduce asymmetric street profiles. However, the most preferable street layout depends on site-specific variables and should therefore be modelled and researched in advance. In any case, side effects (such as noise nuisance) and the impact on the pedestrian experience should be carefully considered.

4.3.5 Additional findings

During the literature review, a number of in-canyon parameters were found which were less suitable for the aforementioned categorization, but which are still worth mentioning. Few studies (Litschke and Kuttler,2008; Lazzari et al., 2016; Pugh et al., 2016; Qin et al., 2018) have been carried out on the impact of green walls on air quality in a street canyon configuration. These studies estimate a reduction in concentration levels by 9 % - 34 % (CO_2), 23 % - 29,3 % (PM_{10}) and 15 % (NO_2) due to the presence of green walls, however due the lack of further research, these results should not be generalized. Litschke and Kuttler (2008) estimated that extensive greening (with trees and maximal facade greening) could be within the bounds of possibility to compensate for local vehicle emissions. However, the study takes into account a 100% facade greening, which is in most cases impossible due to window openings and other irregularities. Also, the negative effect of vegetation on the in-canyon ventilation capacity has not been taken into consideration. Notwithstanding the uncertainties, studies of Vos et al. (2013) and Kumar et al. (2019) advise to use green walls in most canyon configurations. The research conducted on the effect of green roofs in street canyons is also fairly limited, but a rather minor impact can be expected (Pugh et al., 2012; Baik et al., 2012; Speak et al., 2012; Qin et al., 2018).

It was also found that in field studies, in-canyon flows are largely altered by small-scale elements (Karra et al., 2017). Gavey and Savory (1999) described these obstacles (e.g. small constructions, kiosks and stationary vehicles) as in-canyon roughness elements which create complex in-canyon flow patterns. A CFD study by Lin et al. (2019) for example indicates that all types and arrangements of wall-hanged advertisement boards result in increased in-canyon pollution levels. On a very small scale, Jiang et al. (2019) discovered that even wall elements such has louver blinds could reduce in-canyon ventilation, since sub-vortices are generated between the louver blinds, decreasing the wind speed near the facade.

Previous findings indicate that small-scale roughness elements can large affect local pollution concentration. The results however depend on site-specific conditions and meteorological variables. Therefore, the usage or destruction of roughness elements in urban planning should be careful considered and analyzed on the level of one specific site.

5. Guidelines

5.1 Guidelines for urban planning and implementation strategy

It is clear that, despite the high number of reviewed studies, no rigid guidelines to enhance air ventilation can be formulated due to the high number of variables that should be considered. However, this study aims to formulate a number of guidelines that can be used as a rule of thumb for urban planners. In urban planning, it is clear that different cities have different planning systems and thus different stages in which these guidelines can be implemented. However, in general, some similarities between most planning systems can be found, such as the existence of hierarchic planning levels (state/province/city/county/districts) and a presence of a spatial policy framework to guide spatial interventions (Jain and Pallagst, 2015; Biesewig, 2016; Meng et al., 2020). On city level, overall city plans (or city master plans) and city regulatory plans are mostly supported by specialized subject plans (SSP) which all together represent the overarching spatial framework for construction projects (Meng et al., 2019). Based on the implementation strategy of the air ventilation assessment (AVA) of Hong Kong (Ng, 2009), a distinction has been made between guidelines applicable on city-wide scale and guidelines applicable on a local project scale. On the city-wide scale, quantitative guidelines can be formulated in a SSP (e.g. ventilation plan) which can be used to assess project proposals/areas against pre-set design parameters and criteria (e.g. permeability or BHR).

On the other hand, numerous guidelines can be derived which are not suitable for translation into quantitative guidelines. Ng (2009) suggests therefore the development of a number of qualitative guidelines which provide designers with a strategic sense on how to improve the ventilation capacity in their projects. All aforementioned guidelines are brought together in Table 2, and an indication has been made on their applicability for specialized subject plans (SSP) or for qualitative guidelines for urban planners (QG). It should be noted that some of these guidelines are in need of further research before implementation.

Table 2. Guidelines for the optimization of the ventilation capacity in street canyons, with a selection of quantitative guidelines suitable for a specialized subject plan (SSP) and qualitative guidelines (QG)

Configuration level	Guidelines	SSP	QG
Street-canyon config			
- Orientation	- A parallel orientation of the street canyons axis towards the main wind direction seems preferable to improve in-canyon ventilation. When oriented oblique or perpendicular to the main wind direction (and AR > 0.65), additional measures have to be taken to ensure a sufficient ventilation capacity.	x	
- Aspect ratio (AR)	- Lower ARs are recommended to improve in-canyon ventilation. Street canyons with AR < 0.65 tend to be less vulnerable for pollutant accumulation. Once AR > 0.65, additional measures have to be taken to ensure a sufficient ventilation capacity.	x	
- Street canyon depth	- In deep street canyon, the threshold value of AR = 5.0 should be respected in order to avoid limited ventilation and peak pollution levels at pedestrian height.	x	
	- Wind catchers may improve in-canyon ventilation in deep street canyons.		x
- Street canyon length	- Limiting the street canyon length improves in-canyon ventilation and therefore enhance pollution dispersion and dilution. In general, the lateral aspect ratio should not exceed the threshold value of LAR = 3.0.	x	
Building configuration			
- Building height variation	- Increasing the building height variation results in increased turbulence, which potentially improves pollutant dilution and in-canyon ventilation. Homogeneous building heights should be avoided if possible.	x	
	- A step-up configuration towards the main wind direction is preferable to improve ventilation.		x
- Building setback	- Building setbacks seem potentially favorable to reduce in-canyon pollution levels, whereas in case of perpendicular winds, full-length horizontal setbacks seem more favorable in deep street canyons (AR > 2) and full-height vertical setbacks are recommended in regular street canyons (AR < 2).		x
- Roof shape	- In street canyons with a low AR < 1, pitched roofs can improve ventilation. Once AR > 1, all roof typologies seem to limit in-canyon ventilation compared to a flat-roof situation.		x
	- Inward-slanted, upward slanted and trapezoidal roofs seem less favorable in terms of in-canyon ventilation and should therefore be avoided if possible.	x	
- Building permeability	- Ground-level permeability seems highly effective in dispersing pollution and reducing pollution levels near pedestrian height. A building permeability of 20 % is recommended in dense urban areas.	x	
In-canyon configuration			
- Semi-open settings	- All semi-open settings tend to reduce ventilation and should therefore be limited or replaced by flexible solutions.	x	
	- Hanged balconies should be avoided. When balconies are applied, they should be placed in the building volume in order to avoid a reduction of the AR and thus the ventilation capacity.	x	
- Trees	- Tree species with a lower crown and stand density are recommended in order to allow wind penetration. Trunk heights are preferably low.	x	
- Hedges and low boundary walls	- Hedges should be placed close to the pollutant source and should be less permeable by wind, in order to serve as a barrier which reduces pedestrian exposure to air pollution.		x
	- Under perpendicular wind conditions, LBWs may reduce pedestrian exposure to air pollution. A central LBW seems more effective than 2 roadside LBWs.		x
- Source position	- Under perpendicular wind conditions, a lateral displacement of the source towards the windward facade reduces pedestrian exposure to air pollution.		x
- Additional findings	- Green walls seem to have a very modest impact on the ventilation capacity but may enhance the deposition of PM and are therefore generally recommended.	x x	

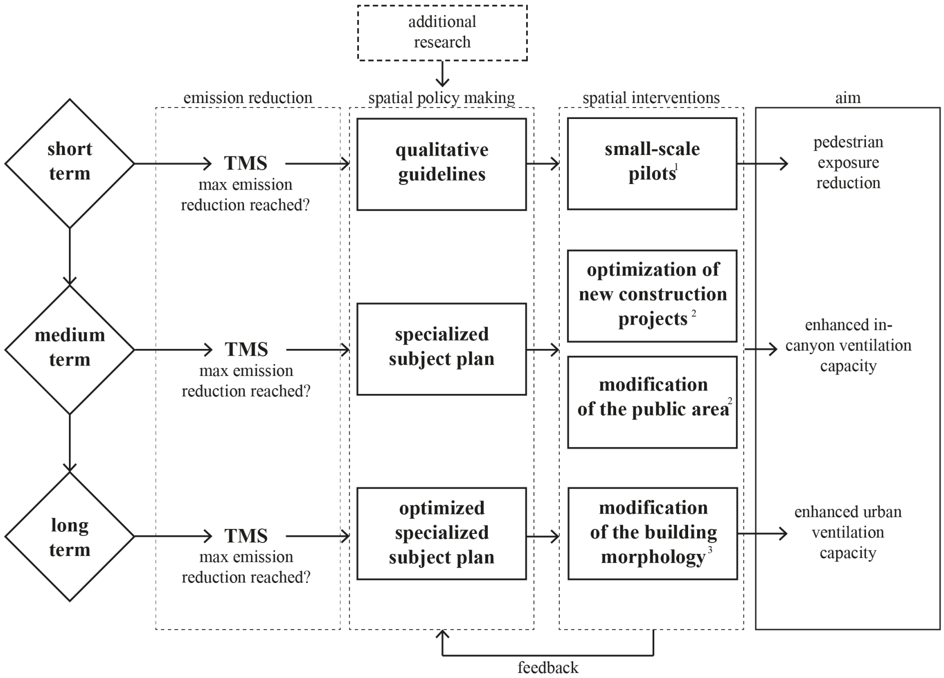
	- Laterally wall-hanged billboards reduce the in-canyon ventilation capacity. When applying billboards, it is recommended to place them in the surface of the building facade in order to minimize the reduction of wind.

It is clear that most guidelines suitable for SSP are generally well investigated, whereas for most qualitative guidelines, the results are largely dependent on site-specific characteristics. Therefore, it is suggested these guidelines are always subjected to a preliminary (CFD) study and a multiple scenario's which alter these parameters in a specific street canyon under different meteorological condition are tested. Since it is proposed to integrate these guidelines in urban planning, it is important to bare in mind other parameters such as for example the pedestrian comfort or ecological value/cooling effect of trees. High wind speeds may favor pollution dispersion and dilution but can also create uncomfortable environments for pedestrians (Lenzholzer, 2015). The study by Fan et al. (2017) on building permeability already takes pedestrian comfort related to wind speed into account. However, in most other studies, this point of view is fairly neglected. It is self-evident that for the purpose of urban planning, the positive effect of increased wind speed on reducing pollution levels should be carefully weighed against the potential loss of pedestrian comfort and emotional wellbeing.

It is also clear that the spatial implementation of these guidelines is largely time-dependent. In case of an existing urban fabric, the morphology of the street canyon configuration and building configuration is rather static compared to the in-canyon configuration. Implementing guidelines on the street canyon and building configuration is less evident and demands a long period of implementation time which contradicts to the urgent demand to improve air quality in street canyons. Therefore, a time-dependent implementation strategy is suggested, represented in Fig. 6. For every time period (short, medium and long term) it is suggested that firstly the traffic management strategies (TMS) are reviewed and optimized in order to maximize pollutant reduction. On the level of spatial policy making, a number of qualitative guidelines can already be drafted based on the preliminary research in a short-term period (< 1 year). These guidelines can be used to produce a number of "small-scale pilots" such as the implementation of LBWs or the removal of in-canyon wind obstacles (e.g. billboards) which aim to contribute to the short-term goal of decreasing the pedestrian exposure to air pollution. Before implementing these interventions on a city-wide scale, the pilots should be tested and used for further validation of the implemented measures. On a medium-term time frame (1-3 years), the SSP (e.g. ventilation plan) can be developed as a spatial policy framework to guide the optimization of new construction projects and the modification of the public area. The main aim of the framework should be to enhance/improve the in-canyon ventilation capacity.

By conducting additional research and investigating the implemented guidelines on-site, an optimization of the qualitative guidelines and the SSP can be developed on the long-term period. Within this long-term time frame, the ambition should be to be able to apply justified modifications to the existing building morphology (e.g. varying building height or increasing building permeability), with the ambition to improve the urban ventilation capacity. However, these measures demand longer implementation terms (up to 10 years). The impact of all spatial interventions should be investigated in time, in order to generate feedback to optimize the policy making process. By doing this, an iterative optimization process is developed.

For most urban planners, the first and second part of the strategy is generally interesting, since the ability is created to improve air quality by small and short-term modification is the public terrain. For city planning in general, the threefold part of this strategy indicates the necessity to develop short-term, mid-term and long-term strategies to assess air quality and ventilation in street canyons. Still, it is highly important to emphasize that designing for improved ventilation in street canyons is a highly complex matter, and a high number of limitations and variabilities should be kept in mind. This indicates that none of the aforementioned guidelines should be implemented on site without additional research or validation by (CFD) models.



1. limited amount of general guidelines, detailed CFD study necessary
2. some general guidelines are applicable but a high number of variablities should be taken into account, detailed CFD study necessary
3. general guideline are applicable in most cases, CFD study recommended for specific cases

Figure 6. Potential implementation strategy of the guidelines to improve air quality in street canyons based on the implementation time (Source: author)

5.2 Limitations and variabilities

For complex building arrangements (real cities) with buildings varying in height and shape and different spacing between buildings, the flow field will most likely be a complex combination of 3D vortices and channelized flow (Brown, 2004). Figure 7 illustrates that these complex flow fields even exist for idealized street canyons, with more complex vortices than shown in previous visualisations. Kim and Baik (2004) illustrate the emerging of complex portal and roll-type vortices for an idealized street canyon (W/H-ratio = 1) with perpendicular wind. The study also indicates that slight changes in wind direction ($5° \leq \theta \leq 20°$) can distort the shape of the vortices (see Fig 7a,b). Another study by Yang and Fu (2019) indicates the presence of very complex wind patterns in existing urban environments (Fig 7e). Therefore, it should be noted that the representations in previous sections are simplified, and more complex flow fields are likely to appear.

Brown (2014) and Wood et al. (2009) also indicate the complexity of flow fields near the end of a street canyon or near intersections. Sudden changes in building heights (such as high-rise buildings) are also thought to have a large impact on the local air flow fields. This observation already illustrates the impact of variabilities and uncertainties, which is an inherent characteristic of the real-world wind field (Neophytou et al., 2011). This variability is created by urban morphology, ambient and meteorological conditions (e.g., wind speed and wind direction), atmospheric stability, source strength of pollutants and the effect of solar irradiation (Kim and Baik, 1999, Yazid et al., 2014). In numerous CFD studies, the impact of the surrounding built-up area is neglected or reduced to a very simplistic representation. A study by Michioka and Sato (2012) suggests that, even when idealized, the shape of the surrounding environment influences the turbulent structure of the incoming wind near the street canyon, and therefore affects the pollution dispersion process. Therefore, it can be concluded that a more complex modeling of the direct urban environments of a street canyon (e.g., Moon et al., 2014) could be beneficial for obtaining more realistic results. Not only the urban form, but also the presence of other pollutant sources in the environment could affect in-canyon pollution levels. On a large scale, transboundary pollutants can affect in-canyon pollutant levels. Other pollutant sources could be traffic in adjacent street canyons (Dabberdt and Hoydysh, 1991) or even pollution (especially PM) from chimneys on adjacent roofs (Badas et al., 2018). On a local scale, moving vehicles, trees, and exhaust vents among other things initiate further complications (DePaul and Sheih, 1985; Brown, 2004; Yazid et al., 2014). It should be emphasized that the impact of these pollutants can largely affect the dispersion procedures.

Numerous studies on wall heating (Sini et al., 1996; Kim and Baik, 2001; Xie et al., 2005; Offerle et al., 2007; Kang et al., 2008; Park et al., 2012; Nazarian and Kleissl, 2016; Allegrini, 2018; Hang et al., 2019) indicate that uniform and nonuniform wall heating (solar-induced or due to anthropogenic heating of the building interiors) or ground heating strongly affects the in-canyon vortex formation due to the development of buoyancy driven flows near the surface. In most cases, wall or ground heating will improve in-canyon ventilation and therefore reduce pollution levels (Kim and Baik, 2001; Kang et al., 2008; Nazarian and Kleissl, 2016). However, Xie et al. (2005) indicate that this effect largely depends on which surface (leeward/windward facade or ground) is heated. The effects of wall heating should carefully be considered, since this indicates that in-canyon flow patterns can change during long-term seasonal transitions or even short-term solar changes (Offerle et al., 2017). However, the aforementioned field study by Offerle et al. (2017) also indicates that buoyancy effects from the heated walls seem to have less impact on in-canyon flow regimes in real situations (field measurements) compared to the estimated impact shown in numerical experiments.

Lastly, it should be stressed that most of the guidelines are derived from studies which use passive scalars (e.g. CO / CO_2) or only introduce one traffic-related pollutant (a summary of all pollutants per reviewed study can be found in the **Appendix**). Therefore, these guidelines are applicable for most of these pollutants (PM, NO_x / NO_2, CO / CO_2). However, it should be stressed that results can vary due to the different behavior of pollutants, especially due to deposition effects when for example green infrastructures are introduced (e.g. Vos et al., 2013; Buccolieri et al., 2018). Furthermore, traffic-related emissions consist mostly of reactive pollutants, such as nitrogen oxides (NO_x=NO+NO_2), volatile organic compounds (VOCs) and secondary pollutants (e.g. ozone, O3). The chemical reaction between these reactive pollutants can alter the dispersion process (Zhang et al., 2020). CFD studies (Kwak and Baik, 2012; Park et al., 2015) and field measurements (Kwak et al., 2016) on multiple reactive pollutants (NO, NO_x, VOCs and O_3) found a reduction in NO_2 and O_3 levels when NO levels increased due to the NOx-O3 photochemistry. Therefore, street canyons with higher NO_x values tend to have lower O_3 concentrations than the background concentration. This indicates that, due to chemical reactions, the aforementioned guidelines are less suitable for reducing O_3 values, and their impact on other reactive pollutants should be reconsidered based on the potential chemical reactions.

Despite these issues, Neophytou et al. (2011) conclude that computational models such as CFD models are suitable for predicting flow fields and dispersion patterns, but the given variability and uncertainty in the field should always be considered.

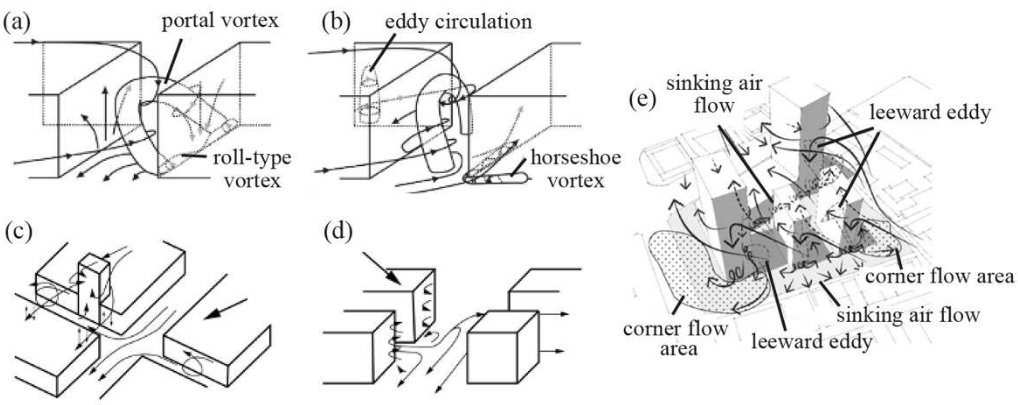


Figure 7. Complex flow fields for different urban morphologies with: (a) a schematic representation of complex 3D vortices in an idealized street canyon with perpendicular wind and (b) oblique winds (Kim and Baik, 2014), (c,d) assumed flow fields in complex urban environments (near intersections and high-rise buildings, based on Wood et al., 2009) and (e) assumed flow patterns in a real urban environment (Yang and Fu, 2019)

5.3 Advantages and limitations of CFD modelling

Previous findings indicate the necessity to validate urban design interventions and their impact on local air quality in street canyons. In the reviewed studies, CFD is used as a validation tool (see **Appendix**). In most cases, CFD modelling is a cost-effective way for evaluating the effects of air pollution mitigation strategies (only in case of Reynolds-averaged Navier Stokes (RANS) studies, Large Eddy Simulations (LES) are, however, much more time consuming and costly). Urban CFD simulations, however, require specific care in order to obtain reliable results. CFD simulations should therefore be performed in accordance with existing best practice guidelines (e.g. Franke et al., 2007; Blocken et al., 2007; Tominaga et al., 2008). Elaborate reviews dealing specifically with this matter are also available in the literature (e.g. Blocken et al., 2011; Lateb et al., 2016; Blocken et al., 2014; Moonen et al, 2012). CFD studies should, moreover, be validated with experimental data (Moonen et al, 2012) from field measurements or databases with experimental data (e.g. CODASC, n.d.; CEDVAL, n.d.; CEDVAL-LES, n.d.; AIJ, n.d.; Joint Urban 2003, 2003).

In addition to the care that urban CFD studies require, important problems in this research field have yet to be resolved, since inaccurate results and deviations from reality are still obtained in CFD models (Blocken et al., 2016; García-Sánchez et al., 2018). In general, it is concluded that most computational models are suitable to predict time-averaged concentrations, but maximum concentrations vary greatly and are therefore difficult to predict. Despite the current problems in urban CFD modelling, it is expected that it will increasingly be used for evaluating urban air pollution, since it is a very active field and its strategies and methodologies are still evolving. In general, as displayed by many studies mentioned in this literature review, CFD has become a powerful tool for modeling the impact of urban design interventions on the ventilation performance and air quality in street canyons. However, due to the complexity and unresolved issues of CFD, it is not a feasible tool to be used by urban planners. This indicates the necessity for a closer collaboration between engineering sciences and urban planning.

6. Conclusion

For the purpose of urban planning, a broad literature review was conducted on 12 spatial parameters which potentially affect the in-canyon ventilation capacity of urban street canyons. The aim of this literature review was to formulate a number of spatial guidelines for urban planners, as a supplement to the traffic management strategies that are applied in several cities. More than 200 fragmented studies were reviewed and brought together in a comprehensive overview. Hereby, a thorough overview is created and 18 general guidelines were derived from the reviewed studies. An implementation strategy of this guidelines is suggested, where some guidelines are more likely to support the policy framework and other more qualitative guidelines can be used to guide urban planners. However, by doing the literature review, a large number of uncertainties, variabilities and limitations were detected, which should be born in mind by urban planners. The literature review also indicated CFD-modelling as a useful tool to validate the implementation of different design measures. However, for the usage of CFD, a closer collaboration between engineering sciences and urban planning is recommended.

An additional value of this literature review is the detection of knowledge gaps. It is clear that some parameters (e.g. building setback) are still in need of further investigation. Also, few studies were conducted using variable wind conditions (e.g. wind direction and speed), which reduces the reliability of the results when compared to realistic situations. This indicates the necessity of studies which use a realistic probability distribution for the wind conditions, in order to develop more realistic insights on the average impact of different measures. It is also clear that only few studies (e.g. Abhijith and Gokhale, 2015; Hao et al., 2019) were conducted on combining multiple of the aforementioned parameters (e.g. building height variation, roof shape, source position), hence the potential synergies between these parameters can still be explored. Lastly, the number of field studies seems scarce compared to wind/water tunnel or CFD studies (in only 28 studies field measurements were used, in contrast to 137 studies which used CFD or a wind/water tunnel setup, see **Appendix**). This indicates the necessity of more field studies, to test and complement the mere computational studies.

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