A CFD model to obtain human exposure to direct vehicular emissions in a street-canyon with different mitigation strategies: preliminary results.

Juan C. Zavala-Reyes[a, *], A.P.R. Jeanjean[b], R.J. Leigh[c], Irma Rosas-Pérez[a], Aron Jazcilevich[a].

[a]Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, México, CDMX, 04510, México.
[b]EarthSense Systems Ltd, The Dock, Leicester, UK.
[c]Department of Physics and Astronomy, University of Leicester, Leicester, UK.

*Corresponding author:
E-mail address: jcz_5@hotmail.com (Juan C. Zavala-Reyes)

Abstract

A modeling system based on computational fluid dynamics is used to obtain human exposure while walking, running or cycling in a street-canyon, providing a tool to identify exposure mitigation strategies. In our computational experiments, adult pedestrians and cyclists traverse a virtual street canyon that corresponds to a residential area with primary roads. The mitigation strategies were: placement of tree zones, green and solid barriers. Green and solid barriers were used to isolate pedestrian and cyclists from road environment. In addition, two wind intensities were used to determine corresponding exposure changes.

Results suggests that green and solid barriers reduce exposure levels. The solid barrier showed reductions of ~17.7%. Solid barrier was the most effective, better isolating pedestrians from road environment. The presence of trees produced a reduction on the efficiency of the barrier, causing pollutants concentration to increase near pedestrian height. When the wind intensity was doubled from 2 to 4 m s^{-1}, exposure to $PM_{2.5}$ and NO_x decreased 50%, showing ventilation effects.

Keywords: Air quality, Vehicle emissions, Policy development, Human exposure, Street canyon, Computational Fluid Dynamics (CFD).

1. Introduction

Human exposure to outdoor air pollution was estimated to cause 4.2 million deaths every year (WHO 2018). Particle matter with equivalent aerodynamic diameter <2.5 µm ($PM_{2.5}$) causes cardiovascular, respiratory disease and cancer (Kim, Kabir, and Kabir 2015). Jazcilevich et al. (2018) considers that children are at a higher sidewalk exposure risk due to traffic wake and emissions. In addition, acute short-term diesel exhaust produces a systematic and pulmonary inflammatory response in healthy humans (Salvi et al. 1999), and proximity to main roads increase infantile bronchiolitis and childhood asthma (Lee et al. 2018).

Air quality in street canyons is of major importance since high levels of pollution are found there due to direct vehicle emissions. The exposed population are pedestrians and cyclist, which include children and the elderly. Therefore, air quality models that include wind-flow dynamics to study the interrelation between urban infrastructure, vehicular traffic pollution transport and human exposure, are important tools. Although meteorological conditions play an important role decreasing or increasing pollution levels, improvements under human control, such as vegetation placement and urban morphology, play an important role to mitigate pollution at street level. Therefore, assessing exposure to direct vehicular emissions requires high spatial-temporal emissions, pedestrian activity data and urban morphology.

The virtual street-canyon, where our computational experiments take place, is a street horizontally bordered by parallel buildings aligned on both sides and is vertically delimited by roof height and ground (Jeong and Andrews 2002). Inside the street-canyon pollutants are emitted by vehicles. Wind flow, interacting with buildings, produce a characteristic central vortex (Berkowicz 1998). These flow dynamics in the street-canyon, limits the exchange of clean air from the outside, increasing pollutants levels (DePaul and Sheih 1986). In addition, wind flow distribution inside the street canyon yields inhomogeneous pollutant distribution, causing that pedestrian routes to exhibit different exposure levels (Zavala-Reyes et al. 2019).

The street canyon presented here employs human exposure to evaluate scenarios using different strategies to decrease human exposure inside the canyon. The proposed modeling system uses an urban mobility simulator, a computational fluid dynamic model (CFD) and an integral exposure model to obtain cyclist and pedestrian exposure.

2. Materials and methods

The modelling system proposed is shown in Fig. 1. The system is based on Zavala-Reyes et al. (2019), where more information can be found.

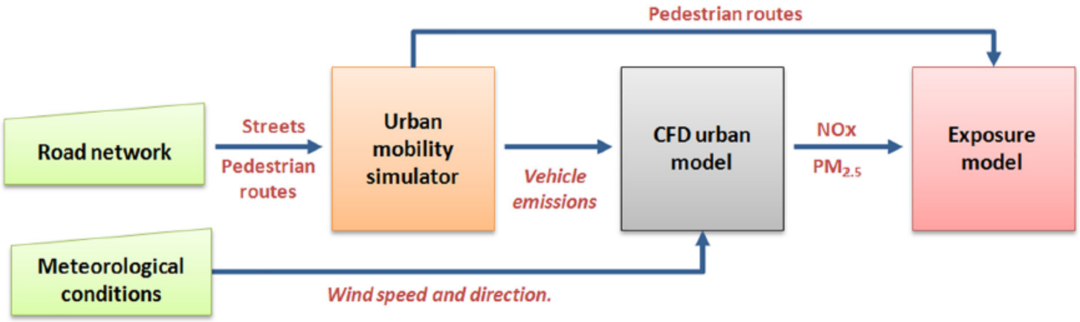

Fig. 1. Modelling system outline, (Zavala-Reyes et al. 2019).

The system consists of three components:

1. An urban mobility simulator, SUMO (http://sumo.dlr.de/). It is a microscopic space-continuous and time-discrete traffic flow simulator. It is used to obtain vehicular emissions ($PM_{2.5}$, NO_x) and pedestrian dynamics. The pedestrian dynamics gives information about pedestrian route location (longitude-latitude-time) and residence time.

2. A CFD model, OpenFoam (https://openfoam.org/), is used to obtain air-flow dynamics and pollutant transport. It has been validated using wind tunnel data.
3. An exposure model is used to obtain pedestrian exposure of a given pedestrian and cyclist route. It is based on the equation given by NRC (1994):

$$E = \sum_{i=0}^{N} C(i \ \delta t) \ \delta t \quad , \tag{1}$$

where C_i is the pollutant concentration at the discrete time $\delta t = 1$ s. The exposure, E, is evaluated over the entire pedestrian route. Summation is taken to include the residence time in the canyon of the pedestrian or cyclist.

Briefly, the urban mobility simulator provides vehicle emisions due to a traffic flow and pedestrian dynamics scenario. The CFD transports the corresponding emisssions to obtain concentration fields in the canyon, that are used by the exposure model. A detailed description is found in (Zavala-Reyes et al. 2019).

Equation 1 provides exposure due to the physical activities of an average adult pedestrian or cyclist, see Table 1. Exposure E is evaluated along a pedestrian route, see Fig 2. Residence time varies according to activity: cycling, running or walking.

Table 1. Physical activity defining the average adult pedestrian and cyclist profile. Modified from Hernández-Paniagua et al. (2017).

Pedestrian activity speed [km h^{-1}]	**Walking**	**Running**	**Cycling**
Average adult (height = 1.6 m)	3	7	11

The modelling system in Fig. 1 is used to evaluate human exposure in a street canyon with different mitigation strategies. The street-canyon setup is shown in Fig. 2, the height of the buildings is H=11 m, width and length of street are W=36 m and L=250 m, respectively. Aspect ratios of H/W=0.3 and L/W=7 were used to characterize the canyon as a avenue-long canyon (Yazid et al. 2014). This setup is identified as a residential area with primary roads, as shown in Fig. 2.

Vehicular flow in SUMO was set to 33.3 vehicles per minute. NO_x and $PM_{2.5}$ emission factors for Euro-5 gasoline passenger cars were considered.

The wind direction of 90°, perpendicular to canyon, was implemented to create high exposure levels (Zavala-Reyes et al. 2019), with 2 and 4 m s^{-1} intensity at 10 m. Initial boundary conditions were set according to Richards and Hoxey (1993) for the $k - \epsilon$ turbulence model.

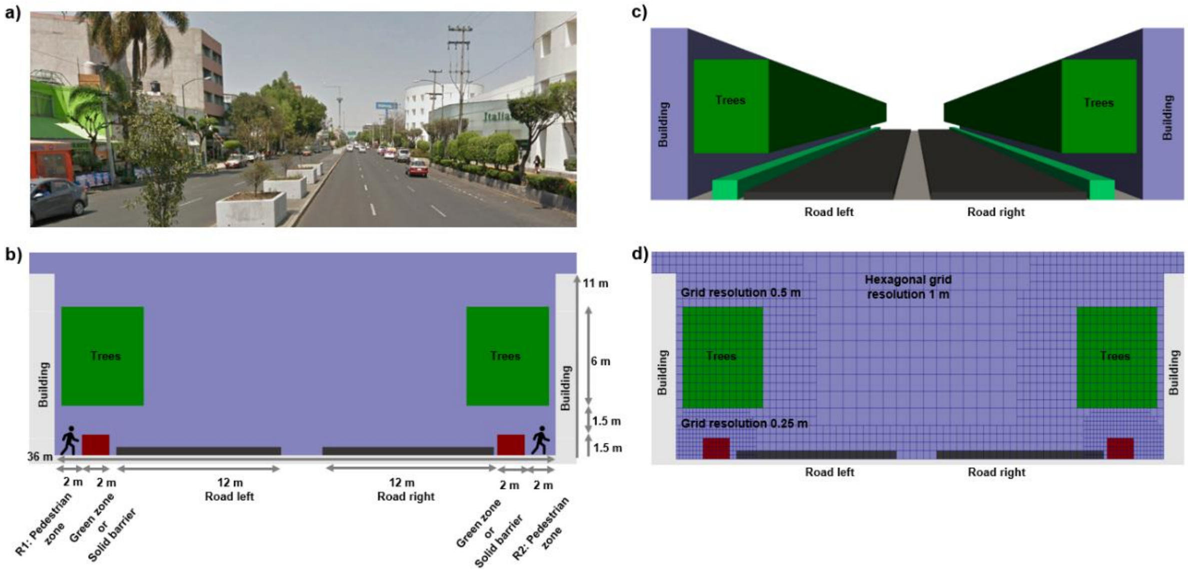

Fig. 2.: Implemented street canyon: a) photography of a real residential area with primary roads, (source google Earth), b) street canyon dimensions, c) CFD mesh used inside the street canyon, d) 3D street canyon model.

Two street-canyon layouts were used for the computational experiments:

a) **Layout L-1**, consisting of a green barrier between sidewalk and road.
   Reference scenario: same street canyon but without trees and green barrier.
   The mitigation scenarios were:
   - **L-1 A**. Tree placement
   - **L-1 B**. A green zone acting as a barrier between the sidewalk and the road.
   - **L-1 A + B**. Street canyon with trees and a green zone acting as a barrier between the sidewalk and the road.

b) **Layout L-2**, consisting of a solid barrier between sidewalk and road.
   Reference scenario: same as in L-1.
   The mitigation scenarios were:
   - **L-2 A.** Street canyon with a solid barrier between the sidewalk and the road.
   - **L-2 B.** Street canyon with trees and a solid barrier between the sidewalk and the road.

For L-1 and L-2, the leaf area density, LAD, to model tree crowns was set to 1.5 m^{-1}.

3. Results

Using SUMO, physical activity speed reduced exposure time in the canyon with respect to walking: running by 56% and cycling by 72%. Exposure results (E) for two street-canyon layouts are shown in Table 2. An exposure reduction of 50% was obtained for $PM_{2.5}$ and NO_x when wind intensity is doubled due to ventilation.

Due to a vortex created inside the street canyon, $PM_{2.5}$ and NO_x road emissions are transported as shown in Fig. 3. To compare scenarios, Eq. (2) was used to obtain the exposure comparison,

$$\mathrm{EV_{scenario}} = \frac{\mathrm{E_{scenario}} - \mathrm{E_{Ref.Scenario}}}{\mathrm{E_{Ref.Scenario}}} * 100 \tag{2}$$

Table 2. Human exposure E to $PM_{2.5}$ and NO_x.

Street canyon	**Scenario**	**Green barrier**	**With trees**	**Profile activity**	**$PM_{2.5}$ Wind speed**		**NO_x Wind speed**	
					2 m s^{-1}	**4 m s^{-1}**	**2 m s^{-1}**	**4 m s^{-1}**
L-1	**Reference**	False	False	Walking	143.2	71.5	1,909.0	953.9
				Running	59.8	29.9	798.0	398.8
				Cycling	38.8	19.4	517.2	258.5
	A	False	True	Walking	173.8	86.9	2,320.0	1,159.6
				Running	71.5	35.7	954.1	476.9
				Cycling	47.2	23.6	629.6	314.7
	B	True	False	Walking	142.0	71.0	1,893.7	946.4
				Running	59.5	29.7	793.0	396.3
				Cycling	38.5	19.2	513.6	256.7
	A + B	True	True	Walking	176.2	88.1	2,352.5	1,175.9
				Running	72.6	36.3	969.6	484.6
				Cycling	47.8	23.9	638.5	319.1
L-2	**A**	NA	False	Walking	116.7	58.3	1,555.4	777.4
				Running	49.7	24.9	663.1	331.4
				Cycling	31.7	15.8	422.7	211.3
	B	NA	True	Walking	141.2	70.6	1,884.7	942.9
				Running	59.4	29.7	792.9	396.7
				Cycling	38.4	19.2	512.0	256.2

Table 3 shows EV for each scenario. For L-1, we have that respective to reference scenario:

- L-1 A, trees increase exposure 19.5-21.8%.
- L-1 B, green barrier reduce exposure 0.6-0.8%.
- L-1 A + B: Trees and green barrier increase exposure 21.3-23.5%.

Results point out that trees increase exposure. In contrast, the green barrier scenario reduces exposure, but only by ~0.7%. This could be explained by an increase in pollutant diffusion close to the pedestrian height that helps reducing pollutant levels. Trees with green barrier increase exposure, but only slightly more when compared to tree scenario.

The L-1 B scenario shows that green barriers could reduce exposure levels by 1%, but other scenarios predict an increase.

For L-2:

- L-2 A, the solid barrier reduce exposure by 16.9-18.5%.

- L-2 B, trees and solid barrier reduce exposure by 0.5-1.4%.

The results point out that solid barriers reduce exposure by ~17.7%. The scenario with trees and solid barriers, decrease the efficiency of the barrier. The L-2A scenario shows that solid barriers could reduce important exposure levels.

In summary, the effect of green barriers reduce exposure, but the solid barriers perform better to isolate road and pedestrian zones. On the other hand, trees increase exposure levels by diminishing the efficiency of green or solid barriers.

Table 3. Exposure variation EV, for $PM_{2.5}$ and NO_x.

					$PM_{2.5}$ Wind speed		**NO_x Wind speed**		
Street Canyon	**Scenario**	**Green barrier**	**With trees**	**Profile activity**	**$2\ m\ s^{-1}$**	**$4\ m\ s^{-1}$**	**$2\ m\ s^{-1}$**	**$4\ m\ s^{-1}$**	**Scenario setup**
L-1	**A**	False	True	Walking	21.4	21.5	21.5	21.6	Trees
				Running	19.5	19.5	19.6	19.6	
				Cycling	21.6	21.7	21.7	21.8	
	B	True	False	Walking	-0.8	-0.8	-0.8	-0.8	Green barrier
				Running	-0.7	-0.7	-0.6	-0.6	
				Cycling	-0.7	-0.7	-0.7	-0.7	
	A + B	True	True	Walking	23.0	23.1	23.2	23.3	Trees + Green barrier
				Running	21.3	21.3	21.5	21.5	
				Cycling	23.2	23.3	23.4	23.5	
L-2	**A**	--	False	Walking	-18.5	-18.5	-18.5	-18.5	Solid barrier
				Running	-16.9	-16.9	-16.9	-16.9	
				Cycling	-18.3	-18.3	-18.3	-18.3	
	B	--	True	Walking	-1.4	-1.3	-1.3	-1.2	Trees + Solid barrier
				Running	-0.8	-0.6	-0.6	-0.5	
				Cycling	-1.1	-1.0	-1.0	-0.9	

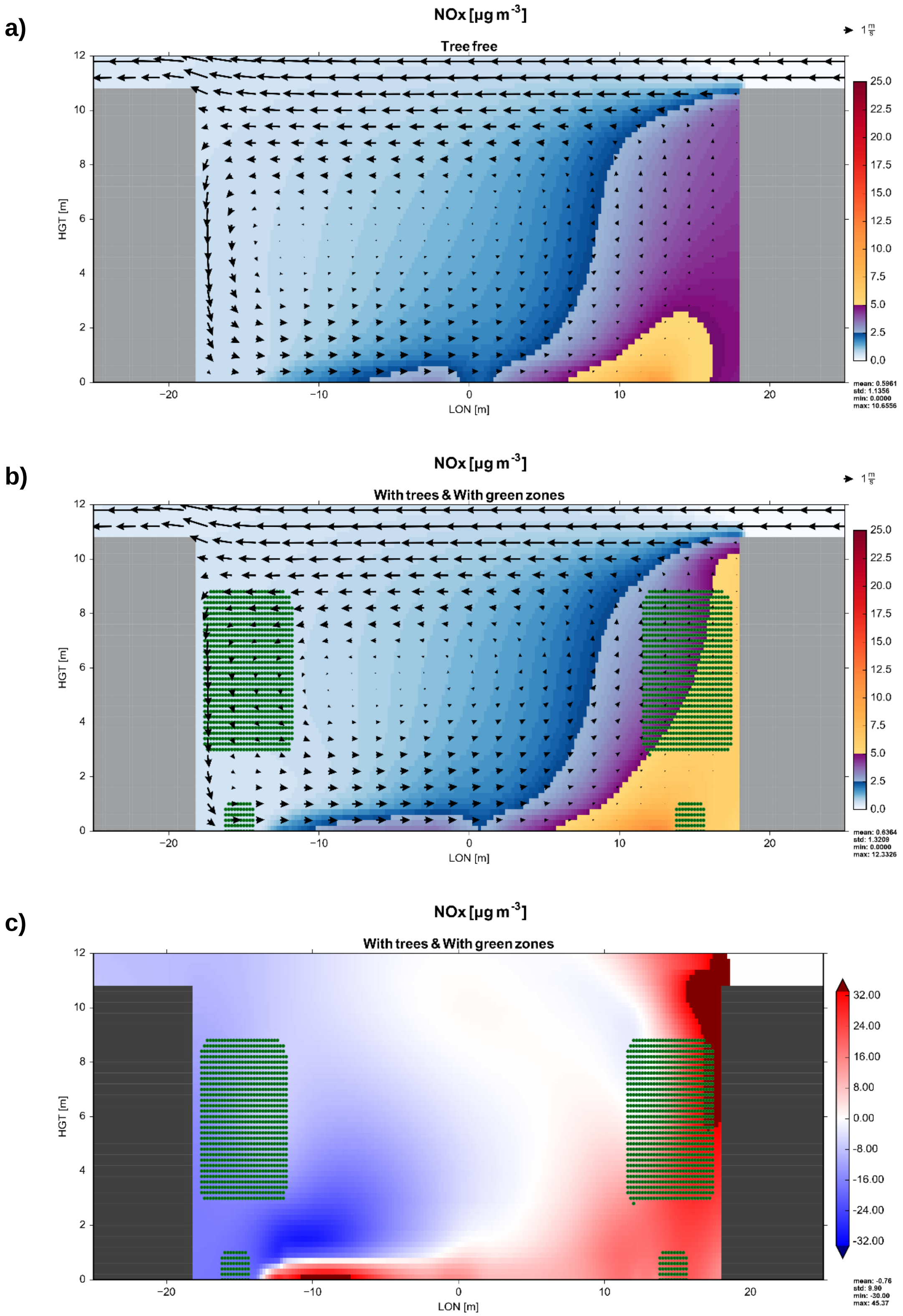

Fig. 3. NO_x cross section concentrations for L-1 and wind vectors: a) reference scenario, b) scenario with trees and green barrier. In c) concentration variation. Green dots represent tree zones.

4. Conclusions and future work

Using a computational system, human exposure was obtained while walking, running or cycling. This provides a tool to compare street-canyons layouts to identify exposure mitigation strategies. The strategies were: tree zones, green and solid barriers. Green and solid barriers were used to isolate pedestrian zones from road environment. Two wind intensities were implemented to include pollution ventilation effect. When the wind intensity was doubled from 2 to 4 m s^{-1}, $PM_{2.5}$ and NO_x exposure decreased 50%.

The implemented street canyon is identified as a residential area with primary roads. Results point out that green and solid barriers reduce exposure levels. The solid barrier showed best reduction levels of ~17.7% with respect to reference scenario. The presence of trees reduced efficiency of the barrier, by causing pollutant concentration increase near pedestrian height.

Although, results presented here were obtained for an idealized street canyon, the proposed methodology can be applied for real urban canyons. Further improvements of the system, including traffic-induced-turbulence and a more detailed vehicular simulator are currently under development. In addition, other effects such as buoyancy should be incorporated. Also, tree species, placement and season could affect air flow dynamics. Vegetation emissions increasing atmospheric reactivity is an important consideration to be included in the future.

Acknowledgements

To SECITI/103/2016 for providing funds for this research. To CONACYT for the Ph.D. grant given to Juan C. Zavala-Reyes (CVU: 385989). To DGTIC-UNAM for the supercomputer resources obtained through project LANCAD-UNAM-DGTIC-056.

Reference

Berkowicz, R. 1998. “Street Scale Models in Urban Air Pollution.” *Edited by J. Fenger, O. Hertel, and F. Palmgren, Kluwer Academic Publishers*, 223–52.

DePaul, F T, and C M Sheih. 1986. “Measurements of Wind Velocities in a Street Canyon.” *Atmospheric Environment (1967)* 20 (3): 455–59.

Hernández-Paniagua, Ivan Y., Juan Zavala-Reyes, Pablo López- Ramírez, Ulises Diego-Ayala, Irma Rosas, and Arón Jazcilevich. 2017. “Use of SUMO to Assess Human Exposure and Intake to PM2.5 near Motorways: Preliminar Results.” *Sumo 2017 - Towards Simulation for Autonomous Mobility* 31 (June): 63–70. http://www.dlr.de/ts/Portaldata/16/Resources/projekte/sumo/Proceedings_SUMO2017.pdf.

Jazcilevich, Aron, Juan de la Cruz Zavala, Ayda Marcela Erazo Arcos, Isao Kanda, and Irma Rosas. 2018. “Sidewalk Pollution Flows Caused by Vehicular Traffic Place Children at a Higher Acute Exposure Risk.” *Journal of Exposure Science and Environmental Epidemiology*, 2018. https://doi.org/10.1038/s41370-018-0083-4.

Jeong, Sang Jin, and Malcom J Andrews. 2002. “Application of the K-Epsilon Turbulence

Model to the High Reynolds Number Skimming Flow Field of an Urban Street Canyon." *Atmospheric Environment* 36 (7): 1137–45.

Kim, Ki-Hyun, Ehsanul Kabir, and Shamin Kabir. 2015. "A Review on the Human Health Impact of Airborne Particulate Matter." *Environment International* 74: 136–43. https://doi.org/10.1016/j.envint.2014.10.005.

Lee, Ji Young, Jong Han Leem, Hwan Cheol Kim, Dirga Kumar Lamichhane, Seung Sik Hwang, Jeong Hee Kim, Myung Sook Park, et al. 2018. "Effects of Traffic-Related Air Pollution on Susceptibility to Infantile Bronchiolitis and Childhood Asthma: A Cohort Study in Korea." *Journal of Asthma* 55 (3): 223–30. https://doi.org/10.1080/02770903.2017.1313270.

NRC. 1994. *Science and Judgment in Risk Assessment*. Washington, DC: The National Academies Press. https://doi.org/10.17226/2125.

Richards, P J, and R P Hoxey. 1993. "Appropriate Boundary Conditions for Computational Wind Engineering Models Using the K-ϵ Turbulence Model." *Journal of Wind Engineering and Industrial Aerodynamics* 46: 145–53.

Salvi, Sundeep, Anders Blomberg, Bertil Rudell, Frank Kelly, Thomas Sandström, Stephen T. Holgate, and Anthony Frew. 1999. "Acute Inflammatory Responses in the Airways and Peripheral Blood after Short-Term Exposure to Diesel Exhaust in Healthy Human Volunteers." *American Journal of Respiratory and Critical Care Medicine* 159 (3): 702–9. https://doi.org/10.1164/ajrccm.159.3.9709083.

WHO. 2018. "Ambient Air Pollution: Pollutants." Who. 2018. https://www.who.int/airpollution/ambient/pollutants/en/.

Yazid, Afiq Witri Muhammad, Nor Azwadi Che Sidik, Salim Mohamed Salim, and Khalid M Saqr. 2014. "A Review on the Flow Structure and Pollutant Dispersion in Urban Street Canyons for Urban Planning Strategies." *Simulation* 90 (8): 892–916.

Zavala-Reyes, Juan C, A P R Jeanjean, R J Leigh, Iván Y Hernández-Paniagua, Irma Rosas-Pérez, and Aron Jazcilevich. 2019. "Studying Human Exposure to Vehicular Emissions Using Computational Fluid Dynamics and an Urban Mobility Simulator: The Effect of Sidewalk Residence Time, Vehicular Technologies and a Traffic-Calming Device." *Science of The Total Environment*.