# A review of strategies for mitigating roadside air pollution in urban street canyons

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## Abstract

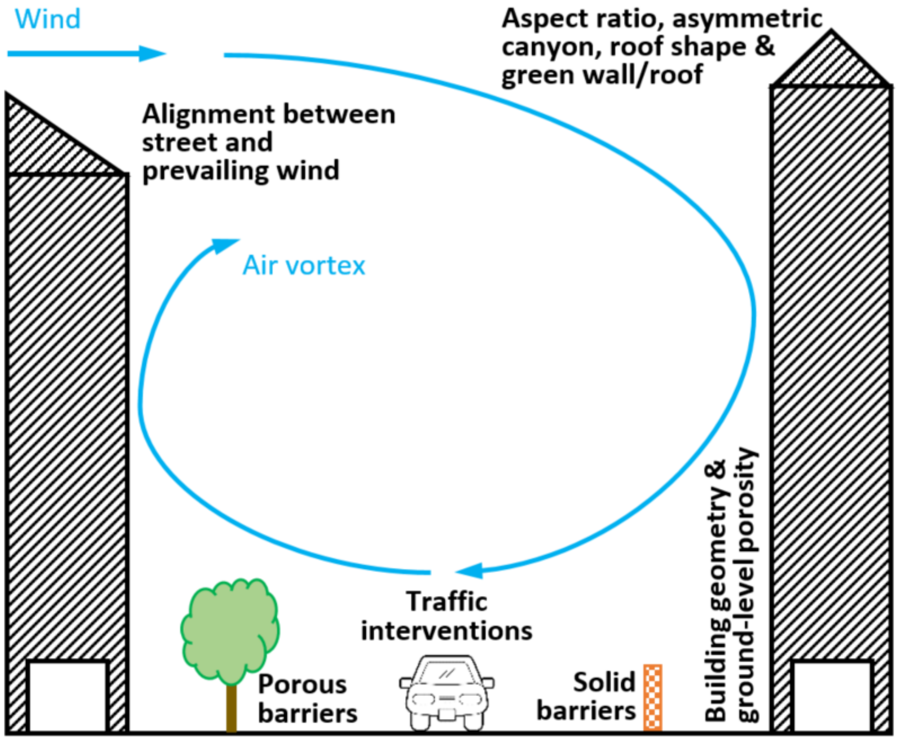
Urban street canyons formed by high-rise buildings restrict the dispersion of vehicle emissions, which pose severe health risks to the public by aggravating roadside air quality. However, this issue is often overlooked in city planning. This paper reviews the mechanisms controlling vehicle emission dispersion in urban street canyons and the strategies for managing roadside air pollution. Studies have shown that air pollution hotspots are not all attributed to heavy traffic and proper urban design can mitigate air pollution. The key factors include traffic conditions, canyon geometry, weather conditions and chemical reactions. Two categories of mitigation strategies are identified, namely traffic interventions and city planning. Popular traffic interventions for street canyons include low emission zones and congestion charges which can moderately improve roadside air quality. In comparison, city planning in terms of building geometry can significantly promote pollutant dispersion in street canyons. General design guidelines, such as lower canyon aspect ratio, alignment between streets and prevailing winds, non-uniform building heights and ground-level building porosity, may be encompassed in new development. Concurrently, in-street barriers are widely applicable to rectify the poor roadside air quality in existing street canyons. They are broadly classified into porous (e.g. trees and hedges) and solid (e.g. kerbside parked cars, noise fences and viaducts) barriers that utilize their aerodynamic advantages to ease roadside air pollution. Post-evaluations are needed to review these strategies by real-world field experiments and more detailed modelling in the practical perspective.

**Keywords:** Roadside air quality; Urban street canyons; Vehicle emission dispersion; Control measures; Urban planning

## Highlights

- Key influences are canyon geometry, traffic and weather conditions, and chemical reactions.
- Traffic interventions in street canyons lead to moderate improvement of roadside air quality.
- Well-designed canyon geometry significantly enhances dispersion of emissions.
- Combining solid and porous in-street barriers is more effective than individual use.
- Traffic control and in-street barriers are more implementable than canyon geometry design.

## Graphical abstract



Mitigation strategies for roadside air pollution in street canyons

# 1. Introduction

Many countries, especially developing countries, are becoming urbanised rapidly. The global urban population has increased by 4.6 times from 751 million (30% of world population) in 1950 to 4.2 billion (55%) in 2018, and the number is projected to reach 6.4 billion (68%) in 2050 (United Nations, 2019). Urbanisation is important to economic growth, poverty reduction and human development. However, the rapid growth of cities has significantly challenged the United Nations Sustainable Development Goals (Fuso Nerini *et al.*, 2019). One of the main hurdles is urban air pollution which is a top public health risk worldwide. The World Health Organization (WHO, 2020) reported that over 80% of the people living in cities that had air quality monitoring systems were breathing polluted air exceeding the WHO limits. Each year, 4.2 million deaths worldwide are attributed to ambient air pollution (WHO, 2021).

Various sources, such as road transport, industry and household, contribute to urban air pollution. Among them, vehicle emissions are often found to be the major contributors (Anenberg *et al.*, 2017; Huang *et al.*, 2020c; Karagulian *et al.*, 2015). Urban streets are important communal spaces for outdoor activities. Street-canyon air pollution thus poses adverse health impacts on the public such as pedestrians, drivers and residents in naturally ventilated buildings (Ai and Mak, 2015). Anenberg *et al.* (2019) estimated that vehicle emissions had caused approximately 385,000 premature deaths and US$ 1 trillion in health damages globally in 2015. To combat air pollution, the WHO issued guidelines for the four criteria air pollutants, i.e. particulate matter (PM), nitrogen dioxide ($NO_2$), ozone ($O_3$) and sulphur dioxide ($SO_2$). Many cities have established air quality monitoring networks to assess their compliance with the guidelines (Lai *et al.*, 2013; The Lancet, 2006). Existing networks are mostly concerned with ambient air pollutants. However, roadside pollutant concentrations are usually much higher than their ambient counterparts because of the proximity to emission sources (Huang *et al.*, 2020a). The rapid growth of urban population not only increases traffic and emissions, but also propels the development of medium to high density housing an inevitable solution for many cities, especially around transport hubs and shopping centres. High-rise and dense buildings form deep street canyons which restrict pollutant dispersion and thus further worsen the roadside air pollution problem. It was reported that street-level pollutant concentrations in an urban street canyon were much higher than those in a wide and open street, although the traffic was much lighter in the urban street (Rakowska *et al.*, 2014).

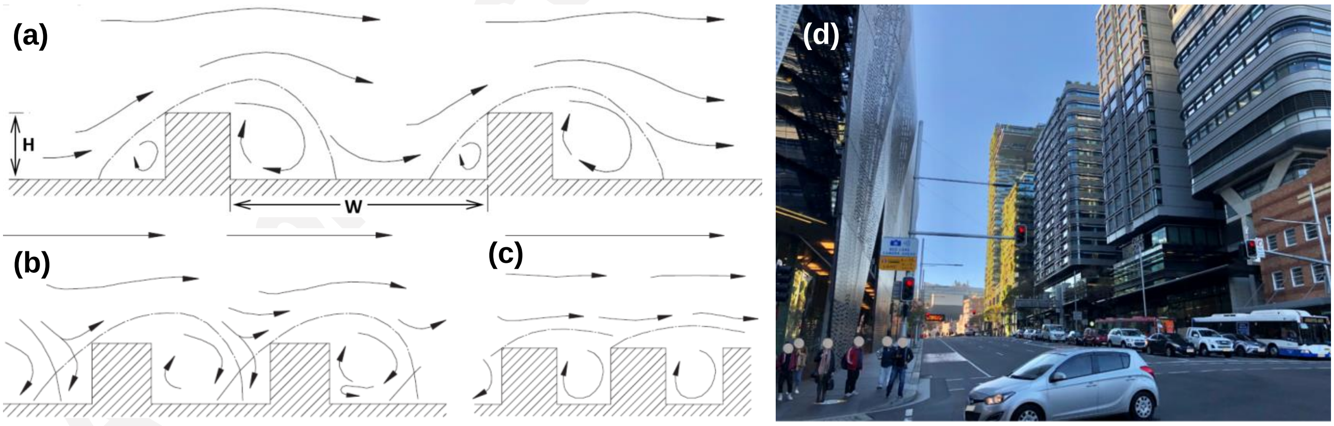


**Fig. 1.** Flow regimes with different aspect ratios (AR) (Li *et al.*, 2006): **(a)** isolated roughness flow (AR < 0.3), **(b)** wake interference flow (0.3 < AR < 0.7), **(c)** skimming flow (AR > 0.7), and **(d)** a typical newly-developed deep street canyon on Sydney Broadway, Australia that restricts emission dispersion and puts the public and vehicle emissions in close proximity.

The debates on city planning are usually concerned with infrastructure capacity, housing affordability, and sunlight access for neighbouring buildings and public parks. However, an often-overlooked factor is the effect of high-rise buildings on vehicle emission dispersion and roadside air quality. Street-level air pollution hotspots are not necessarily all associated with heavy traffic (Beckwith *et al.*, 2019; Miskell *et al.*, 2015; Rakowska *et al.*, 2014; Shi *et al.*, 2016), and poor city planning can also play an important role. The ventilation and pollutant removal in a street canyon depend on many factors, such as street canyon features, weather conditions, traffic conditions, and green infrastructure. Among them, street canyon designs are of the utmost importance which are under the direct control of urban planners. A crucial parameter is the aspect ratio (AR) of building height (H) to street width (W). Three distinct flow regimes exist in street canyons, namely isolated roughness flow regime ($AR<0.3$), wake interference flow regime ($0.3<AR<0.7$) and skimming flow regime ($AR>0.7$) (**Fig. 1**) (Li *et al.*, 2006; Vardoulakis *et al.*, 2003). Air ventilation and pollutants removal are weakened with the increase of AR. Particularly, in the skimming flow regime (**Fig. 1c**), a stable recirculation is formed inside the canyon so the street flow is decoupled from the ambient flow. It in turn tremendously reduces ventilation, resulting in poor street-level air quality. Street canyons with $AR \geq 0.7$ are not rare in our cities (**Fig. 1d**). For instance, two six-storey buildings (~24 m high) form an $AR > 0.7$ street canyon on a typical six-lane road (~27 m wide, assuming 3.5 m per lane plus 6 m pavement). Many cities are relaxing their building height limits to accommodate the rapidly increasing urban population (Sculthorpe, 2016; Taylor, 2019). The implication of this trend to pollutant dispersion in street canyons needs to be addressed.

The development of high-rise buildings would also alter the thermal balance in street canyons compared with neighbouring rural areas, leading to an urban heat island (UHI) effect which is an important issue for urban planning and has been the subject of numerous studies. The UHI effect can significantly increase building energy consumption, worsen thermal comfort and increase heat-related mortality (Lai *et al.*, 2019; Li *et al.*, 2019a; Parker, 2021; Santamouris, 2020). UHI and urban air pollution (also called as urban pollution island (UPI)) are two closely related problems (Ulpiani, 2021). Accordingly, some of the mitigation strategies reviewed in this study can also be applied to address the UHI problem, such as street canyon design that promotes air ventilation, traffic reduction measures, planting trees, and green roofs and walls (Chew and Norford, 2019; Hien, 2016; Koch *et al.*, 2020; Lai *et al.*, 2019). Nevertheless, UHI is beyond the scope of this study and the readers are referred to the many recent studies on this topic for further details, e.g. Jamei *et al.* (2020); Santamouris (2020); Ulpiani (2021); Wang *et al.* (2021).

The dispersion of vehicle emissions in urban street canyons is not a new topic and has been widely studied over the past decades. A number of review studies have focused on specific aspects of emission dispersion, such as monitoring and modelling techniques (Vardoulakis *et al.*, 2003), computational fluid dynamics (CFD) (Li *et al.*, 2006), air pollution at street intersections (Tiwary *et al.*, 2011), flow structures (Yazid *et al.*, 2014), chemistry-dynamics coupling (Zhong *et al.*, 2016), and modelling of street-level traffic emissions (Forehead and Huynh, 2018). A thorough understanding of emission dispersion is crucial for better city planning and air quality management. However, there is a lack of critical evaluation of how to implement these findings for mitigating air pollution in urban street canyons. Recently, increasing studies have been carried out to explore the mitigation of roadside air pollution. Therefore, this review aims to systematically evaluate the effectiveness of different strategies in reducing roadside air pollution. This paper is organised as follows. Firstly, all the factors that influence vehicle emission dispersion and roadside air quality are discussed. Secondly, various potential strategies for mitigating roadside air pollution are compared, including traffic management, canyon geometry design and in-street barriers. Finally, the challenges and future perspectives are elaborated. The findings from this review are expected to help policy makers and urban planners to effectively plan and manage city development and to safeguard a high standard of air quality in our cities.

## 2. Vehicle emission production and dispersion in urban street canyons

The roadside air quality in street canyons is determined by many factors, such as traffic composition and conditions, canyon geometry, weather conditions and chemical reactions. A thorough understanding of the impacts of each of these factors is critical for air pollution exposure assessment and mitigation. This section discusses and compares their effects on vehicle emission dispersion and roadside air quality. The implications for potential mitigation strategies and their feasibility are also discussed.

### 2.1. *Traffic conditions*

Vehicle exhaust is the dominant contributor of air pollutants in a street canyon environment. A larger traffic volume generally produces more emissions and thus results in higher pollution levels for a given street canyon. However, vehicles are emitting at different rates and some vehicles may have a disproportionally higher contribution to the total emissions. The fleet composition and driving conditions play important roles in vehicle emissions.

For fleet composition, it was estimated that diesel heavy-duty vehicles (HDVs) on average emitted 40%-60% of nitrogen oxides ($NO_x$) and PM emissions and 70%-90% black carbon emissions on highways, in spite of their small percentage (<5%) of the global on-road vehicle population (Posada *et al.*, 2015). The estimates could vary greatly between countries and regions. Therefore, many experimental studies reported higher pollutant concentrations for roads with higher volumes of diesel vehicles (Hatzopoulou *et al.*, 2013; Huong Giang and Kim Oanh, 2014; Rakowska *et al.*, 2014; Targino *et al.*, 2016). Further, a small fraction of dirty vehicles could produce significantly higher emissions than the rest, such as those with outdated emission standards (Bishop and Haugen, 2018), high mileage (Bishop *et al.*, 2016), or malfunctions in the engine emission control systems (Huang *et al.*, 2019a; Organ *et al.*, 2020).

Driving conditions can influence the roadside air quality via two ways, namely emission rate and vehicle-induced turbulence. Vehicles under heavy loads produce more emissions, and thus elevated air pollutants have been reported on road sections with uphill slope (Kean *et al.*, 2003; Targino *et al.*, 2016), acceleration after traffic lights or bus stops (Beckwith *et al.*, 2019; Xing *et al.*, 2019), and frequent acceleration and deceleration in stop-start driving in congested traffic (Choudhary and Gokhale, 2016; Dirks *et al.*, 2016; Forehead and Huynh, 2018; Huang *et al.*, 2018a). Vehicle-induced turbulence is an important factor in roadside air quality assessment due to the close proximity between the emission sources and receptors (comparable to vehicle size). Comparing with idling vehicles, moving vehicles induce turbulent wakes which greatly enhance emission dispersion, leading to reduced emission levels in street canyons (Beckwith *et al.*, 2019; Thaker and Gokhale, 2016; Wang *et al.*, 2019b). In addition, one-way traffic is more favourable for emission dispersion than two-way traffic due to the so-called piston effect (Jicha *et al.*, 2000; Kastner-Klein *et al.*, 2001; Yazid *et al.*, 2014). It should be noted that moving vehicles would cause high non-exhaust $PM_{10}$ emissions due to abrasion and resuspension processes (Beddows and Harrison, 2021; Gehrig *et al.*, 2010; Thouron *et al.*, 2018; Weinbruch *et al.*, 2014), which are unavoidable as vehicles have to move to pass through a street canyon. Reducing numbers of heavy vehicles and better road pavement can help reduce these non-exhaust emissions (Gehrig *et al.*, 2010; Timmers and Achten, 2016).

### 2.2. *Canyon geometry*

Street canyons create semi-enclosed spaces which are bounded by the ground at the bottom and buildings on both sides, hence vehicle emissions can only be removed via the open roof (Li *et al.*, 2006). This greatly constrains pollutant removal via natural ventilation and causes elevated air pollutant concentrations compared with wide and open streets. The most important parameter of a street canyon is the AR (= H/W, **Fig. 1**). In general, deeper canyons (i.e. larger H/W) weaken ventilation and pollutant removal. In particular, the airflows inside a street canyon are decoupled from the ambient ones when H/W is larger than 0.7, forming a stable air recirculation. This is referred as skimming flow regime and often causes high roadside pollutant concentrations. The ground-level airflows of a street canyon will come to a calm condition when H/W is further increased to be over 4 (He *et al.*, 2019; Ng, 2009).

The ratio of building length to street width (L/W) is another key parameter that affects pollutant removal from a street canyon. The dispersion process can be simplified to a two-dimensional problem when L/W is very large. In the real world, however, urban areas are split into blocks with finite L/W. Under this circumstance, road intersections become important places for air exchange and emission re-distribution among street canyons. These processes are complicated by the ambient wind, building heights, building symmetry and atmospheric stability (Tiwary *et al.*, 2011).

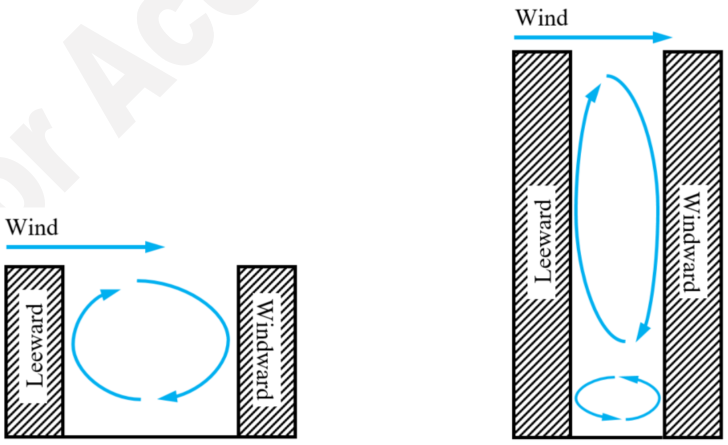
In addition, real-world street canyons vary in heights (symmetric/asymmetric) and roof shapes (flat/triangular/slant). These features affect the wind-induced turbulence inside the street canyons and consequently the air quality. Llaguno-Munitxa and Bou-Zeid (2018) compared the canyon ventilation rates of five different building geometries, including flat roof, pitched roof, round roof, terraced building and building with balconies. They found that the air exchange rate was very sensitive to the building geometry: with the round roof and building with balconies having the best and worst ventilation, respectively. Regarding building asymmetry, it was reported that highly symmetric or highly asymmetric street canyons could lower pollutant concentrations at pedestrian level (Fu *et al.*, 2017).

Finally, the presence of in-street barriers such as trees, viaducts, noise barriers and kerbside parked cars also modifies the street canyon geometry. Unlike H/W, L/W and building configurations that determine the overall flow fields, in-street barriers only affect the airflows in the bottom of a street canyon. Nonetheless, local dilution is important to the air quality in pedestrian breathing zones.

### 2.3. *Weather conditions*

Weather conditions include various meteorological parameters such as wind speed and direction, temperature, humidity and sunlight. Among them, wind speed and direction are of the primary importance in influencing emission dispersion in street canyons. Higher wind speeds generally promote wind-induced turbulence and remove vehicle emissions more quickly, leading to better roadside air quality.

Regarding wind direction, winds parallel to the street axis are favourable for emission removal. However, parallel winds generate limited vertical flows so a potential issue is the accumulation of emissions in the downwind region for long street canyons (Soulhac *et al.*, 2008; Soulhac and Salizzoni, 2010; Vardoulakis *et al.*, 2002). Winds perpendicular to the street axis, on the other hand, are unfavourable for emission dispersion and cause heterogeneous emission distribution due to the building roof induced vortices, which are analogous to lid-driven cavity flows (AbdelMigid *et al.*, 2017; Sousa *et al.*, 2016). Such flow patterns usually lead to higher pollutant concentrations reside on the leeward side of street canyons with unity H/W (Berkowicz *et al.*, 1996; Chan *et al.*, 2002; Tsai and Chen, 2004; Vardoulakis *et al.*, 2002; Xie *et al.*, 2003). However, an opposite scenario may be observed with different building configurations (He *et al.*, 2017; Xia and Leung, 2001; Yang *et al.*, 2020).



(a) Shallow street canyon (H/W≤4)  (b) Deep street canyon (H/W>4)

**Fig. 2.** Schematics of the formation of single vortex (a) and double vortices (b) induced by the building roofs in shallow and deep urban street canyons, respectively. The double vortices occur in full scale street canyons when H/W ratio changes from 4 to 5 (He *et al.*, 2017).

This is because the number of vortices depends on the H/W (**Fig. 2**). For shallow street canyons (e.g. H/W $\leq$ 4), only one vortex is induced which carries vehicle emissions from the windward to leeward side (He *et al.*, 2017). As the H/W increases (e.g. H/W = 5) (He *et al.*, 2017), two counter-rotating vortices are layered vertically, switching the higher pollutant concentrations to the windward side. More vortices may be formed in deeper canyons. Multiple vortices are observed in wind tunnel tests of small-scale canyons at a much smaller H/W ratio (e.g. H/W = 2) than full-scale canyons (He *et al.*, 2017; Xie *et al.*, 2006; Yazid *et al.*, 2014), which implies the necessity of real-world experiments. In addition, other factors such as roof shapes (e.g. slanted roofs) and in-street barriers (e.g. viaduct) may induce multiple vortices (Ding *et al.*, 2019; Huang *et al.*, 2016). It should be noted that the secondary vortex is much weaker than the primary one, causing adverse conditions for emission dispersion. This also makes the vehicle-induced turbulence dominant in emission dispersion, which explains why experiments in a deep street canyon (H/W = 5.7) reported negligible difference in pollutant concentrations between the leeward and windward sides, regardless of wind direction (Murena *et al.*, 2008). Counterintuitively, oblique winds rather than parallel or perpendicular winds may generate both the best and worst conditions for pollutant removal, as a small change in wind direction can significantly change the in-street airflows and pollutant distribution (Boddy *et al.*, 2005; Hargreaves and Baker, 1997; Kim and Baik, 2004; Miao *et al.*, 2020; Scaperdas and Colvile, 1999; Tomlin *et al.*, 2009).

Sunlight has significant effect on roadside air quality. It heats up the building facades and ground surfaces. This thermal effect generates buoyancy that drives the airflows and emission dispersion in street canyons (Chen *et al.*, 2020; Wang *et al.*, 2011; Zhao *et al.*, 2020). Other weather parameters such as ambient temperature and humidity have relatively insignificant effects on emission dispersion, and have been rarely investigated. These weather conditions can have significant effects on emission production in street canyons. Hot and cold weather increase energy consumption in buildings and vehicles due to increased use of air conditioning, leading to higher emissions (Ulpiani, 2021). Hot weather also contributes to higher $O_3$ formation through photochemical reactions (Mika *et al.*, 2018; Pascal *et al.*, 2021).

### *2.4. Chemical reactions*

Chemical reactions do not change the airflows but can significantly influence the pollutant compositions in street canyons (Střižík *et al.*, 2016). The short length scales of street canyons imply that only fast reactions play an important role. Most vehicle emissions, such as carbon monoxide (CO), carbon dioxide ($CO_2$) and hydrocarbon (HC) can be considered inert. However, $NO_x$ reacts quickly with $O_3$ in the time scale of tens of seconds and thus should be considered chemically reactive in roadside air quality assessment (Vardoulakis *et al.*, 2003). A simplified $NO_x$-$O_3$ chemistry can be described as the dissociation of $NO_2$ in the presence of sunlight and the formation of $NO_2$ through NO titration (Zhang *et al.*, 2020a; Zhong *et al.*, 2016). $O_3$ is not directly emitted from vehicles but a secondary pollutant from photochemical reactions with $O_3$ precursors (i.e. $NO_x$ and volatile organic compound (VOC)) in the troposphere (Cao and Yin, 2020; Wang *et al.*, 2019a; Zhang *et al.*, 2019a). $NO_x$ emissions are dominated by diesel vehicles and are mostly in the form of NO (Anenberg *et al.*, 2017; Gentner and Xiong, 2017; Grange *et al.*, 2017), which usually causes lower $O_3$ but higher $NO_2$ concentrations at roadside than in the ambient (Bright *et al.*, 2013; Huang *et al.*, 2020a). The $NO_x$-$O_3$ reactions in a street canyon can be influenced by all the factors discussed above, including weather conditions (mainly wind, temperature and sunlight) (Kang *et al.*, 2008; Kwak and Baik, 2014), traffic conditions (the source of $NO_x$ and VOC) (Park *et al.*, 2015) and canyon geometry (e.g. aspect ratios that affect sunlight access and in-street airflows) (Grawe *et al.*, 2007; Park *et al.*, 2015; Tong and Leung, 2012; Zhang *et al.*, 2020a). Furthermore, vegetation could have significant impacts on reactive pollutants. Vegetation can reduce air pollution via deposition of PM emissions on leaf surfaces and absorption of gaseous emissions (e.g. $O_3$ and $NO_x$) through leaf stomata (Abhijith *et al.*, 2017; Eisenman *et al.*, 2019; Han *et al.*, 2020; Janhäll, 2015; Sicard *et al.*, 2018). On the other hand, vegetation would produce biogenic VOC and pollen emissions (Calfapietra *et al.*, 2013; Eisenman *et al.*, 2019). Both the emission reduction and production capabilities depend strongly on vegetation species, as well as environmental conditions. Therefore, traffic interventions especially on diesel vehicles and urban planning such as careful choice of trees and green walls are the key to control reactive pollutants in urban street canyons.

### 2.5. *Comparison between influencing factors and implications for air pollution control*

**Table 1** summarises the key influencing factors for the dispersion of vehicle emissions in street canyons and proposes potential strategies for controlling roadside air pollution. As motor vehicles are the dominant sources of air pollutants in urban environment, traffic interventions are the most effective strategy to improve the roadside air quality, such as low emission zones and congestion charges. These measures are under the full control of city planners and policy makers and are widely applicable for both existing and future street canyons. Proper design of street canyon geometry can greatly improve emission dispersion and thus avoid the creation of pollution hotspots. Overall features of street canyons such as building height, street width, roof shape and symmetric/asymmetric canyon can only be changed with new development. However, control of in-street barriers such as trees, noise barriers and kerbside parked cars applies to both existing and future street canyons. Although weather conditions are beyond the control of city planners, there may exist specific weather patterns for a given region, such as a prevailing wind direction. Urban design such as the orientation of thoroughfares and the configuration of building heights can be adapted to these patterns to maximise pollutant removal. Regarding chemical reactions, traffic interventions can effectively reduce $NO_x$ and VOC emissions which are the precursors of $O_3$ and PM emissions. Further, reactive pollutants can be reduced by city planning such as careful choices of tree species, hedges and green infrastructure which can filter and absorb air pollutants in street canyons (Kessler, 2013; Tomson *et al.*, 2021).

**Table 1.** Factors influencing roadside emission levels and implications for mitigation strategies.

| **Factors** | **Parameters considered** | **Potential mitigation strategies** | **Feasibility** |
|---|---|---|---|
| Traffic conditions | Traffic volume, fleet composition, driving conditions. | Traffic interventions such as low emission zones and congestion charging schemes. | Wide applicability |
| Canyon geometry | Aspect ratio, building symmetry, roof shape, in-street barriers. | Urban planning such as building height, roof shape, design of in-street barriers, etc. | Moderate applicability |
| Weather conditions | Wind speed and direction, sunlight, temperature, humidity. | Urban planning can be adapted to weather conditions such as street orientation. | Limited applicability |
| Chemical reactions | Traffic conditions, canyon geometry, weather conditions. | Traffic interventions and urban planning such as trees and green walls. | Wide applicability |

## 3. Strategies for controlling roadside air pollution

This section discusses the effectiveness of various mitigation strategies for controlling roadside air pollution in street canyons. Two major strategies are identified, namely traffic interventions and urban planning. The first is pollution source control while the second is enhancing pollutant removal from street canyons.

### 3.1. *Traffic interventions*

#### 3.1.1. New vehicle technologies and regulations

Advanced vehicle technologies (e.g. electric vehicles (EVs) and cleaner engines) and stringent emission regulations (e.g. Euro 6) are widely adopted to alleviate the traffic-related air pollution problem. Among them, EVs are often considered the most effective solution. Zheng *et al.* (2020) estimated the well-to-wheel emissions of EVs and gasoline passenger vehicles in China. They found that EVs had 98% lower VOC and 34% lower $NO_x$, but comparable or slightly higher primary $PM_{2.5}$ and $SO_2$ than gasoline vehicles. Ke *et al.* (2017) predicted that a moderate EV penetration scenario (i.e. 20% private passenger vehicles and 80% commercial passenger vehicles electrified) could reduce average $PM_{2.5}$ concentrations by 0.4-1.1 $\mu g/m^3$ in the Yangtze River Delta region in China in 2030. Higher EV penetration ratios could synergistically deliver greater air quality, climate and health benefits (Liang *et al.*, 2019). It should be noted that clean power generation is critical for realising the air quality benefits of EVs. Yu and Stuart (2017) investigated the effects of urban planning strategies and EV adoption on air quality in Florida, USA. It was found that a compact urban growth scenario had lower $NO_x$ but higher butadiene and benzene exposures than a sprawl growth within the Hillsborough County. With a complete EV fleet, the compact scenario mitigated the in-county increases for butadiene and benzene exposures but resulted in higher $NO_x$ exposures due to increased demand on power plants.

In spite of the benefits, EVs face several challenges (e.g. price, range anxiety and charging infrastructure) and only account for a small share of global car sales (e.g. 2.6% in 2019) (IEA, 2020). Currently, conventional vehicles powered by internal combustion engines still dominate the market and will co-exist with EVs for many years to come (Kalghatgi, 2018; Reitz *et al.*, 2020). Therefore, cleaner engine technologies driven by increasingly stringent regulations are of equal importance for reducing transport-related air pollution, such as exhaust after-treatment technologies, advanced combustion concepts, and cleaner and renewable fuels. Comparing with Euro 1 standard, the CO, HC and $NO_x$ emission limits in Euro 6 standard are >80% lower for diesel passenger cars and >60% lower for gasoline passenger cars (Huang *et al.*, 2018c; The Automobile Association, 2021), which have led to significant reductions of on-road vehicle emissions. Bishop and Haugen (2018) conducted a long-term emission measurement campaign (1989-2016) for light-duty vehicles (mostly gasoline vehicles) in Chicago, USA using on-road remote sensing technology. The results showed large emission reductions and remarkable improvements in emission control durability, with an order of magnitude reduction for CO and over a factor of 20 for HC since 1989, and 79% reduction for NO since 1997. In comparison, diesel vehicles were often observed with a slower emission reduction pace and even with increases at some Euro stages (Carslaw *et al.*, 2011; Huang *et al.*, 2018b; 2018d; Pujadas *et al.*, 2017), indicating that emission reduction technologies and regulations were less effective for diesel vehicles under real-world conditions.

### 3.1.2. Emission control on in-use vehicles

Although new emission reduction technologies and regulations can substantially reduce traffic emissions in the long term (e.g. 80% reduction of $NO_x$ emissions by 2040 (Matthias *et al.*, 2020)), the benefits of these strategies can usually be seen only after years of implementation. Controlling the emissions from the large stock of in-use vehicles can bring immediate benefits to urban air quality and has attracted great attention in recent years (Wagner and Rutherford, 2013; Yang *et al.*, 2015). There are many ways to reduce in-use vehicle emissions, such as utilization of drop-in fuels like GTL or HVO (Parravicini *et al.*, 2021), changing the modal split (Vierth *et al.*, 2018), retiring older vehicles (Lavee *et al.*, 2014; Zhou *et al.*, 2019), high-emitters screening (Organ *et al.*, 2019), odd-even driving restrictions (Mishra *et al.*, 2019; Xie *et al.*, 2017) and engine retrofits (Giechaskiel *et al.*, 2018). These programs are usually implemented at a city or national scale and aim to reduce the vehicle emissions inventory. Higher emission standards and controlling emissions from other sources such as power plants usually bring larger impacts on future air quality at a city or national scale. In this review, we focus on traffic interventions that target at street canyon scales.

Roadside air pollution and human exposure exhibit large spatial variations. Streets having intensive human activity (e.g. city centres) usually come with heavy traffic and deep street canyons, and thus more serious air pollution. As discussed in Section 2.1, some vehicles may emit significantly more pollutants than others. Therefore, low emission zones (LEZs) are created to restrict the access of high-emitting vehicles to designated streets or city centres. Although over 250 LEZs have been setup worldwide (with over 200 in Europe) (Holman *et al.*, 2015; Tartakovsky *et al.*, 2020), there is a lack of studies on their effect on air pollution control. **Table 2** summarises the LEZs that have been assessed using air quality monitoring data. Since diesel vehicles are the main sources of air pollutants in particular PM and $NO_x$, most LEZs restricted the access of outdated HDVs while some LEZs restrict all vehicles older than a specific emission standard, such as in Germany (Fensterer *et al.*, 2014) and Portugal (Ferreira *et al.*, 2015). PM and $NO_x$ are generally reduced in LEZs, although there are mixed results on the extent of reduction (**Table 2**). This is expected as LEZs vary greatly in the covered area, enforced time and restricted vehicles. In addition, different evaluation methods were adopted. The improvement tabulated in **Table 2** should be interpreted with caution because usually multiple vehicle emission control programs are implemented simultaneously (Huang *et al.*, 2020a), and it is difficult to isolate the effects of individual programs. Moreover, the seasonal variations could mask the actual effect of an LEZ in a short-term evaluation (Brimblecombe and Ning, 2015; Huang *et al.*, 2020d; Shen *et al.*, 2021).

**Table 2.** Methods and effectiveness of selected low emission zones.

| **Location (year introduced)** | **Covered area, enforced time and restricted vehicles** | **Emission reduction (studied period)** | **Reference** |
|---|---|---|---|
| London, UK (2008) | Greater London; All times; Mainly Euro 0-III HDVs (introduced in 4 phases) | PM reduced by 2.5%-3.1% in LEZ vs 1% outside LEZ, but no $NO_x$ reduction (2001-2011) | Ellison *et al.* (2013) |
| | | $NO_2$ reduced by 0.97-1.35 μg/m$^3$, but no $PM_{10}$ or $PM_{2.5}$ reduction (2006-2014) | Mudway *et al.* (2019) |
| Germany (2008) | City area; All times; >3.5t and Euro 0-2 vehicles (introduced in 3 phases) | $PM_{10}$ reduced by 13.0% at traffic site vs 4.5% at background site in Munich (2006-2010) | Fensterer *et al.* (2014) |
| | | $NO_x$ reduced by 4% in 17 cities enact LEZs (2005-2009) | Morfeld *et al.* (2014) |
| | | $PM_{10}$ reduced by 4%-8% in 44 cities enact LEZs (2005-2012) | Gehrsitz (2017) |
| Netherlands (2009) | City centre; All times; Euro 0-II and some Euro III HDVs (introduced in 2 phases) | Insignificant reductions observed in five cities enact LEZs (2008-2010) | Boogaard *et al.* (2012) |
| | | $PM_{10}$ reduced by 5.8%, $NO_x$ reduced by 5.9% in Amsterdam (2007-2010) | Panteliadis *et al.* (2014) |
| Lisbon, Portugal (2011) | City centre; 7:00-21:00 weekdays; Euro 0-1 vehicles (introduced in 2 phases) | $PM_{10}$ reduced by 23%, $NO_2$ reduced by 12% (2001-2013) | Ferreira *et al.* (2015) |
| Hong Kong, China (2015) | 3 busy corridors in city centre; All times; Euro 0-III franchised buses | $NO_2$ reduced by 19% at roadside sites vs 8% at background sites (2014-2016) | Huang *et al.* (2020a) |
| Haifa, Israel (2018) | Residential areas; All times; Euro 0-3/III diesel vehicles and Euro 0-3 taxis (introduced in 2 phases) | $NO_x$ reduced by 12.9%, black carbon reduced by 10.6% (2018-2019) | Tartakovsky *et al.* (2020) |

Roadside air pollution and human exposure also show large temporal variations. Pedestrian and traffic activities usually peak simultaneously in rush hours that also involve congestions. Congested traffic not only reduces productivity, but also worsens air pollution. The problems are more apparent in street canyons because of the intensive vehicle emissions and weakened vehicle-induced turbulence. Congestion charging schemes (CCSs) are developed to reduce the traffic and air pollution, which have been implemented in some cities such as London, Stockholm and Singapore. So far, very few studies have evaluated the effects of CCSs on air pollution. London introduced a CCS in its central area in 2003, which was initially a single charge of £5 between 7:00-18:30 on weekdays (Beevers and Carslaw, 2005) and has now been raised to £15 between 7:00-22:00 every day except Christmas Day (Transport for London, 2020). Using detailed traffic data and emission model, Beevers and Carslaw (2005) reported that total $NO_x$ and $PM_{10}$ reduced by 12.0% and 11.9%, respectively in the CCS zone due to increased vehicle speed and reduced vehicle number, both of which had the same importance. Dispersion modelling also demonstrated moderate reductions in $NO_2$ and $PM_{10}$ concentrations in the CCS zone (Tonne *et al.*, 2008). Meanwhile, air quality monitoring data was also used to evaluate the London CCS. Atkinson *et al.* (2009) observed reductions in NO, CO and $PM_{10}$ concentrations but increases in $NO_2$ and $O_3$ concentrations in the CCS zone during 2001-2005. However, they did not attribute these changes to the CCS because there were other traffic interventions being implemented concurrently. Lately, using the other 20 largest UK cities as the control groups, it was shown that the London CCS reduced CO, NO and $PM_{10}$ substantially but increased $NO_2$ sharply (Green *et al.*, 2020). A seven-month "Stockholm Trial" of congestions tax was carried out to reduce congestion and air pollution in the inner city of Stockholm, Sweden. Dispersion modelling showed up to 12% and 7% reductions in annual $NO_x$ and $PM_{10}$ concentrations, respectively in the most densely trafficked streets if the CCS was permanent (Johansson *et al.*, 2009). The effectiveness of CCS on emission reduction is mainly affected by the charging rate, method and zone size (Wu *et al.*, 2017). Coria *et al.* (2015) further suggested that CCS should be optimised in a response to emission dispersion capacities due to seasonal changes in meteorological conditions.

### *3.2. Urban planning*

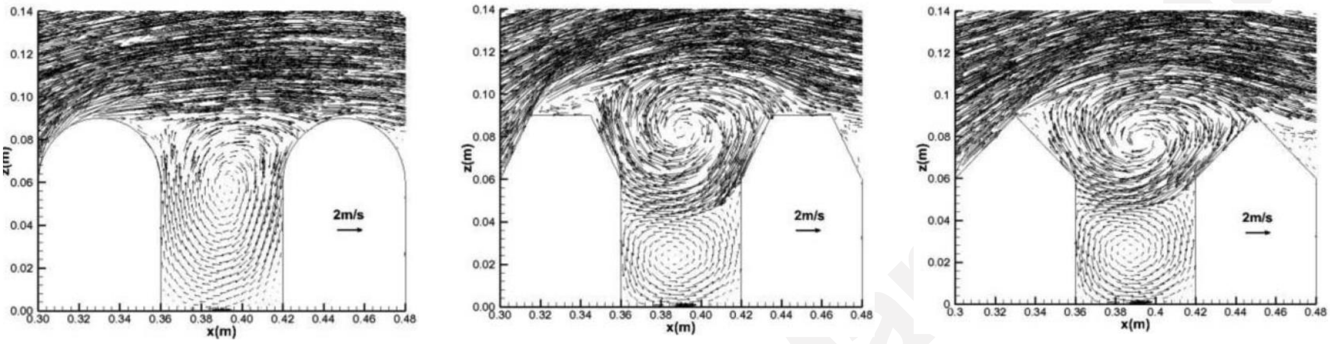
The severity of roadside air pollution is not necessarily all due to heavy traffic, and street canyon features also play important roles. Air pollution typically soars in urban settings that prioritize road transport over pedestrians and that allow uncontrolled sprawl of large, grey, unbroken blocs of asphalt and concrete (Neira, 2018). Careful urban design can help mitigate air pollution noticeably (Zhang and Gu, 2013). The WHO suggests that health and wellbeing must be the top priority in city planning (Neira, 2018). Urban design that aims to improve air quality can be classified into two strategies, namely design of overall canyon geometry and design of in-street barriers. The first strategy influences the overall airflows inside street canyons which can significantly affect emission dispersion and roadside air quality. However, it is limited to new development. The second strategy mainly influences the airflows in lower canyon region. It has broad applicability to both existing and future street canyons.

#### 3.2.1. Design of overall canyon geometry

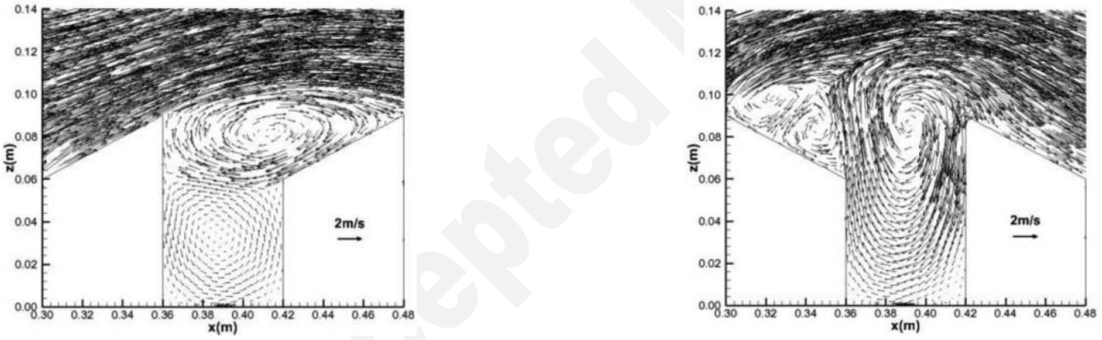
For planning future street canyons, the most important factor is the design of the overall canyon geometry parameters, including the aspect ratio, street/building orientation, building height configuration and roof shape. These factors significantly affect the wind-induced turbulence inside the street canyons, and consequently the air ventilation and pollutant removal. They are key parameters for avoiding air pollution hotspots but are often overlooked in city planning. Generally, lower aspect ratios, streets in parallel to the prevailing wind direction, and buildings with shorter sides in parallel to the boulevard are favourable for dispersion and are recommended for urban designers (Kurppa *et al.*, 2018; Zhang *et al.*, 2019b). However, aspect ratios are often constrained by the land shortage and rapid population growth which make medium to high density housing development an inevitable solution in many cities. Under this circumstance, other parameters become important in urban design.

Optimising building height configurations enhances emission dispersion in street canyons. Previous studies have revealed that street canyons with non-uniform heights better favoured dispersion than those with uniform heights (Gu *et al.*, 2011; Kurppa *et al.*, 2018; Nosek *et al.*, 2018; Zhang *et al.*, 2020b). Particularly, step-up canyons (i.e. upwind buildings lower than downwind buildings) had better roadside air quality than step-down canyons (Assimakopoulos *et al.*, 2003; Nosek *et al.*, 2018). In addition, Gu *et al.* (2011) found that separating step-up and step-down notches in non-uniform street canyons was better for pollutant dispersion than adjoining step-up and step-down notches.

Proper roof shape helps reduce air pollution by enhancing ventilation (Xie *et al.*, 2005). So far, most studies are concerned with flat roofs and only a few have considered other roof shapes. **Fig. 3** shows the effect of roof shape on the induced in-street airflows. Huang *et al.* (2015); (2016) contrasted the airflows and dispersion for five roof shapes, including vaulted, trapezoidal, slanted, and upward/downward wedged roofs. For canyons with the same roof shape on both sides, downward wedged roof (**Fig. 3e**) led to the best pollutant removal, while trapezoidal (**Fig 3b**), slanted (**Fig 3c**) and especially upward wedged (**Fig. 3d**) roofs were unfavourable for pollutants dispersion due to the formation of double vortices. For canyons with different upstream roof shapes but flat downstream roof, upward wedged and vaulted roofs resulted in the highest and lowest pollution levels, respectively (Huang *et al.*, 2015). Takano and Moonen (2013) studied the effect of slope of slanted roof on pollutant dispersion. It was found that a single vortex was formed regardless of wind direction when roof slope was less than 18º. Steeper slopes could either extend this vortex or break it into two vortices depending on wind direction. Pollutant levels decreased with the increase of roof slope in the single vortex case. Therefore, slightly upward slanted roofs had higher vortex airflow rates and similar average air quality than the widely-studied flat roofs. However, double vortices caused elevated street-level air pollution.



(a) Vaulted roof (b) Trapezoidal roof (c) Slanted roof



(d) Upward wedged roof (e) Downward wedged roof

**Fig. 3.** In-street airflow structures induced by different roof shapes (Huang *et al.*, 2016).

Apart from the above common influencing parameters, other design features of the overall canyon geometry have been explored to improve roadside air quality as well. Yuan *et al.* (2014) investigated the effect of various building geometries on pollutants dispersion in high-density urban areas. It was found that strategies promoting convection effects such as building separation, porosity and stepped podium void were more effective in pollutant removal than strategies promoting turbulence diffusion such as building setback. Building porosity, especially at the ground level, enhances ventilation and thermal comfort for pedestrians. Chew and Norford (2018); (2019) reported that building void decks could enhance pedestrian-level wind speeds by over twofold than that without void decks, and the benefit was more noticeable with the increase of void deck height. Zhang *et al.* (2019b) found that elevated building design (a concept similar to void decks) could create a wind pathway for ventilation through the elevated space, which could reduce pollutant exposure by 2-5 orders, especially for street canyons with high aspect ratios. Moreover, first-floor elevation was more effective in pollutant exposure reduction than second-floor elevation (Zhang *et al.*, 2019b).

### 3.2.2. Design of in-street barriers

For existing street canyons, the most feasible design improvements are in-street barriers, such as trees, kerbside parked cars, noise barriers and viaducts. Their presence alters airflows in the lower canyon region and thus affects roadside air quality. The core design principle of in-street barriers is to minimise the emission transport from tailpipes to roadside breathing zones in the condition of minimal impact on ventilation. **Table 3** compares the effects of various in-street barriers on emission dispersion and summarises the key design factors and guidelines for better air quality.

Urban vegetation such as trees, hedges and green infrastructure is essential to urban environments and has attracted significant attention in air quality control in recent years. Urban vegetation is usually believed to be good for urban environments because it can improve urban aesthetics, reduce traffic noise (Ow and Ghosh, 2017), absorb/deposit pollutants (Han *et al.*, 2020; Sicard *et al.*, 2018; Tiwari *et al.*, 2019) and enhance thermal comfort (Lee *et al.*, 2020). However, urban vegetation, especially dense trees with big crowns, may restrain airflows and pollutant removal in street canyons (Vos *et al.*, 2013). Urban vegetation mainly affects dispersion in two ways, namely deposition/absorption and aerodynamic effects. The aerodynamic effect of trees is more significant than the deposition effect, especially under low wind speed conditions (Jeanjean *et al.*, 2017; Vos *et al.*, 2013). Many studies have observed reduced airflows and increased pollutant concentrations in street canyons with trees compared with those without trees (Abhijith *et al.*, 2017; Amorim *et al.*, 2013; Gromke and Blocken, 2015; Gromke and Ruck, 2007; Moradpour *et al.*, 2017; Santiago *et al.*, 2019; Vranckx *et al.*, 2015; Wang *et al.*, 2020; Yang *et al.*, 2020). Urban vegetation can also act as porous barriers to improve air quality in built environments (Gallagher *et al.*, 2015). Therefore, careful choice of vegetation, in particular with regard to planting density, crown size, leaf area density and height, is crucial for air quality control in urban street canyons.

**Table 3.** Effects of in-street barriers on emission dispersion and the key design factors and general guidelines for better urban air quality.

| In-street barriers | Effects on emission dispersion | Key design factors | General design guidelines |
|---|---|---|---|
| Vegetation | Porous barriers: aerodynamic and deposition effects | Planting density, tree height, crown size, leaf area density | High-level vegetation deteriorates air quality while low-level vegetation improves air quality (Abhijith *et al.*, 2017) |
| Kerbside parked cars | Solid barriers: aerodynamic effects | Parking angles, occupancy rates, car shapes | Parallel parking is more effective than perpendicular and 45º parking in improving air quality (Gallagher *et al.*, 2011) |
| Noise barriers | Solid barriers: aerodynamic effects | Wind speed, barrier height, canyon features | Noise barriers reduce near-road pollution for both highways and street canyons, with the penalty of elevated on-road pollution (Hagler *et al.*, 2011; Hang *et al.*, 2017) |
| Viaducts | Solid barriers: aerodynamic effects | Viaduct height, traffic re-distribution, aspect ratio, roof shape | Diverting more traffic to viaducts and using noise barriers on viaducts are beneficial for roadside air quality (Hang *et al.*, 2017) |

Generally, high-level vegetation (i.e. trees) degrades air quality while low-level vegetation (i.e. hedges) improves air quality in street canyons (Abhijith *et al.*, 2017). To minimise the negative effect on air ventilation, Gromke and Ruck (2007) recommended that 1) tree crowns should not occupy large canyon volumes, 2) sufficient free space should be reserved between crowns and adjacent building walls, and 3) trees should be lower than building roof. To control vehicle particle emissions, Janhäll (2015) recommended that vegetation should be 1) low and close to road surfaces to maximise emission dilution with clean air from aloft, 2) close to emission sources to enhance deposition, and 3) vegetation barriers should be high and porous enough to let the air through. Tong *et al.* (2016) investigated the effects of six conceptual designs of vegetation barriers on roadside air quality. Two viable designs were recommended, including 1) wide vegetation barriers with high leaf area densities and 2) vegetation-solid combined barriers. Other factors such as canyon geometry and weather conditions should also be considered in vegetation design. For example, Moradpour *et al.* (2017) found that denser trees did not always worsen air quality and aspect ratio also played an important role, indicating that urban geometry should be considered in tree planting. The impact of trees on air quality is more significant for shallow canyons. Yang *et al.* (2020) reported that, compared with tree-free cases, trees increased personal pollution exposure by 46%, 26%-46%, 16%-50%, 9%-23% for canyons with aspect ratios of 0.5, 1, 3 and 5, respectively. While trees worsened air quality under perpendicular and oblique winds, it was found that the presence of trees was beneficial for air quality under parallel winds (Amorim *et al.*, 2013; Jeanjean *et al.*, 2017). Li *et al.* (2016) reported that the optimal height of roadside vegetation barriers depended on the aspect ratio but was largely insensitive to the speeds of perpendicular winds. Gromke *et al.* (2016) found that continuous hedges could improve air quality in street canyons under perpendicular winds, and one central hedgerow arrangement reduced pollutant concentrations more than two sidewise hedgerows. However, sidewise discontinuous hedgerows generally worsened air quality. Recent urban greening interventions tend to move beyond tree-based and density-controlled solutions. Green walls, screens and roofs are becoming more popular with municipalities and might alleviate some of the negative effects of tree-based solutions (Tomson *et al.*, 2021). This green infrastructure can effectively capture pollutants from nearby emission sources via pollutant deposition to leaf surfaces, while with minimal effect of canyon airflows.

Other in-street barriers such as kerbside parked cars, viaducts and noise barriers can also be used as solid barriers to improve roadside air quality in urban street canyons (Gallagher *et al.*, 2015). Unlike vegetation barriers whose effects come from aerodynamics and deposition, these solid barriers affect the air quality in street canyons merely via the aerodynamic effect.

Kerbside parked cars are commonly seen in urban street canyons and are presented as non-stationary barriers. Gallagher et al. (2011; 2013; 2019) have conducted a series of studies to investigate the impacts of various factors of parked cars on footpath air quality, including parking angles, occupancy rates, wind directions and car body shapes. They found that parallel parking could reduce pollutant concentrations over footpaths (i.e. zones where pedestrians breathe) by up to 35%-49% and 33% under perpendicular and parallel winds, respectively when comparing with the no-parking case (Gallagher *et al.*, 2011). In comparison, perpendicular and 45º parking was less effective in pollution control, which could even increase pollutant concentrations in some cases (Gallagher *et al.*, 2011). The reduction increased steadily with the increase of parking occupancy rate under perpendicular winds, but was only evident when occupancy rate was over 45% under parallel winds (Gallagher *et al.*, 2011). In addition, car shapes had significant effect on footpath pollutant concentrations and decay rates, which demonstrated the importance of geometry details in CFD modelling and pollution control (Gallagher and Lago, 2019). Parked cars can also be used with others in-street barriers to achieve better air quality control. Gallagher *et al.* (2013) investigated the effect of parked cars and/or low boundary walls on footpath pollutant exposure in an urban street canyon. They found that the car-wall combined barrier showed the biggest improvements in footpath air quality. When compared individually, parallel parking provided comprehensive pollutant reductions on the whole footpath under all wind conditions, and thus was a more suitable passive control method than low boundary walls. Abhijith and Gokhale (2015) investigated the effect of trees and/or parked cars on pedestrian pollutant exposure. They found that, when combined with parked cars, trees with high porosity crown and low-stand density could greatly reduce roadside air pollution.

Noise barriers are widely constructed at roadside to remediate traffic noise nuisance. A number of field experiments were conducted to investigate their effects on the air quality on highways. It was found that the pollutant concentrations behind noise barriers could be up to 50% lower than that of road sections without noise barriers (Baldauf *et al.*, 2008; Baldauf *et al.*, 2016; Hagler *et al.*, 2012; Lee *et al.*, 2018; Ning *et al.*, 2010). The reductions were more noticeable under low wind conditions (Lee *et al.*, 2018) and within 50 m from the barriers (Baldauf *et al.*, 2016). In addition, combining noise barriers with vegetation could have larger pollutant reductions than using them individually (Lee *et al.*, 2018; Ranasinghe *et al.*, 2019). CFD simulations were also performed to evaluate the effect of key parameters of noise barriers on roadside air quality. Hagler *et al.* (2011) found that noise barriers with heights of 3-18 m exhibited the maximum pollutant reductions by 15%-61% at 20 m from the road when comparing with the barrier-free case, while the penalty was an increase of on-road pollution by a factor of 1.1-2.3. Enayati Ahangar *et al.* (2017) reported that dual barriers on both sides of a highway had larger downwind pollutant reductions than a single barrier. Moreover, the barrier effect diminished beyond 10 barrier heights from the highway. It should be noted that highways are usually built in open spaces so the effects of noise barriers on emission dispersion are determined by the ambient winds directly. For confined spaces in urban street canyons, the barrier effects are determined by the canyon-induced airflows so the canyon features also play an important role. In urban street canyons, noise barriers are usually built on viaducts to reduce the noise nuisance on the neighbouring buildings. Analogously, using noise barriers increased the pollutant concentrations on the viaducts, but sheltered the nearby buildings from pollutant exposure (Hang *et al.*, 2017; He *et al.*, 2017). Hao *et al.* (2019) found that noise barriers on viaducts could reduce the integral pollutant concentrations in pedestrian breathing zones for symmetric street canyons. The barrier effect was smaller for step-up canyons, and increasing windward building height hindered pollutant dispersion. For step-down canyons, $H_1/H_2=1.2$ (ratio of upwind to downwind building heights) had the lowest integral concentrations while $H_1/H_2=2$ had extremely high integral concentrations.

Viaducts are built to improve the traffic efficiency in busy urban areas. Their presence in urban street canyons influences roadside air quality via 1) re-distributing emission sources by diverting some vehicles from ground streets to viaducts and 2) altering emission dispersion process. The key factors of viaducts that impact roadside air quality include viaduct height, traffic re-distribution, canyon aspect ratio, and roof shape. Compared with viaduct-free canyons, pollutant exposure in street canyons with viaducts was reduced if all ground emissions were diverted to viaducts, but was increased by 3-6 times if emissions were from both the grounds and viaducts (Hang *et al.*, 2017; He *et al.*, 2017). The increase was more significant for high aspect ratio canyons (He *et al.*, 2017). In addition, the presence of a viaduct could reverse the initial viaduct-free airflows when the viaduct height was about 0.7-1.0 of the building height. Such reversed flows increased air pollution in canyons with flat roofs, but significantly reduced air pollution in canyons with triangle roofs (Ding *et al.*, 2019).

## 4. Challenges and future perspectives

Urban street canyons pose a major challenge for assessing air pollution caused by the traffic through them due to the limited understanding of the dynamics and chemistry of the complex dispersion process. Pollutant dispersion in street canyons has been extensively investigated for decades. So far, however, little research has been done to quantify vehicle emission dispersion based on real-world measurements and accurate numerical modelling. There are major knowledge gaps in the experiments, numerical modelling and the development of roadside air pollution control measures, as described below.

***Experimental studies:*** The majority of existing experimental studies used small-scale models in wind tunnels to measure pollutant dispersion, and there is a lack of studies in real-world street canyons. Despite the apparent advantages of wind tunnel testing (e.g. controlled conditions, repeatable results, and well-established measurement techniques), the results of wind tunnel experiments cannot fully replicate the real-world conditions due to the complex processes involved such as turbulence and chemical reactions. Experiments in real-world street canyons need to characterise the emissions on both the source and receptor sides. However, real-world experiments face several major challenges: lack of a suitable tracer gas, long response time of gas analysers, characterisation of emission sources and receptors, and dynamic environmental conditions. Conventional tracer gas sulphur hexafluoride ($SF_6$) is unsuitable for real street canyons because of its high cost, long response time (~tens of seconds), high warming potential (>23,000 times of $CO_2$ (Li *et al.*, 2019b)) and much heavier density (6.17 kg/m$^3$) than air (1.23 kg/m$^3$) and vehicle emissions (e.g. 1.98 kg/m$^3$ for $CO_2$). In addition, previous experiments usually used a line or point emission source to simulate tailpipe emissions which ignored the dynamics of vehicles. However, neglecting the vehicle-induced turbulence could introduce significant errors to roadside air quality assessment because the pollutant sources and receptors are close to each other in a street canyon. To account for the vehicle-induced dynamics, characterisation of the tailpipe emissions under real driving conditions is needed.

Traditionally, vehicle emissions were measured in laboratory by engine or chassis dynamometers. Real driving emissions (RDE) have attracted great attention in recent years after the discovery of the

Volkswagen scandal in 2015 (Schiermeier, 2015). It involved defeat devices installed on Volkswagen light-duty diesel vehicles that aimed to pass certification tests in the laboratory but emitted tens of times higher $NO_x$ in real-world driving (Li *et al.*, 2018; Oldenkamp *et al.*, 2016; Schiermeier, 2015; Tanaka *et al.*, 2018). The excess diesel RDE (totalling 4.6 million tons from on-road diesel vehicles of 11 major automotive markets) have caused serious air pollution and health problems, resulting in about 38,000 premature deaths globally in 2015 (Anenberg *et al.*, 2017). To address this problem, the portable emission measurement system (PEMS) technique has been developed according to the recent Euro 6d standards (Sep 2019), which realises RDE measurements (Huang *et al.*, 2019b; O'Driscoll *et al.*, 2016).

On the receptor side, existing roadside air quality assessments usually only measured pollutant concentrations at limited locations (Li *et al.*, 2016; Wong *et al.*, 2019), posing challenges for data interpretation due to the high variabilities in space and time (Rakowska *et al.*, 2014; Targino *et al.*, 2016; Wadlow *et al.*, 2019). The recent development of low-cost air quality sensors makes high spatial resolution measurements (e.g. a sensors network) possible (Forehead *et al.*, 2020; Morawska *et al.*, 2018; Popoola *et al.*, 2018). The combination of PEMS and low-cost air sensors will provide a full picture from emission sources to receptors and generate comprehensive and novel datasets for dispersion analysis and model validation. This novel concept has not been reported in the literature to date.

***Numerical simulations:*** Pollutant dispersion models can be categorised into three groups: operational (or Gaussian), CFD (or Eulerian) and Lagrangian models (Bahlali *et al.*, 2019; Li *et al.*, 2006; Trini Castelli *et al.*, 2018). Operational models are mostly Gaussian-based empirical or semi-empirical equations, such as CALINE4 and CPBM. Operational models are very useful tools for routine air quality monitoring and assessment at a relatively low cost. While the major shortcomings of operational models are: 1) they can only provide very limited information; 2) they are inapplicable to different street configurations that have not yet been parameterised; and 3) they are accurate for far-field applications but unsuitable for roadside air quality assessment because the rapid pollutant mixing in vehicle wakes is overlooked. With the rapid increase of computer power, CFD modelling is becoming more popular now. CFD is a powerful and economical tool that can provide detailed and visualised information about turbulent mixing and dispersion. CFD simulates the turbulence field by solving a set of partial differential equations for continuity, momentum (i.e. Navier-Stokes equations), energy and thermodynamic variables (Elger *et al.*, 2012). Based on the resolved turbulence scales, there are mainly two CFD approaches for street canyon investigations, namely the Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) approaches (Huang *et al.*, 2020b; Trini Castelli *et al.*, 2018). RANS simulates all the flow structures using a Reynolds stress equation model (e.g. $k$-$\varepsilon$ and $k$-$\omega$ two-equation models), while LES models the sub-grid scale flow structures but explicitly resolves the larger flow structures. LES is more sophisticated and accurate than RANS, while the drawback is its much higher computational cost. Both RANS and LES approaches are widely adopted for pollutant dispersion modelling in street canyons. Lagrangian particle dispersion models (also called as Lagrangian stochastic models) are developed as a compromise between the lower computational cost of operational models and the higher accuracy of CFD models (Trini Castelli *et al.*, 2018; Wang *et al.*, 2018). Lagrangian models calculate and follow the trajectories of particles in a turbulent flow, and then deduce the concentration field over computational domain based on particle positions (Bahlali *et al.*, 2019; Bellasio *et al.*, 2017; Gomez *et al.*, 2021; Jia *et al.*, 2021). Models have also been developed at system levels (e.g. a city or nation) (Alam *et al.*, 2018; Johansson *et al.*, 2009; Moldanova *et al.*, 2015; Romero *et al.*, 2020; Wu *et al.*, 2017), which can help identify emission sources in urban areas and assist policy making and assessment.

The majority of the studies reviewed in Sections 2 and 3 adopted CFD to investigate vehicle emission dispersion in urban street canyons and its control. However, they were based on highly simplified models, and mostly adopted static computational meshes and assumed line or band emission sources on road surface at constant emission rates. As a result, the effect of vehicle-induced turbulence was not accounted for. However, wakes behind vehicles promote the recirculation and mixing of pollutants, leading to a prolonged retention at pedestrian level. Therefore, ignoring vehicle-induced turbulence would lead to errors in roadside air quality assessment. In addition, due to the lack of real-world experiments, these CFD models have rarely been validated directly against experimental data.

***Control measures:*** Roadside air quality strongly depends on the synergies between the traffic conditions, meteorological conditions, street canyon features and the presence of in-street barriers (Amorim *et al.*, 2013). Roadside air quality in existing street canyons may be improved by implementing some potential emission control measures, such as small trees, hedges, noise barriers and low emission zones. Urban design, such as building height, roof shape and street direction, is also an important factor for roadside air quality management. To date, there is a lack of systematic investigations and generic guidelines of control measures and urban planning for improving roadside air quality, which are of great importance to policy makers and urban planners. As reviewed in Sections 2 and 3, the air quality in street canyons is affected by many factors. Aristodemou *et al.* (2018) demonstrated that even simply changing the height of a single building could create zones with stagnant air and pollution hotspots that did not exist previously. Therefore, carefully assessing the effect of building design on emission dispersion is an important step for maintaining a sustainable and liveable urban environment. Moreover, appropriate strategies need to consider the specific circumstance of individual projects (Yuan *et al.*, 2014).

## 5. Conclusions

Urban streets are important places for social and commercial outdoor activities. However, roadside air pollution poses a serious health threat to the public due to the close proximity to vehicle emissions. Meanwhile, many cities are relaxing building height limits to accommodate the rapidly growing urban population, leading to taller and denser buildings around people. These deep street canyons restrict air ventilation and pollutant removal, which further worsens roadside air pollution but yet are often overlooked in city planning. This paper critically reviews the mechanisms controlling vehicle emission dispersion in urban street canyons and the strategies to mitigate roadside air pollution. The major findings are summarised as follows:

1) Studies have shown that roadside air pollution hotspots are not necessarily all associated with heavy traffic and that proper urban design can help mitigate air pollution noticeably. The key factors that influence roadside air quality are traffic conditions, canyon geometry, weather conditions and chemical reactions. Two groups of mitigation strategies are identified, namely traffic interventions and urban planning.

2) Popular traffic interventions at a street canyon scale include imposing low emission zones and congestion charges which have demonstrated moderate improvements in roadside air quality. More studies are needed to quantify their improvements observed from air quality monitoring stations, as multiple emission control programs are usually implemented simultaneously.

3) Regarding urban planning, the design of overall canyon geometry can significantly improve the emission dispersion process and roadside air quality, while the major limitation of this strategy is that it is only applicable to future street canyons. General design guidelines for overall canyon geometry include lower aspect ratios, streets in parallel to the prevailing wind direction, non-uniform building heights, and high building porosity at the ground level.

4) For existing street canyons, the design of in-street barriers is a widely applicable strategy for improving the roadside air quality. In-street barriers can be classified into porous (e.g. trees and hedges) and solid (e.g. kerbside parked cars, noise barriers and viaducts) barriers. Both types of barriers have the potential to improve roadside air quality by preventing the transport of pollutants from vehicle tailpipes to roadside breathing zones.

5) Current studies on urban street canyons mostly adopted small-scale experiments in wind tunnels or highly simplified CFD models without validation by real-world experimental data. We recommend future studies to confirm the effectiveness of these strategies on improving roadside air quality by real-world experiments and more sophisticated CFD modelling.

## CRediT authorship contribution statement

**Yuhan Huang:** Conceptualization, Investigation, Writing – original draft, Writing - review & editing. **Chengwang Lei:** Supervision, Writing - review & editing. **Chun-Ho Liu:** Writing - review & editing. **Pascal Perez:** Writing - review & editing. **Hugh Forehead:** Writing - review & editing. **Shaofei Kong:** Writing - review & editing. **John L. Zhou:** Supervision, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

AbdelMigid, T.A., Saqr, K.M., Kotb, M.A., *et al.*, 2017. Revisiting the lid-driven cavity flow problem: Review and new steady state benchmarking results using GPU accelerated code. ***Alex. Eng. J.*** 56, 123-135.

Abhijith, K.V., Gokhale, S., 2015. Passive control potentials of trees and on-street parked cars in reduction of air pollution exposure in urban street canyons. ***Environ. Pollut.*** 204, 99-108.

Abhijith, K.V., Kumar, P., Gallagher, J., *et al.*, 2017. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. ***Atmos. Environ.*** 162, 71-86.

Ai, Z.T., Mak, C.M., 2015. From street canyon microclimate to indoor environmental quality in naturally ventilated urban buildings: Issues and possibilities for improvement. ***Build. Environ.*** 94, 489-503.

Alam, M.S., Duffy, P., Hyde, B., *et al.*, 2018. Downscaling national road transport emission to street level: A case study in Dublin, Ireland. ***J. Clean. Prod.*** 183, 797-809.

Amorim, J.H., Rodrigues, V., Tavares, R., *et al.*, 2013. CFD modelling of the aerodynamic effect of trees on urban air pollution dispersion. ***Sci. Total Environ.*** 461-462, 541-551.

Anenberg, S., Miller, J., Henze, D., *et al.*, 2019. A global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015. *The International Council on Clean Transportation*.

Anenberg, S.C., Miller, J., Minjares, R., *et al.*, 2017. Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets. ***Nature*** 545, 467-471.

Aristodemou, E., Boganegra, L.M., Mottet, L., *et al.*, 2018. How tall buildings affect turbulent air flows and dispersion of pollution within a neighbourhood. ***Environ. Pollut.*** 233, 782-796.

Assimakopoulos, V.D., ApSimon, H.M., Moussiopoulos, N., 2003. A numerical study of atmospheric pollutant dispersion in different two-dimensional street canyon configurations. ***Atmos. Environ.*** 37, 4037-4049.

Atkinson, R.W., Barratt, B., Armstrong, B., *et al.*, 2009. The impact of the congestion charging scheme on ambient air pollution concentrations in London. ***Atmos. Environ.*** 43, 5493-5500.

Bahlali, M.L., Dupont, E., Carissimo, B., 2019. Atmospheric dispersion using a Lagrangian stochastic approach: Application to an idealized urban area under neutral and stable meteorological conditions. ***J. Wind Eng. Ind. Aerod.*** 193, 103976.

Baldauf, R., Thoma, E., Khlystov, A., *et al.*, 2008. Impacts of noise barriers on near-road air quality. ***Atmos. Environ.*** 42, 7502-7507.

Baldauf, R.W., Isakov, V., Deshmukh, P., *et al.*, 2016. Influence of solid noise barriers on near-road and on-road air quality. ***Atmos. Environ.*** 129, 265-276.

Beckwith, M., Bates, E., Gillah, A., *et al.*, 2019. NO2 hotspots: Are we measuring in the right places? ***Atmos. Environ. X*** 2, 100025.

Beddows, D.C.S., Harrison, R.M., 2021. PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. ***Atmos. Environ.*** 244, 117886.

Beevers, S.D., Carslaw, D.C., 2005. The impact of congestion charging on vehicle emissions in London. ***Atmos. Environ.*** 39, 1-5.

Bellasio, R., Bianconi, R., Mosca, S., *et al.*, 2017. Formulation of the Lagrangian particle model LAPMOD and its evaluation against Kincaid SF6 and SO2 datasets. ***Atmos. Environ.*** 163, 87-98.

Berkowicz, R., Palmgren, F., Hertel, O., *et al.*, 1996. Using measurements of air pollution in streets for evaluation of urban air quality — meterological analysis and model calculations. ***Sci. Total Environ.*** 189-190, 259-265.

Bishop, G.A., Haugen, M.J., 2018. The Story of Ever Diminishing Vehicle Tailpipe Emissions as Observed in the Chicago, Illinois Area. ***Environ. Sci. Technol.*** 52, 7587-7593.

Bishop, G.A., Stedman, D.H., Burgard, D.A., *et al.*, 2016. High-Mileage Light-Duty Fleet Vehicle Emissions: Their Potentially Overlooked Importance. ***Environ. Sci. Technol.*** 50, 5405-5411.

Boddy, J.W.D., Smalley, R.J., Dixon, N.S., *et al.*, 2005. The spatial variability in concentrations of a traffic-related pollutant in two street canyons in York, UK—Part I: The influence of background winds. ***Atmos. Environ.*** 39, 3147-3161.

Boogaard, H., Janssen, N.A.H., Fischer, P.H., *et al.*, 2012. Impact of low emission zones and local traffic policies on ambient air pollution concentrations. ***Sci. Total Environ.*** 435-436, 132-140.

Bright, V.B., Bloss, W.J., Cai, X., 2013. Urban street canyons: Coupling dynamics, chemistry and within-canyon chemical processing of emissions. ***Atmos. Environ.*** 68, 127-142.

Brimblecombe, P., Ning, Z., 2015. Effect of road blockages on local air pollution during the Hong Kong protests and its implications for air quality management. ***Sci. Total Environ.*** 536, 443-448.

Calfapietra, C., Fares, S., Manes, F., *et al.*, 2013. Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review. ***Environ. Pollut.*** 183, 71-80.

Cao, B., Yin, Z., 2020. Future atmospheric circulations benefit ozone pollution control in Beijing-Tianjin-Hebei with global warming. ***Sci. Total Environ.*** 743, 140645.

Carslaw, D.C., Beevers, S.D., Tate, J.E., *et al.*, 2011. Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. ***Atmos. Environ.*** 45, 7053-7063.

Chan, T.L., Dong, G., Leung, C.W., *et al.*, 2002. Validation of a two-dimensional pollutant dispersion model in an isolated street canyon. ***Atmos. Environ.*** 36, 861-872.

Chen, G., Yang, X., Yang, H., *et al.*, 2020. The influence of aspect ratios and solar heating on flow and ventilation in 2D street canyons by scaled outdoor experiments. ***Build. Environ.*** 185, 107159.

Chew, L.W., Norford, L.K., 2018. Pedestrian-level wind speed enhancement in urban street canyons with void decks. ***Build. Environ.*** 146, 64-76.

Chew, L.W., Norford, L.K., 2019. Pedestrian-level wind speed enhancement with void decks in three-dimensional urban street canyons. ***Build. Environ.*** 155, 399-407.

Choudhary, A., Gokhale, S., 2016. Urban real-world driving traffic emissions during interruption and congestion. ***Transp. Res. Part D*** 43, 59-70.

Coria, J., Bonilla, J., Grundström, M., *et al.*, 2015. Air pollution dynamics and the need for temporally differentiated road pricing. ***Transp. Res. Part A*** 75, 178-195.

Ding, S., Huang, Y., Cui, P., *et al.*, 2019. Impact of viaduct on flow reversion and pollutant dispersion in 2D urban street canyon with different roof shapes - Numerical simulation and wind tunnel experiment. ***Sci. Total Environ.*** 671, 976-991.

Dirks, K.N., Wang, J.Y.T., Khan, A., *et al.*, 2016. Air Pollution Exposure in Relation to the Commute to School: A Bradford UK Case Study. ***Int. J. Environ. Res. Public Health*** 13, 1064.

Eisenman, T.S., Churkina, G., Jariwala, S.P., *et al.*, 2019. Urban trees, air quality, and asthma: An interdisciplinary review. ***Landsc. Urban Plan.*** 187, 47-59.

Elger, D.F., Williams, B.C., Crowe, C.T., *et al.*, 2012. Engineering Fluid Mechanics (10th Edition). Wiley.

Ellison, R.B., Greaves, S.P., Hensher, D.A., 2013. Five years of London’s low emission zone: Effects on vehicle fleet composition and air quality. ***Transp. Res. Part D*** 23, 25-33.

Enayati Ahangar, F., Heist, D., Perry, S., *et al.*, 2017. Reduction of air pollution levels downwind of a road with an upwind noise barrier. ***Atmos. Environ.*** 155, 1-10.

Fensterer, V., Küchenhoff, H., Maier, V., *et al.*, 2014. Evaluation of the Impact of Low Emission Zone and Heavy Traffic Ban in Munich (Germany) on the Reduction of PM10 in Ambient Air. ***Int. J. Environ. Res. Public Health*** 11, 5094-5112.

Ferreira, F., Gomes, P., Tente, H., *et al.*, 2015. Air quality improvements following implementation of Lisbon's Low Emission Zone. ***Atmos. Environ.*** 122, 373-381.

Forehead, H., Barthelemy, J., Arshad, B., *et al.*, 2020. Traffic exhaust to wildfires: PM2.5 measurements with fixed and portable, low-cost LoRaWAN-connected sensors. ***PLOS ONE*** 15, e0231778.

Forehead, H., Huynh, N., 2018. Review of modelling air pollution from traffic at street-level - The state of the science. ***Environ. Pollut.*** 241, 775-786.

Fu, X., Liu, J., Ban-Weiss, G.A., *et al.*, 2017. Effects of canyon geometry on the distribution of traffic-related air pollution in a large urban area: Implications of a multi-canyon air pollution dispersion model. ***Atmos. Environ.*** 165, 111-121.

Fuso Nerini, F., Sovacool, B., Hughes, N., *et al.*, 2019. Connecting climate action with other Sustainable Development Goals. ***Nat. Sustain.*** 2, 674-680.

Gallagher, J., Baldauf, R., Fuller, C.H., *et al.*, 2015. Passive methods for improving air quality in the built environment: A review of porous and solid barriers. ***Atmos. Environ.*** 120, 61-70.

Gallagher, J., Gill, L.W., McNabola, A., 2011. Optimizing the use of on-street car parking system as a passive control of air pollution exposure in street canyons by large eddy simulation. ***Atmos. Environ.*** 45, 1684-1694.

Gallagher, J., Gill, L.W., McNabola, A., 2013. The passive control of air pollution exposure in Dublin, Ireland: A combined measurement and modelling case study. ***Sci. Total Environ.*** 458-460, 331-343.

Gallagher, J., Lago, C., 2019. How parked cars affect pollutant dispersion at street level in an urban street canyon? A CFD modelling exercise assessing geometrical detailing and pollutant decay rates. ***Sci. Total Environ.*** 651, 2410-2418.

Gehrig, R., Zeyer, K., Bukowiecki, N., *et al.*, 2010. Mobile load simulators – A tool to distinguish between the emissions due to abrasion and resuspension of PM10 from road surfaces. ***Atmos. Environ.*** 44, 4937-4943.

Gehrsitz, M., 2017. The effect of low emission zones on air pollution and infant health. ***J. Environ. Econ. Manag.*** 83, 121-144.

Gentner, D.R., Xiong, F., 2017. Tracking pollutant emissions. ***Nat. Geosci.*** 10, 883-884.

Giechaskiel, B., Suarez-Bertoa, R., Lähde, T., *et al.*, 2018. Evaluation of NOx emissions of a retrofitted Euro 5 passenger car for the Horizon prize "Engine retrofit". ***Environ. Res.*** 166, 298-309.

Gomez, F., Ribstein, B., Makké, L., *et al.*, 2021. Simulation of a dense gas chlorine release with a Lagrangian particle dispersion model (LPDM). ***Atmos. Environ.*** 244, 117791.

Grange, S.K., Lewis, A.C., Moller, S.J., *et al.*, 2017. Lower vehicular primary emissions of NO2 in Europe than assumed in policy projections. ***Nat. Geosci.*** 10, 914-918.

Grawe, D., Cai, X.-M., Harrison, R.M., 2007. Large eddy simulation of shading effects on NO2 and O3 concentrations within an idealised street canyon. ***Atmos. Environ.*** 41, 7304-7314.

Green, C.P., Heywood, J.S., Navarro Paniagua, M., 2020. Did the London congestion charge reduce pollution? ***Reg. Sci. Urban Econ.*** 84, 103573.

Gromke, C., Blocken, B., 2015. Influence of avenue-trees on air quality at the urban neighborhood scale. Part II: Traffic pollutant concentrations at pedestrian level. ***Environ. Pollut.*** 196, 176-184.

Gromke, C., Jamarkattel, N., Ruck, B., 2016. Influence of roadside hedgerows on air quality in urban street canyons. ***Atmos. Environ.*** 139, 75-86.

Gromke, C., Ruck, B., 2007. Influence of trees on the dispersion of pollutants in an urban street canyon—Experimental investigation of the flow and concentration field. ***Atmos. Environ.*** 41, 3287-3302.

Gu, Z.-L., Zhang, Y.-W., Cheng, Y., *et al.*, 2011. Effect of uneven building layout on air flow and pollutant dispersion in non-uniform street canyons. ***Build. Environ.*** 46, 2657-2665.

Hagler, G.S.W., Lin, M.-Y., Khlystov, A., *et al.*, 2012. Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. ***Sci. Total Environ.*** 419, 7-15.

Hagler, G.S.W., Tang, W., Freeman, M.J., *et al.*, 2011. Model evaluation of roadside barrier impact on near-road air pollution. ***Atmos. Environ.*** 45, 2522-2530.

Han, D., Shen, H., Duan, W., *et al.*, 2020. A review on particulate matter removal capacity by urban forests at different scales. ***Urban For. Urban Green.*** 48, 126565.

Hang, J., Luo, Z., Wang, X., *et al.*, 2017. The influence of street layouts and viaduct settings on daily carbon monoxide exposure and intake fraction in idealized urban canyons. ***Environ. Pollut.*** 220, 72-86.

Hao, C., Xie, X., Huang, Y., *et al.*, 2019. Study on influence of viaduct and noise barriers on the particulate matter dispersion in street canyons by CFD modeling. ***Atmos. Pollut. Res.*** 10, 1723-1735.

Hargreaves, D.M., Baker, C.J., 1997. Gaussian puff model of an urban street canyon. ***J. Wind Eng. Ind. Aerod.*** 69-71, 927-939.

Hatzopoulou, M., Weichenthal, S., Dugum, H., *et al.*, 2013. The impact of traffic volume, composition, and road geometry on personal air pollution exposures among cyclists in Montreal, Canada. ***J. Expo. Sci. Environ. Epidemiol.*** 23, 46-51.

He, B.-J., Ding, L., Prasad, D., 2019. Enhancing urban ventilation performance through the development of precinct ventilation zones: A case study based on the Greater Sydney, Australia. ***Sustain. Cities Soc.*** 47, 101472.

He, L., Hang, J., Wang, X., *et al.*, 2017. Numerical investigations of flow and passive pollutant exposure in high-rise deep street canyons with various street aspect ratios and viaduct settings. ***Sci. Total Environ.*** 584-585, 189-206.

Hien, W.N., 2016. Urban heat island research: Challenges and potential. ***Frontiers of Architectural Research*** 5, 276-278.

Holman, C., Harrison, R., Querol, X., 2015. Review of the efficacy of low emission zones to improve urban air quality in European cities. ***Atmos. Environ.*** 111, 161-169.

Huang, Y.-D., He, W.-R., Kim, C.-N., 2015. Impacts of shape and height of upstream roof on airflow and pollutant dispersion inside an urban street canyon. ***Environ. Sci. Pollut. Res.*** 22, 2117-2137.

Huang, Y.-D., Xu, X., Liu, Z.-Y., *et al.*, 2016. Impacts of shape and height of building roof on airflow and pollutant dispersion inside an isolated street canyon. ***Environ. Forensics*** 17, 361-379.

Huang, Y., Mok, W.-c., Yam, Y.-s., *et al.*, 2020a. Evaluating in-use vehicle emissions using air quality monitoring stations and on-road remote sensing systems. ***Sci. Total Environ.*** 740, 139868.

Huang, Y., Ng, E.C.Y., Surawski, N.C., *et al.*, 2020b. Large eddy simulation of vehicle emissions dispersion: Implications for on-road remote sensing measurements. ***Environ. Pollut.*** 259, 113974.

Huang, Y., Ng, E.C.Y., Yam, Y.-s., *et al.*, 2019a. Impact of potential engine malfunctions on fuel consumption and gaseous emissions of a Euro VI diesel truck. ***Energy Convers. Manage.*** 184, 521-529.

Huang, Y., Ng, E.C.Y., Zhou, J.L., *et al.*, 2018a. Eco-driving technology for sustainable road transport: A review. ***Renew. Sustain. Energy Rev.*** 93, 596-609.

Huang, Y., Organ, B., Zhou, J.L., *et al.*, 2018b. Emission measurement of diesel vehicles in Hong Kong through on-road remote sensing: Performance review and identification of high-emitters. ***Environ. Pollut.*** 237, 133-142.

Huang, Y., Organ, B., Zhou, J.L., *et al.*, 2018c. Remote sensing of on-road vehicle emissions: Mechanism, applications and a case study from Hong Kong. ***Atmos. Environ.*** 182, 58-74.

Huang, Y., Surawski, N.C., Organ, B., *et al.*, 2019b. Fuel consumption and emissions performance under real driving: Comparison between hybrid and conventional vehicles. ***Sci. Total Environ.*** 659, 275-282.

Huang, Y., Surawski, N.C., Yam, Y.S., *et al.*, 2020c. Re-evaluating effectiveness of vehicle emission control programs targeting high-emitters. ***Nat. Sustain.*** 3, 904-907.

Huang, Y., Yam, Y.S., Lee, C.K.C., *et al.*, 2018d. Tackling nitric oxide emissions from dominant diesel vehicle models using on-road remote sensing technology. ***Environ. Pollut.*** 243, 1177-1185.

Huang, Y., Zhou, J.L., Yu, Y., *et al.*, 2020d. Uncertainty in the Impact of the COVID-19 Pandemic on Air Quality in Hong Kong, China. ***Atmosphere*** 11, 914.

Huong Giang, N.T., Kim Oanh, N.T., 2014. Roadside levels and traffic emission rates of PM2.5 and BTEX in Ho Chi Minh City, Vietnam. ***Atmos. Environ.*** 94, 806-816.

IEA, 2020. Global EV Outlook 2020. *International Energy Agency*.

Jamei, E., Ossen, D.R., Seyedmahmoudian, M., *et al.*, 2020. Urban design parameters for heat mitigation in tropics. ***Renew. Sustain. Energy Rev.*** 134, 110362.

Janhäll, S., 2015. Review on urban vegetation and particle air pollution – Deposition and dispersion. ***Atmos. Environ.*** 105, 130-137.

Jeanjean, A.P.R., Buccolieri, R., Eddy, J., *et al.*, 2017. Air quality affected by trees in real street canyons: The case of Marylebone neighbourhood in central London. ***Urban For. Urban Green.*** 22, 41-53.

Jia, M., Huang, X., Ding, K., *et al.*, 2021. Impact of data assimilation and aerosol radiation interaction on Lagrangian particle dispersion modelling. ***Atmos. Environ.*** 247, 118179.

Jicha, M., Pospisil, J., Katolicky, J., 2000. Dispersion of Pollutants in Street Canyon under Traffic Induced Flow and Turbulence. ***Environ. Monit. Assess.*** 65, 343-351.

Johansson, C., Burman, L., Forsberg, B., 2009. The effects of congestions tax on air quality and health. ***Atmos. Environ.*** 43, 4843-4854.

Kalghatgi, G., 2018. Is it really the end of internal combustion engines and petroleum in transport? ***Appl. Energy*** 225, 965-974.

Kang, Y.-S., Baik, J.-J., Kim, J.-J., 2008. Further studies of flow and reactive pollutant dispersion in a street canyon with bottom heating. ***Atmos. Environ.*** 42, 4964-4975.

Karagulian, F., Belis, C.A., Dora, C.F.C., *et al.*, 2015. Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. ***Atmos. Environ.*** 120, 475-483.

Kastner-Klein, P., Fedorovich, E., Rotach, M.W., 2001. A wind tunnel study of organised and turbulent air motions in urban street canyons. ***J. Wind Eng. Ind. Aerod.*** 89, 849-861.

Ke, W., Zhang, S., Wu, Y., *et al.*, 2017. Assessing the Future Vehicle Fleet Electrification: The Impacts on Regional and Urban Air Quality. ***Environ. Sci. Technol.*** 51, 1007-1016.

Kean, A.J., Harley, R.A., Kendall, G.R., 2003. Effects of Vehicle Speed and Engine Load on Motor Vehicle Emissions. ***Environ. Sci. Technol.*** 37, 3739-3746.

Kessler, R., 2013. Green Walls Could Cut Street-Canyon Air Pollution. ***Environ. Health Perspect.*** 121, a14-a14.

Kim, J.-J., Baik, J.-J., 2004. A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyons using the RNG k–ε turbulence model. ***Atmos. Environ.*** 38, 3039-3048.

Koch, K., Ysebaert, T., Denys, S., *et al.*, 2020. Urban heat stress mitigation potential of green walls: A review. ***Urban For. Urban Green.*** 55, 126843.

Kurppa, M., Hellsten, A., Auvinen, M., *et al.*, 2018. Ventilation and Air Quality in City Blocks Using Large-Eddy Simulation—Urban Planning Perspective. ***Atmosphere*** 9, 65.

Kwak, K.-H., Baik, J.-J., 2014. Diurnal variation of NOx and ozone exchange between a street canyon and the overlying air. ***Atmos. Environ.*** 86, 120-128.

Lai, D., Liu, W., Gan, T., *et al.*, 2019. A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. ***Sci. Total Environ.*** 661, 337-353.

Lai, H.-K., Hedley, A.J., Thach, T.Q., *et al.*, 2013. A method to derive the relationship between the annual and short-term air quality limits—Analysis using the WHO Air Quality Guidelines for health protection. ***Environ. Int.*** 59, 86-91.

Lavee, D., Moshe, A., Berman, I., 2014. Accelerated vehicle retirement program: Estimating the optimal incentive payment in Israel. ***Transp. Res. Part D*** 26, 1-9.

Lee, E.S., Ranasinghe, D.R., Ahangar, F.E., *et al.*, 2018. Field evaluation of vegetation and noise barriers for mitigation of near-freeway air pollution under variable wind conditions. ***Atmos. Environ.*** 175, 92-99.

Lee, H., Mayer, H., Kuttler, W., 2020. Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E-W urban street canyons under Central European conditions. ***Urban For. Urban Green.*** 48, 126558.

Li, L., McMurray, A., Xue, J., *et al.*, 2018. Industry-wide corporate fraud: The truth behind the Volkswagen scandal. ***J. Clean. Prod.*** 172, 3167-3175.

Li, X.-B., Lu, Q.-C., Lu, S.-J., *et al.*, 2016. The impacts of roadside vegetation barriers on the dispersion of gaseous traffic pollution in urban street canyons. ***Urban For. Urban Green.*** 17, 80-91.

Li, X.-X., Liu, C.-H., Leung, D.Y.C., *et al.*, 2006. Recent progress in CFD modelling of wind field and pollutant transport in street canyons. ***Atmos. Environ.*** 40, 5640-5658.

Li, X., Zhou, Y., Yu, S., *et al.*, 2019a. Urban heat island impacts on building energy consumption: A review of approaches and findings. ***Energy*** 174, 407-419.

Li, Y., Zhang, X., Zhang, J., *et al.*, 2019b. Assessment on the toxicity and application risk of C4F7N: A new SF6 alternative gas. ***J. Hazard. Mater.*** 368, 653-660.

Liang, X., Zhang, S., Wu, Y., *et al.*, 2019. Air quality and health benefits from fleet electrification in China. ***Nat. Sustain.*** 2, 962-971.

Llaguno-Munitxa, M., Bou-Zeid, E., 2018. Shaping buildings to promote street ventilation: A large-eddy simulation study. ***Urban Clim.*** 26, 76-94.

Matthias, V., Bieser, J., Mocanu, T., *et al.*, 2020. Modelling road transport emissions in Germany – Current day situation and scenarios for 2040. ***Transp. Res. Part D*** 87, 102536.

Miao, C., Yu, S., Hu, Y., *et al.*, 2020. How the morphology of urban street canyons affects suspended particulate matter concentration at the pedestrian level: An in-situ investigation. ***Sustain. Cities Soc.*** 55, 102042.

Mika, J., Forgo, P., Lakatos, L., *et al.*, 2018. Impact of 1.5K global warming on urban air pollution and heat island with outlook on human health effects. ***Current Opinion in Environmental Sustainability*** 30, 151-159.

Mishra, R.K., Pandey, A., Pandey, G., *et al.*, 2019. The effect of odd-even driving scheme on PM2.5 and PM1.0 emission. ***Transp. Res. Part D*** 67, 541-552.

Miskell, G., Salmond, J., Longley, I., *et al.*, 2015. A Novel Approach in Quantifying the Effect of Urban Design Features on Local-Scale Air Pollution in Central Urban Areas. ***Environ. Sci. Technol.*** 49, 9004-9011.

Moldanova, J., Tang, L., Gustafsson, M., *et al.*, 2015. Emissions from traffic with alternative fuels - air pollutants and health risks in 2020. *IVL Swedish Environmental Research Institute*.

Moradpour, M., Afshin, H., Farhanieh, B., 2017. A numerical investigation of reactive air pollutant dispersion in urban street canyons with tree planting. ***Atmos. Pollut. Res.*** 8, 253-266.

Morawska, L., Thai, P.K., Liu, X., *et al.*, 2018. Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? ***Environ. Int.*** 116, 286-299.

Morfeld, P., Groneberg, D.A., Spallek, M.F., 2014. Effectiveness of Low Emission Zones: Large Scale Analysis of Changes in Environmental NO2, NO and NOx Concentrations in 17 German Cities. ***PLOS ONE*** 9, e102999.

Mudway, I.S., Dundas, I., Wood, H.E., *et al.*, 2019. Impact of London's low emission zone on air quality and children's respiratory health: a sequential annual cross-sectional study. ***Lancet Public Health*** 4, e28-e40.

Murena, F., Garofalo, N., Favale, G., 2008. Monitoring CO concentration at leeward and windward sides in a deep street canyon. ***Atmos. Environ.*** 42, 8204-8210.

Neira, M., 2018. Health must be the number one priority for urban planners. *World Health Organization*.

Ng, E., 2009. Designing High-Density Cities: For Social and Environmental Sustainability. Taylor & Francis Group.

Ning, Z., Hudda, N., Daher, N., *et al.*, 2010. Impact of roadside noise barriers on particle size distributions and pollutants concentrations near freeways. ***Atmos. Environ.*** 44, 3118-3127.

Nosek, Š., Fuka, V., Kukačka, L., *et al.*, 2018. Street-canyon pollution with respect to urban-array complexity: The role of lateral and mean pollution fluxes. ***Build. Environ.*** 138, 221-234.

O'Driscoll, R., ApSimon, H.M., Oxley, T., *et al.*, 2016. A Portable Emissions Measurement System (PEMS) study of NOx and primary NO2 emissions from Euro 6 diesel passenger cars and comparison with COPERT emission factors. ***Atmos. Environ.*** 145, 81-91.

Oldenkamp, R., van Zelm, R., Huijbregts, M.A.J., 2016. Valuing the human health damage caused by the fraud of Volkswagen. ***Environ. Pollut.*** 212, 121-127.

Organ, B., Huang, Y., Zhou, J.L., *et al.*, 2019. A remote sensing emissions monitoring programme reduces emissions of gasoline and LPG vehicles. ***Environ. Res.*** 177, 108614.

Organ, B., Huang, Y., Zhou, J.L., *et al.*, 2020. Simulation of engine faults and their impact on emissions and vehicle performance for a liquefied petroleum gas taxi. ***Sci. Total Environ.*** 716, 137066.

Ow, L.F., Ghosh, S., 2017. Urban cities and road traffic noise: Reduction through vegetation. ***Appl. Acoust.*** 120, 15-20.

Panteliadis, P., Strak, M., Hoek, G., *et al.*, 2014. Implementation of a low emission zone and evaluation of effects on air quality by long-term monitoring. ***Atmos. Environ.*** 86, 113-119.

Park, S.-J., Kim, J.-J., Kim, M.J., *et al.*, 2015. Characteristics of flow and reactive pollutant dispersion in urban street canyons. ***Atmos. Environ.*** 108, 20-31.

Parker, J., 2021. The Leeds urban heat island and its implications for energy use and thermal comfort. ***Energy and Buildings*** 235, 110636.

Parravicini, M., Barro, C., Boulouchos, K., 2021. Experimental characterization of GTL, HVO, and OME based alternative fuels for diesel engines. ***Fuel*** 292, 120177.

Pascal, M., Wagner, V., Alari, A., *et al.*, 2021. Extreme heat and acute air pollution episodes: A need for joint public health warnings? ***Atmos. Environ.*** 249, 118249.

Popoola, O.A.M., Carruthers, D., Lad, C., *et al.*, 2018. Use of networks of low cost air quality sensors to quantify air quality in urban settings. ***Atmos. Environ.*** 194, 58-70.

Posada, F., Yang, Z., Muncrief, R., 2015. Review of Current Practices and New Developments in Heavy-Duty Vehicle Inspection and Maintenance Programs. *The International Council on Clean Transportation*.

Pujadas, M., Domínguez-Sáez, A., De la Fuente, J., 2017. Real-driving emissions of circulating Spanish car fleet in 2015 using RSD Technology. ***Sci. Total Environ.*** 576, 193-209.

Rakowska, A., Wong, K.C., Townsend, T., *et al.*, 2014. Impact of traffic volume and composition on the air quality and pedestrian exposure in urban street canyon. ***Atmos. Environ.*** 98, 260-270.

Ranasinghe, D., Lee, E.S., Zhu, Y., *et al.*, 2019. Effectiveness of vegetation and sound wall-vegetation combination barriers on pollution dispersion from freeways under early morning conditions. ***Sci. Total Environ.*** 658, 1549-1558.

Reitz, R.D., Ogawa, H., Payri, R., *et al.*, 2020. IJER editorial: The future of the internal combustion engine. ***Int. J. Engine Res.*** 21, 3-10.

Romero, Y., Chicchon, N., Duarte, F., *et al.*, 2020. Quantifying and spatial disaggregation of air pollution emissions from ground transportation in a developing country context: Case study for the Lima Metropolitan Area in Peru. ***Sci. Total Environ.*** 698, 134313.

Santamouris, M., 2020. Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. ***Energy and Buildings*** 207, 109482.

Santiago, J.-L., Buccolieri, R., Rivas, E., *et al.*, 2019. On the Impact of Trees on Ventilation in a Real Street in Pamplona, Spain. ***Atmosphere*** 10, 697.

Scaperdas, A., Colvile, R.N., 1999. Assessing the representativeness of monitoring data from an urban intersection site in central London, UK. ***Atmos. Environ.*** 33, 661-674.

Schiermeier, Q., 2015. The science behind the Volkswagen emissions scandal. https://www.nature.com/news/the-science-behind-the-volkswagen-emissions-scandal-1.18426.

Sculthorpe, T., 2016. Highrise Britain! Government is set to relax height restrictions on buildings in desperate effort to tackle homes shortage. Daily Mail. https://www.dailymail.co.uk/news/article-3945440/Highrise-Britain-Government-set-relax-height-restrictions-buildings-desperate-effort-tackle-homes-shortage.html <accessed 11.09.2020>.

Shen, L., Zhao, T., Wang, H., *et al.*, 2021. Importance of meteorology in air pollution events during the city lockdown for COVID-19 in Hubei Province, Central China. ***Sci. Total Environ.*** 754, 142227.

Shi, Y., Lau, K.K.-L., Ng, E., 2016. Developing Street-Level PM2.5 and PM10 Land Use Regression Models in High-Density Hong Kong with Urban Morphological Factors. ***Environ. Sci. Technol.*** 50, 8178-8187.

Sicard, P., Agathokleous, E., Araminiene, V., *et al.*, 2018. Should we see urban trees as effective solutions to reduce increasing ozone levels in cities? ***Environ. Pollut.*** 243, 163-176.

Soulhac, L., Perkins, R.J., Salizzoni, P., 2008. Flow in a Street Canyon for any External Wind Direction. ***Boundary-Layer Meteorol.*** 126, 365-388.

Soulhac, L., Salizzoni, P., 2010. Dispersion in a street canyon for a wind direction parallel to the street axis. ***J. Wind Eng. Ind. Aerod.*** 98, 903-910.

Sousa, R.G., Poole, R.J., Afonso, A.M., *et al.*, 2016. Lid-driven cavity flow of viscoelastic liquids. ***J. Non-Newton. Fluid Mech.*** 234, 129-138.

Střižík, M., Zelinger, Z., Kubát, P., *et al.*, 2016. Influence of photochemical processes on traffic-related airborne pollutants in urban street canyon. ***J. Atmos. Sol. Terr. Phys.*** 147, 1-10.

Takano, Y., Moonen, P., 2013. On the influence of roof shape on flow and dispersion in an urban street canyon. ***J. Wind Eng. Ind. Aerod.*** 123, 107-120.

Tanaka, K., Lund, M.T., Aamaas, B., *et al.*, 2018. Climate effects of non-compliant Volkswagen diesel cars. ***Environ. Res. Lett.*** 13, 044020.

Targino, A.C., Gibson, M.D., Krecl, P., *et al.*, 2016. Hotspots of black carbon and PM2.5 in an urban area and relationships to traffic characteristics. ***Environ. Pollut.*** 218, 475-486.

Tartakovsky, D., Kordova – Biezuner, L., Berlin, E., *et al.*, 2020. Air quality impacts of the low emission zone policy in Haifa. ***Atmos. Environ.*** 232, 117472.

Taylor, A., 2019. The sky's the limit: Developers and councils transforming Sydney into Manhattan. https://www.smh.com.au/national/nsw/the-sky-s-the-limit-developers-and-councils-transforming-sydney-into-manhattan-20191018-p53207.html.

Thaker, P., Gokhale, S., 2016. The impact of traffic-flow patterns on air quality in urban street canyons. ***Environ. Pollut.*** 208, 161-169.

The Automobile Association, 2021. Limits to improve air quality and health. https://www.theaa.com/driving-advice/fuels-environment/euro-emissions-standards <accessed 24.02.2021>.

The Lancet, 2006. WHO's global air-quality guidelines. ***The Lancet*** 368, 1302.

Thouron, L., Seigneur, C., Kim, Y., *et al.*, 2018. Intercomparison of three modeling approaches for traffic-related road dust resuspension using two experimental data sets. ***Transp. Res. Part D*** 58, 108-121.

Timmers, V.R.J.H., Achten, P.A.J., 2016. Non-exhaust PM emissions from electric vehicles. ***Atmos. Environ.*** 134, 10-17.

Tiwari, A., Kumar, P., Baldauf, R., *et al.*, 2019. Considerations for evaluating green infrastructure impacts in microscale and macroscale air pollution dispersion models. ***Sci. Total Environ.*** 672, 410-426.

Tiwary, A., Robins, A., Namdeo, A., *et al.*, 2011. Air flow and concentration fields at urban road intersections for improved understanding of personal exposure. ***Environ. Int.*** 37, 1005-1018.

Tomlin, A.S., Smalley, R.J., Tate, J.E., *et al.*, 2009. A field study of factors influencing the concentrations of a traffic-related pollutant in the vicinity of a complex urban junction. ***Atmos. Environ.*** 43, 5027-5037.

Tomson, M., Kumar, P., Barwise, Y., *et al.*, 2021. Green infrastructure for air quality improvement in street canyons. ***Environ. Int.*** 146, 106288.

Tong, N.Y.O., Leung, D.Y.C., 2012. Effects of building aspect ratio, diurnal heating scenario, and wind speed on reactive pollutant dispersion in urban street canyons. ***J. Environ. Sci.*** 24, 2091-2103.

Tong, Z., Baldauf, R.W., Isakov, V., *et al.*, 2016. Roadside vegetation barrier designs to mitigate near-road air pollution impacts. ***Sci. Total Environ.*** 541, 920-927.

Tonne, C., Beevers, S., Armstrong, B., *et al.*, 2008. Air pollution and mortality benefits of the London Congestion Charge: spatial and socioeconomic inequalities. ***Occup. Environ. Med.*** 65, 620-627.

Transport for London, 2020. Congestion charge. https://tfl.gov.uk/modes/driving/congestion-charge <accessed 25.10.2020>.

Trini Castelli, S., Armand, P., Tinarelli, G., *et al.*, 2018. Validation of a Lagrangian particle dispersion model with wind tunnel and field experiments in urban environment. ***Atmos. Environ.*** 193, 273-289.

Tsai, M.Y., Chen, K.S., 2004. Measurements and three-dimensional modeling of air pollutant dispersion in an Urban Street Canyon. ***Atmos. Environ.*** 38, 5911-5924.

Ulpiani, G., 2021. On the linkage between urban heat island and urban pollution island: Three-decade literature review towards a conceptual framework. ***Sci. Total Environ.*** 751, 141727.

United Nations, 2019. World Urbanization Prospects 2018 - Highlights. *Department of Economic and Social Affairs, Population Division*.

Vardoulakis, S., Fisher, B.E.A., Pericleous, K., *et al.*, 2003. Modelling air quality in street canyons: a review. ***Atmos. Environ.*** 37, 155-182.

Vardoulakis, S., Gonzalez-Flesca, N., Fisher, B.E.A., 2002. Assessment of traffic-related air pollution in two street canyons in Paris: implications for exposure studies. ***Atmos. Environ.*** 36, 1025-1039.

Vierth, I., Lindgren, S., Lindgren, H., 2018. Vehicle Weight, Modal Split, and Emissions—An Ex-Post Analysis for Sweden. ***Sustainability*** 10, 1731.

Vos, P.E.J., Maiheu, B., Vankerkom, J., *et al.*, 2013. Improving local air quality in cities: To tree or not to tree? ***Environ. Pollut.*** 183, 113-122.

Vranckx, S., Vos, P., Maiheu, B., *et al.*, 2015. Impact of trees on pollutant dispersion in street canyons: A numerical study of the annual average effects in Antwerp, Belgium. ***Sci. Total Environ.*** 532, 474-483.

Wadlow, I., Paton-Walsh, C., Forehead, H., *et al.*, 2019. Understanding Spatial Variability of Air Quality in Sydney: Part 2—A Roadside Case Study. ***Atmosphere*** 10, 217.

Wagner, V., Rutherford, D., 2013. Survey of best practices in emission control of in-use heavy-duty diesel vehicles. *The International Council on Clean Transportation*.

Wang, C., Li, Q., Wang, Z.-H., 2018. Quantifying the impact of urban trees on passive pollutant dispersion using a coupled large-eddy simulation–Lagrangian stochastic model. ***Build. Environ.*** 145, 33-49.

Wang, C., Wang, Z.-H., Kaloush, K.E., *et al.*, 2021. Perceptions of urban heat island mitigation and implementation strategies: survey and gap analysis. ***Sustain. Cities Soc.*** 66, 102687.

Wang, L., Su, J., Gu, Z., *et al.*, 2020. Numerical study on flow field and pollutant dispersion in an ideal street canyon within a real tree model at different wind velocities. ***Comput. Math. Appl.***

Wang, N., Lyu, X., Deng, X., *et al.*, 2019a. Aggravating O3 pollution due to NOx emission control in eastern China. ***Sci. Total Environ.*** 677, 732-744.

Wang, P., Zhao, D., Wang, W., *et al.*, 2011. Thermal Effect on Pollutant Dispersion in an Urban Street Canyon. ***Int. J. Environ. Res.*** 5, 813-820.

Wang, Q., Fang, W., de Richter, R., *et al.*, 2019b. Effect of moving vehicles on pollutant dispersion in street canyon by using dynamic mesh updating method. ***J. Wind Eng. Ind. Aerod.*** 187, 15-25.

Weinbruch, S., Worringen, A., Ebert, M., *et al.*, 2014. A quantitative estimation of the exhaust, abrasion and resuspension components of particulate traffic emissions using electron microscopy. ***Atmos. Environ.*** 99, 175-182.

WHO, 2020. WHO Global Urban Ambient Air Pollution Database (update 2016). https://www.who.int/phe/health_topics/outdoorair/databases/cities/en/ <accessed 09.09.2020>.

WHO, 2021. Ambient air pollution - a major threat to health and climate. https://www.who.int/airpollution/ambient/en/ <accessed 20.01.2021>.

Wong, P.P.Y., Lai, P.-C., Allen, R., *et al.*, 2019. Vertical monitoring of traffic-related air pollution (TRAP) in urban street canyons of Hong Kong. ***Sci. Total Environ.*** 670, 696-703.

Wu, K., Chen, Y., Ma, J., *et al.*, 2017. Traffic and emissions impact of congestion charging in the central Beijing urban area: A simulation analysis. ***Transp. Res. Part D*** 51, 203-215.

Xia, J., Leung, D.Y.C., 2001. Pollutant dispersion in urban street canopies. ***Atmos. Environ.*** 35, 2033-2043.

Xie, S., Zhang, Y., Qi, L., *et al.*, 2003. Spatial distribution of traffic-related pollutant concentrations in street canyons. ***Atmos. Environ.*** 37, 3213-3224.

Xie, X., Huang, Z., Wang, J.-s., 2005. Impact of building configuration on air quality in street canyon. ***Atmos. Environ.*** 39, 4519-4530.

Xie, X., Huang, Z., Wang, J., 2006. The impact of urban street layout on local atmospheric environment. ***Build. Environ.*** 41, 1352-1363.

Xie, X., Tou, X., Zhang, L., 2017. Effect analysis of air pollution control in Beijing based on an odd-and-even license plate model. ***J. Clean. Prod.*** 142, 936-945.

Xing, Y., Brimblecombe, P., Ning, Z., 2019. Fine-scale spatial structure of air pollutant concentrations along bus routes. ***Sci. Total Environ.*** 658, 1-7.

Yang, H., Chen, T., Lin, Y., *et al.*, 2020. Integrated impacts of tree planting and street aspect ratios on CO dispersion and personal exposure in full-scale street canyons. ***Build. Environ.*** 169, 106529.

Yang, Z., Qiu, Y., Muncrief, R., 2015. Review and comparative analysis of in-use vehicle emission control programs in Guangdong Province. *The International Council on Clean Transportation*.

Yazid, A.W.M., Sidik, N.A.C., Salim, S.M., *et al.*, 2014. A review on the flow structure and pollutant dispersion in urban street canyons for urban planning strategies. ***Simulation*** 90, 892-916.

Yu, H., Stuart, A.L., 2017. Impacts of compact growth and electric vehicles on future air quality and urban exposures may be mixed. ***Sci. Total Environ.*** 576, 148-158.

Yuan, C., Ng, E., Norford, L.K., 2014. Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies. ***Build. Environ.*** 71, 245-258.

Zhang, J., Wei, Y., Fang, Z., 2019a. Ozone Pollution: A Major Health Hazard Worldwide. ***Front. Immunol.*** 10.

Zhang, K., Chen, G., Wang, X., *et al.*, 2019b. Numerical evaluations of urban design technique to reduce vehicular personal intake fraction in deep street canyons. ***Sci. Total Environ.*** 653, 968-994.

Zhang, K., Chen, G., Zhang, Y., *et al.*, 2020a. Integrated impacts of turbulent mixing and NOX-O3 photochemistry on reactive pollutant dispersion and intake fraction in shallow and deep street canyons. ***Sci. Total Environ.*** 712, 135553.

Zhang, Y., Gu, Z., 2013. Air quality by urban design. ***Nat. Geosci.*** 6, 506-506.

Zhang, Y., Ou, C., Chen, L., *et al.*, 2020b. Numerical studies of passive and reactive pollutant dispersion in high-density urban models with various building densities and height variations. ***Build. Environ.*** 177, 106916.

Zhao, Y., Chew, L.W., Kubilay, A., *et al.*, 2020. Isothermal and non-isothermal flow in street canyons: A review from theoretical, experimental and numerical perspectives. ***Build. Environ.*** 184, 107163.

Zheng, Y., He, X., Wang, H., *et al.*, 2020. Well-to-wheels greenhouse gas and air pollutant emissions from battery electric vehicles in China. ***Mitigation and Adaptation Strategies for Global Change*** 25, 355-370.

Zhong, J., Cai, X.-M., Bloss, W.J., 2016. Coupling dynamics and chemistry in the air pollution modelling of street canyons: A review. ***Environ. Pollut.*** 214, 690-704.

Zhou, J., Wang, J., Jiang, H., *et al.*, 2019. Cost-benefit analysis of yellow-label vehicles scrappage subsidy policy: A case study of Beijing-Tianjin-Hebei region of China. ***J. Clean. Prod.*** 232, 94-103.