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QUIC Transport and Dispersion Modeling of Vehicle Emissions in Cities for Better Public Health Assessments



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ABSTRACT: The Quick Urban and Industrial Complex (QUIC) plume modeling system is used to explore how the transport and dispersion of vehicle emissions in cities are impacted by the presence of buildings. Using downtown Philadelphia as a test case, notional vehicle emissions of gases and particles are specified as line source releases on a subset of the east–west and north–south streets. Cases were run in flat terrain and with 3D buildings present in order to show the differences in the model-computed outdoor concentration fields with and without buildings present. The QUIC calculations show that buildings result in regions with much higher concentrations and other areas with much lower concentrations when compared to the flat-earth case. On the roads with vehicle emissions, street-level concentrations were up to a factor of 10 higher when buildings were on either side of the street as compared to the flat-earth case due to trapping of pollutants between buildings. However, on roads without vehicle emissions and in other open areas, the concentrations were up to a factor of 100 times smaller as compared to the flat earth case because of vertical mixing of the vehicle emissions to building height in the cavity circulation that develops on the downwind side of unsheltered buildings. QUIC was also used to calculate infiltration of the contaminant into the buildings. Indoor concentration levels were found to be much lower than outdoor concentrations because of deposition onto indoor surfaces and particulate capture for buildings with filtration systems. Large differences in indoor concentrations from building to building resulted from differences in leakiness, air handling unit volume exchange rates, and filter type and for naturally ventilated buildings, whether or not the building was sheltered from the prevailing wind by a building immediately upwind.

KEYWORDS: urban dispersion modeling, indoor infiltration, vehicle emissions

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Introduction

Both short- and long-term exposure to gases and small particles from tailpipe emissions can be deleterious to public health.^{1–4} It is well known that between buildings, vehicle emissions can become trapped in a street canyon vortex resulting in higher concentrations as compared to open flat terrain.^{5–8} In a review of prior vehicle emissions and concentration measurements studies at urban intersections in built environments, Tiwary et al.⁹ wrote that “occupational and commuter exposures to vehicle-generated air pollutants such as carbon monoxide (CO) and particulate matter (PM), in such microenvironments tend to be higher than average.” On the other hand, it is also known that on the downwind side of unobstructed tall buildings, intermittent spiral vortices develop that transport vehicle emissions upward high into the air, thus reducing air pollution concentrations at street level.^{10–12} The experiments of Qin and Kot¹³ and Dabberdt and Hoydysh¹⁴ have indicated that street-level concentrations are sensitive to the details of the building configuration, while Boddy et al.¹⁵

have shown the sensitivity of street canyon CO concentrations as a function of the prevailing wind. Carefully controlled point-source tracer experiments held in the downtown area of several cities with buildings of variable height, alignment, spacing, and shape have shown complex three-dimensional flow patterns and dramatic variations of concentrations at the street scale.^{16–20}

The majority of traffic pollution plume models do not explicitly account for the complex effects of buildings on the transport and dispersion of vehicle emissions in cities, and at the best only approximate the impact of idealized geometries (eg, see reviews by Sharma and Khare²¹ and Vardoulakis et al.²²). Zamurs and Conway²³ conducted CO, traffic count, and traffic flow measurements in Manhattan at several different sites and compared them to two non-building-aware line source plume models. They found little to no correlation for a paired-in-time-and-space comparison of the model predictions to the CO measurements. They indicated that variable wind directions at street level caused by the surrounding



buildings may have been partially responsible. Murena et al.²⁴ also found that a traffic pollution model compared poorly to street-level concentration measurements in a tall building environment.

In order to capture the complex flow fields in cityscapes, computational fluid dynamics (CFD) models have been applied to the transport and dispersion of vehicle emissions.^{25–28} CFD codes are computationally intensive, however, and for assessments in which many scenarios need to be modeled, a fast-running option would be beneficial. In this paper, we discuss a unique fast-running transport and dispersion modeling system that can account for the 3D effects of buildings on the winds and the subsequent plume transport and dispersion. Background on the modeling system is provided, including model limitations and validation studies, followed by application of the system to cases with and without buildings to show the potential differences in street-level concentrations.

Model Background

The Quick Urban and Industrial Complex (QUIC) transport and dispersion modeling system was developed to rapidly compute three-dimensional wind, concentration, and deposition fields around buildings in tens of seconds to tens of minutes on a desktop or laptop computer (see <http://www.lanl.gov/projects/quic/>). QUIC is composed of a wind model, a random-walk plume code, a pressure solver, an infiltration scheme, a well-mixed indoor air quality model, and a graphical user interface. QUIC runs on Linux, OS X, and Windows platforms. Although adapted for chemical, biological, and radiological agent plume modeling applications, it has also been used for air quality applications.^{29–32} QUIC has algorithms to account for multi-particle size distributions, gravitational settling, buoyant cloud rise, dense gas slumping, liquid pool evaporation, droplet evaporation and thermodynamics, two-phase droplet–vapor mixtures, deposition, particle resuspension, and infiltration into buildings. QUIC also includes a US day–night population database that can be linked to different user-defined health-effect thresholds to quickly compute exposures.

The QUIC wind solver is based on the concepts proposed by Röckle³³ and is an empirical-diagnostic model, ie, it is based on equations derived from experiments and mass conservation. Full-physics CFD codes numerically solve the differential equations that describe the conservation of momentum, mass, and turbulent kinetic energy, and then the pressure gradients and 3D recirculation zones around buildings naturally evolve. The QUIC wind solver, on the other hand, produces 3D flow fields around obstacles based on (a) logic that determines whether or not specific recirculation zones develop around or between the buildings (eg, downwind cavity, upwind rotor, rooftop recirculation, street canyon vortex), (b) calculations of the size, shape, and the initial velocity fields found within these flow zones, and then (c) application of the mass consistency constraint. The empirically based equations are

a function of building shape, building dimensions, building spacing, wind direction, and wind speed. Simple backflow is specified in the building flow zones (eg, the downwind cavity on the backside of a building), and after mass conservation is applied, fairly realistic vortices and eddies develop around and between the buildings. The diagnostic–empirical approach provides a CFD-like solution, but does it relatively quickly: a three million grid cell problem takes ~10 seconds to run on a single processor 2010 MacBook Pro, for example. Information on the modifications of the wind solver to work in complex built environments can be found in Pardyjak and Brown,³⁴ Singh et al.³⁵, Gowardhan et al.³⁶, and Brown et al.²⁰ As outlined in Nelson et al.³⁷, the QUIC wind solver also accounts for the reduction in the wind because of forest canopy drag and is based on the work of Cionco.³⁸

The QUIC dispersion model is a Lagrangian random-walk code that tracks the 3D movement of tens to hundreds of thousands of markers that represent gases and aerosols as they disperse through the air. The markers are carried by the mean wind field computed by the QUIC wind solver, and the random-walk equations produce second-by-second stochastic velocity fluctuations that act to turbulently disperse the airborne contaminant as it is drifting through the air. The random-walk equations include a memory term that represents the persistence of a turbulent eddy, a stochastic term that represents the random break-up and regeneration of new turbulent eddies, and the so-called drift terms that approximate the effects of the inhomogeneous turbulence found around buildings. The normal and shear stresses and turbulent dissipation are determined based on atmospheric-stability-dependent similarity theory, gradient transport, and a non-local mixing scheme that approximates the turbulent mixing that occurs in building cavities and street canyons. A resistance-based particle-size-dependent deposition scheme accounts for particle deposition to building and street surfaces, while a traditional deposition velocity approach is used for gases. Details regarding the QUIC random-walk model can be found in Williams et al.³⁹

Built into the QUIC random-walk code is a simple well-mixed box model for computing indoor concentrations resulting from infiltration of the outdoor plume. The well-mixed box model implies that buildings are approximated by one large volume and have uniform concentrations within. The model accounts for fresh air intake through natural ventilation (ie, leakage through cracks around doors and windows) and heating, ventilation, and air conditioning (HVAC) intake (including a particle-size-dependent filtering function), exfiltration of air via natural leakage and/or HVAC exhaust, internal HVAC recirculation, and indoor sink terms such as indoor deposition and radiological or UV decay. The equations relating the indoor concentration to the outdoor concentration are described in the Appendix. QUIC contains a number of different building types (eg, leaky house, tight house, old office with closed or open windows, old office with or without HVAC, modern office with commercial filter, electret filter, or High

Efficiency Particulate Air [HEPA] filter) that have associated air exchange rates and filter types. Owing to lack of information for specific buildings, inlets are uniformly placed on building walls and roofs in a gridded pattern. Note that for cases in which information on inlet locations, air flow between rooms and floors, and HVAC configuration is available for specific buildings, QUIC can be linked via input and output files to the CONTAM zonal indoor air quality model,⁴⁰ which can then provide a better resolved indoor solution room by room.

The QUIC wind solver has been tested against scaled-building experiments in wind tunnels³⁵ and in cities,¹⁸ and the QUIC code as a whole has been shown to perform well when compared to tracer experiments in real cities.^{16, 20} In a blind test led by Pacific Northwest National Laboratory,⁴¹ the QUIC code performed as well as more computer-intensive CFD codes when compared to tracer data from the NYC Midtown Experiment, but ran hundreds of times faster. QUIC is far from perfect: evaluation studies have shown that the wind in particular street canyons can be going in the wrong direction, for example. Overall, however, the model has been shown to approximate the effects of buildings reasonably well and to capture many of the important aspects of building-scale plume transport and dispersion.

Model Set-Up

The QUIC modeling domain is centered on downtown Philadelphia (see map, Fig. 1). The domain covers an area $2550 \text{ m} \times 1500 \text{ m}$, with Logan Square Roundabout near the northwest corner, Franklin Square near the northeast corner, Rittenhouse Square near the southwest corner, and Washington Square near the southeast corner.

Rittenhouse Square near the southwest corner, Washington Square Park near the southeast corner, and the Pennsylvania Convention Center (the large white building) near the center of the domain. In order to align the majority of streets and building faces with the QUIC grid, the domain is rotated 9° counter-clockwise from true north. The horizontal grid size was set to 5 m allowing the smaller streets to be resolved by three to four grid cells while still permitting the wind solver to run relatively quickly. The domain extends 750 m in the vertical direction with a 3 m grid depth in the vertical direction from the surface up to 15 m, and then expands parabolically to 60 m at the domain top. The $510 \times 300 \times 35$ grid cell domain results in winds being computed in 5,355,000 grid cells.

3D building height data were obtained from the National Geospatial-Intelligence Agency, while building footprints were determined from Google Maps orthophotos. The tallest building in the domain is 223 m high, with two other buildings surpassing 200 m in height (Fig. 2). Infiltration parameters for the majority of buildings were arbitrarily set to an old office building with closed windows and standard commercial filtration, while a select few buildings were specified as a modern office building with (1) HEPA filters and (2) an electret filter system, (3) as an old office building with open windows and no HVAC, and (4) as a leaky house in order to have a range of air exchange rates and filtration types. Although QUIC has the capability of representing the wind drag effect because of forested areas, the forest canopy drag parameterization was not turned on in these calculations.

For simplicity, one lane of vehicle emissions was represented by volumetric line sources with height of 1.5 m and

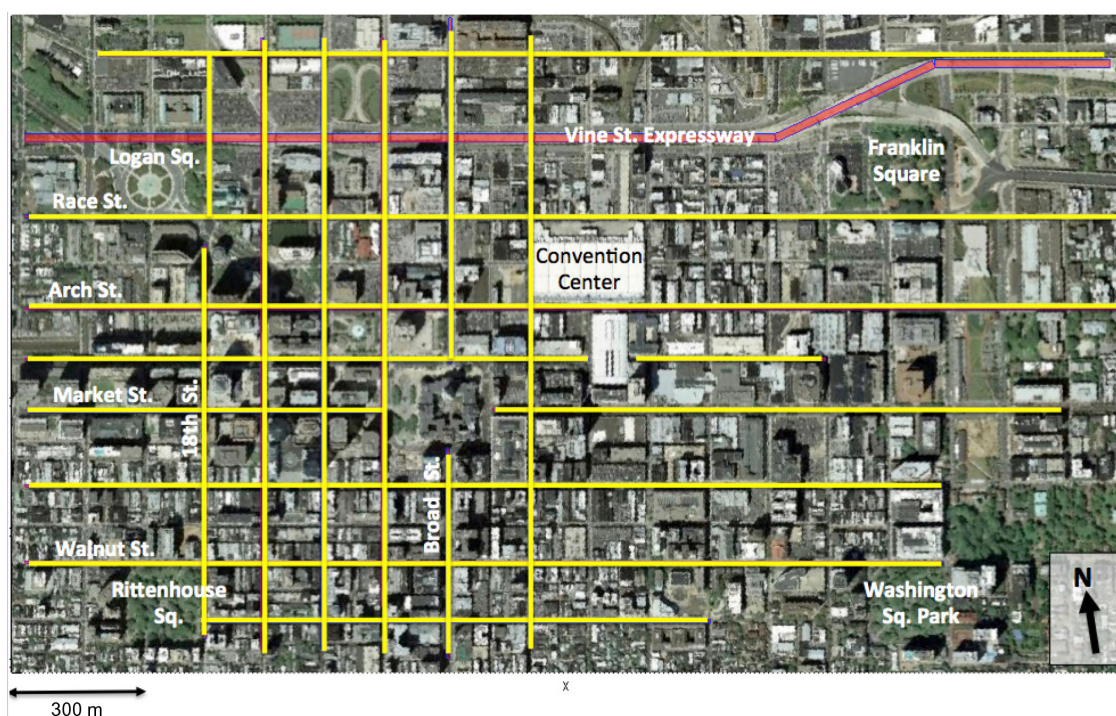


Figure 1. The extent of the downtown Philadelphia modeling domain ($2.55 \text{ km} \times 1.5 \text{ km}$). The yellow and red lines represent notional vehicle-emissions volumetric line sources that will be used in the QUIC transport and dispersion calculations. The image is rotated 9° counter-clockwise (CCW) relative to true north.



Figure 2. 3D representation of the buildings in the downtown Philadelphia QUIC modeling domain (view from the southwest).

width of 2 m, roughly representing the initial mixing of the tailpipe emissions in the wake of a car. Since the focus of this paper is to demonstrate the effect of buildings on the airborne concentrations, we arbitrarily set the emissions rate to be a constant one unit mass per kilometer of two-lane road in order to isolate the impact of the buildings from the spatial and temporal variations of the vehicle emissions. Simulations were performed for a non-reactive gaseous species and 2- μm particles. The line emission sources are shown in Figure 1. Note that the Vine Street Expressway (Highway 30) was subjectively assumed to have a factor of 5 more emissions than other streets because of greater traffic flow. A part of the Vine Street Expressway is below street level, but for simplicity, we have assumed that it runs at street level in the analysis that follows. The prevailing wind direction was specified as blowing from the north (0°), and the wind speed at 10 m above the ground level was set to 3.5 m/s. The atmospheric stability was assumed to be neutral, indicative of a day with moderate winds and/or cloudy skies. Note that it has been found that near-neutral stability conditions typically occur in built-up

urban areas because of anthropogenic heating and the shear-flow turbulence generated around buildings. Table 1 provides a summary of the modeling exercise parameters.

Results/Discussion

Winds. Figure 3 shows a plan-view of the winds near the surface. One can see that although the prevailing wind is from the north (recall that the domain is rotated 9° counter-clockwise), the winds at the street level are in many different directions because of the channeling of the winds between buildings and the horizontally and vertically rotating vortices that develop upwind, between and behind buildings. The building-induced channeling at the street level will direct the vehicle emissions in a different direction as compared to a flat-earth plume model that does not account for the effects of buildings and only utilizes the prevailing wind direction. The street canyon vortices that develop between buildings will result in the vehicle emissions being caught in the swirling motions and generally lead to higher street-level concentrations. Figure 4 shows a north-south vertical cross-section of

Table 1. Model exercise parameters.

Domain Size: 2550 \times 1700 m	Wind Speed = 3 m/s at 10 m agl
Horizontal Grid Size = 5 m	Wind Direction = 0 deg (from the North)
Domain Depth = 700 m	Atmospheric Stability = Neutral
Vertical Grid Size = 3 m at surface with parabolic expansion to 60 m at top	Emissions: Non- reactive gas and 2 μm particles
No. of Grid Cells: 510 \times 300 \times 35	Source Geometry: Volumetric line sources (height = 1.5 m, width = 2.5 m)
Total Cells = 5,355,000	Emissions Rate: one unit mass per km of two-lane road

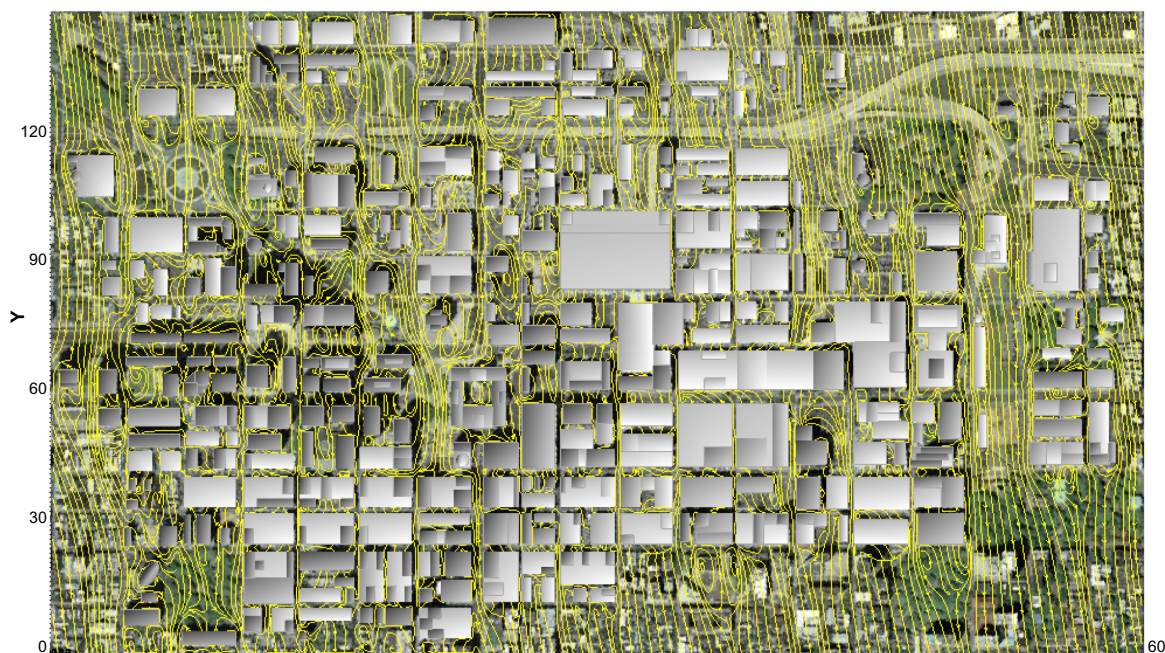


Figure 3. A plan-view of streamlines computed by the QUIC wind solver at a height of 1.5 m above the ground level in downtown Philadelphia. Notice the complicated flows that develop around buildings.

the winds and reveals the large rotating eddies that develop behind and between buildings. For vehicle emissions emitted downwind of a tall building, street-level concentrations may actually be reduced due to rapid vertical transport and mixing.

Concentrations. Figure 5 shows gas concentrations in a vertical cross-section along an east–west transect on Market Street for the domain with (top) buildings and (bottom) no buildings, ie, a flat-earth plume modeling calculation. In both cases, all inputs are identical; the only difference is the presence or absence of buildings. The plume depth for the flat-earth domain is uniform across the east–west transect, rising to about 80 m above ground level. For the case with buildings, the plume depth varies across the east–west transect,

depending on the average building height. On the eastern side of the domain, the depth varies between 100 and 120 m, while in the city center on the western side of the domain, the vertical extent of the plume reaches nearly 300 m. The tall buildings act as “conveyor belts”, transporting the emissions from street level in vertical-rotating vortices as depicted in Figure 4.

Figures 6 compares the street-level gas concentrations computed by QUIC for the case of buildings and flat earth. Clearly, there is greater spatial variation in concentration levels in the simulation with buildings: there are small pockets of very high and very low concentrations as compared to the flat-earth case. Along the streets with line source emissions, the

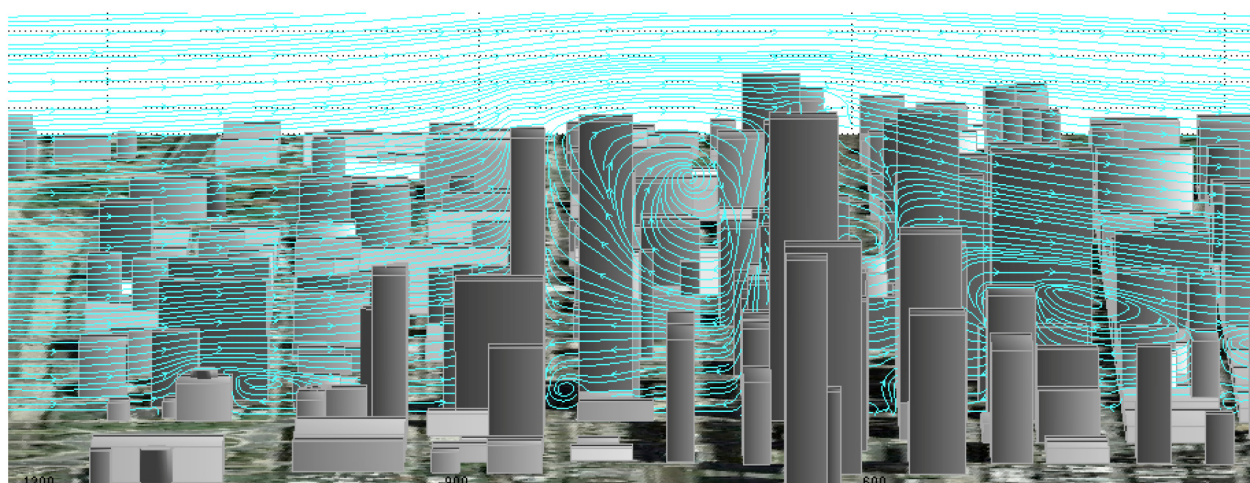


Figure 4. A side-view of the QUIC-computed streamlines showing vertically rotating vortices that develop on the downwind side of buildings. The prevailing northerly winds are blowing from left to right.

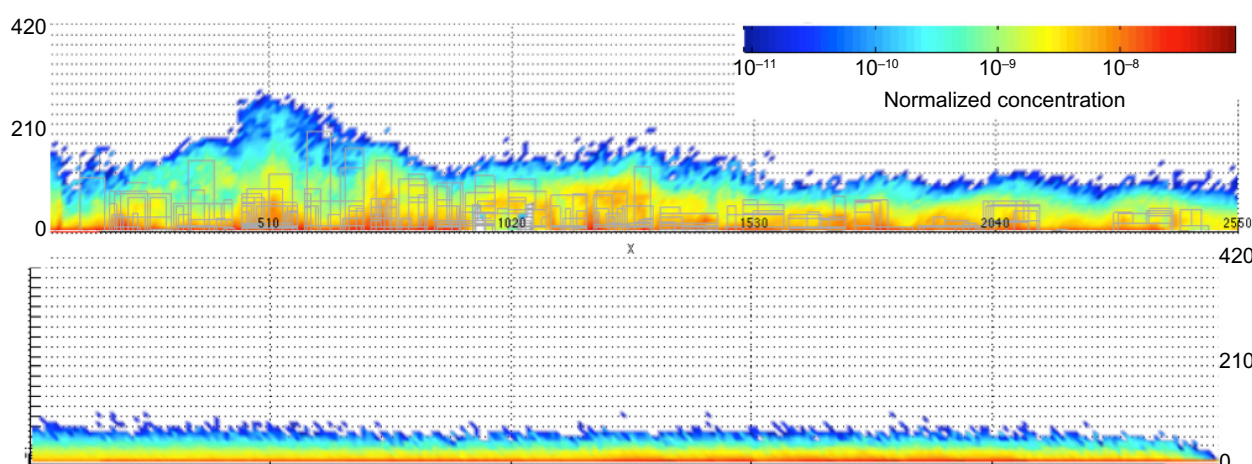


Figure 5. Vertical cross-section along Market Street of the QUIC-computed non-reactive gas concentrations from the vehicle-emissions line sources for the domain (top) with buildings and (bottom) without buildings. In both cases, the emissions, prevailing winds, and atmospheric stability are identical. Differences are because of the impact of the buildings on the flow field. View is from the south, looking northward.

concentrations are often higher in the presence of buildings and they vary dramatically at sub-block distances as a function of whether there is a building immediately upwind or downwind of the line source or not present at all. The high concentrations typically occur in regions with backflow, indicative of a street canyon recirculation between buildings or cavity flow downwind of short isolated buildings trapping the vehicle emissions near the surface and resulting in a longer residence time.

For the flat-earth case, concentrations along the streets with vehicle emissions are fairly uniform with spikes in concentration where the east–west and north–south line sources overlap. In general, the concentrations immediately downwind of the line sources are higher for the flat-earth case throughout the domain. This is because, as shown in Figure 4, the vertical mixing of the plume is larger when buildings are present, thus resulting in greater dilution of the plume and hence lower concentrations at street level as compared to the no-building case. The concentrations in these areas appear to be about a factor of 2–10 times larger for the flat-earth case (note the logarithmic color bar scale).

The scatterplot in Figure 7 compares the gas concentrations computed in Figure 6 point-by-point for the QUIC simulation with and without buildings. At any one location, the scatterplot reveals that there can be large differences in the concentrations when one includes buildings: it shows that there are many locations where the concentrations are lower – up to a thousand times lower – as compared to the flat-earth case.

The statistics in Table 2 show that about one-fourth of the concentrations are within 25% of one another, but that nearly half are a factor of 2 or more different and a little over one-fifth are a factor of 5 or more different. Averaging over all the street-level concentrations, the average concentration for the domain with buildings is almost a factor of 2 smaller than the flat-earth case.

Indoor infiltration. As mentioned earlier, using a vehicle-emissions model and a plume model together, one can assess

the impact of different traffic control strategies on air quality or the effect of new road construction. For example, one could look at the impact of vehicle emissions from a particular street on the concentration levels downwind of the street of interest. This would allow one to evaluate a change in air quality because of, for example, a change in the speed limit, traffic light signal duration, or an expected change in traffic volume. In the example shown in Figure 8, QUIC is used to look at the 2- μ m particle emissions from only the Vine Street Expressway. One can see that the outdoor concentrations fall off with distance about 2 orders of magnitude over a 1-km travel distance. When compared to the case with multiple streets contributing vehicle emissions (Fig. 6, top), the outdoor concentrations are about a factor of 10 smaller at a 1-km distance due south of the expressway, suggesting that the (hypothetical) Vine Street emissions contribute about 10% to the pollution levels at this distance when all (hypothetical) street emissions are considered.

Using the QUIC infiltration algorithms, the indoor concentrations resulting from particles infiltrating into the buildings were also calculated. For convenience, most of the buildings were specified as old office buildings with closed windows and standard commercial filtration, while a handful were specified as other types of buildings with different leakiness, HVAC, and filtration system characteristics. Figure 8 shows that a majority of the buildings show much lower concentrations over a four-hour averaging period, typically a factor of 10 lower, sometimes much more. The lower indoor concentrations are because of two main factors: the filters capturing some of the particles and deposition of the particles on indoor surfaces. Collection efficiency for 2- μ m particles is roughly 70% for minimum efficiency reporting value (MERV-10) commercial filters.⁴² With three supply exchange rates per hour for a typical HVAC system, the total volume of building air goes through the filtration system 12 times during a four-hour period, pushing indoor concentrations toward zero. However, new particles from the outdoors are

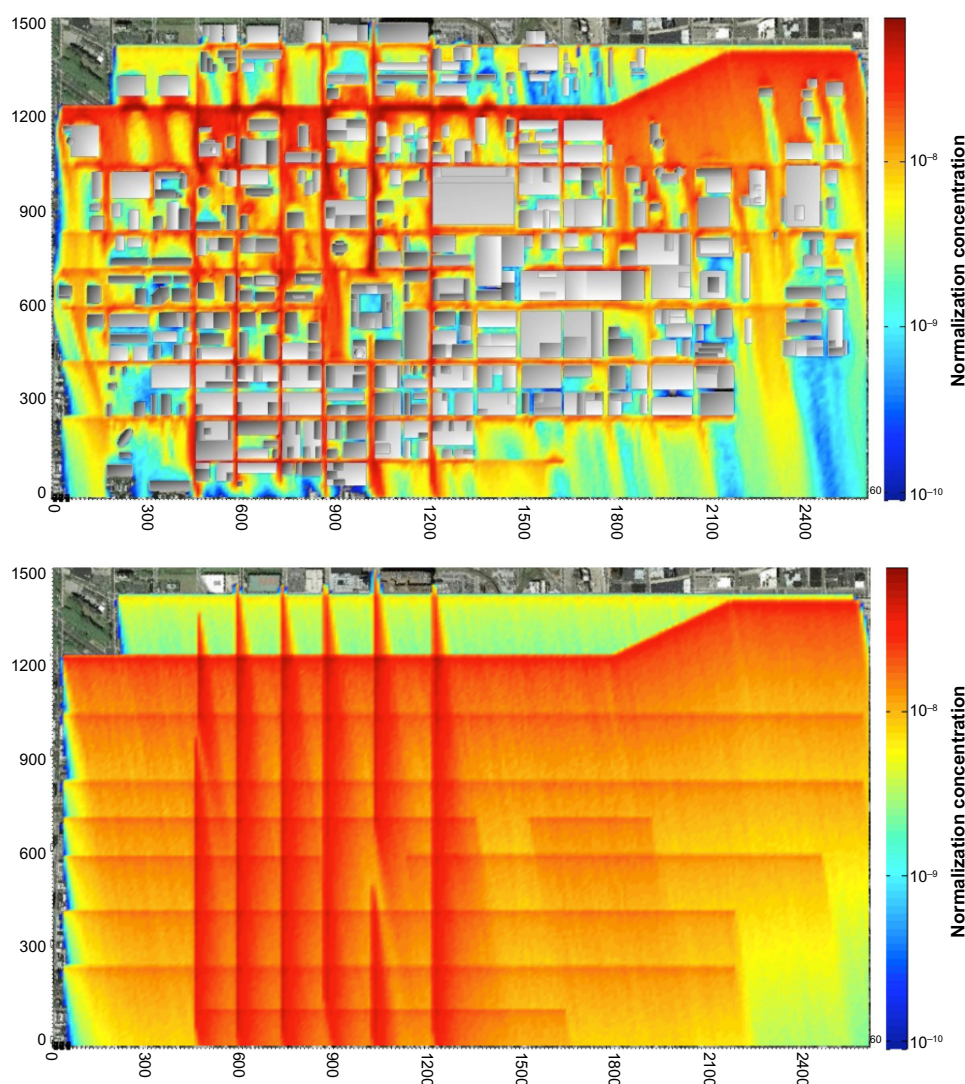


Figure 6. A plan-view of the QUIC-computed near-surface gas concentrations for the domain (top) with buildings and (bottom) without buildings. In both cases, the emissions, prevailing winds, and atmospheric stability are identical. Differences are because of the impact of the buildings on the flow field.

continuously penetrating indoors because of the HVAC fresh air intake (0.5 air exchanges per hour) and leakage (0.3 air exchanges per hour) to push indoor concentrations higher.

Buildings 26, 137, and 171 were set to leaky house type, with a 1.0 air exchange rate because of leakage and no filtration system. Higher indoor concentrations are expected as compared to the buildings with HVAC since the only loss mechanism is because of particle deposition on interior surfaces. Outdoor-to-indoor concentration ratios are approximately 6.7, 5.0, and 2.0 for buildings 26, 137, and 171, respectively. Although all three buildings have similar leakiness properties, the actual air exchange rate actually changes with the wind speed around the building, with stronger winds causing a larger pressure differential around the building and thus enhancing leakage. This explains why building 171 has an indoor concentration closer to the outdoor concentration, ie, it is out in the open and feels the full force of the wind, while buildings 26 and 137 are sheltered from the wind by buildings to the north.

Buildings 129 and 147 were specified to be modern office buildings with HEPA filters. HEPA filters capture greater than 99% of the 2- μm particles. Compared to nearby buildings, the concentrations are a factor of 5–10 lower in the buildings with HEPA filters. Concentrations are about 40 and 190 times smaller indoors as compared to outdoors for buildings 129 and 147, respectively. Building 130 is an old office building with open windows and no HVAC system and has nominally five air changes per hour. Indoor concentrations are very high relative to the surrounding old office buildings because of the large infiltration rate and lack of filtration system, but reduced somewhat as a result of being sheltered from the wind by the convention center immediately north. The outdoor concentration is roughly 4.4 times higher than the indoor concentration. There are several buildings, eg, 299, 301, and 504, that have indoor concentrations 2–3 orders of magnitude lower than the near-surface outdoor concentrations. These buildings are the default old office buildings with commercial-grade filters; the concentrations are extremely low because these

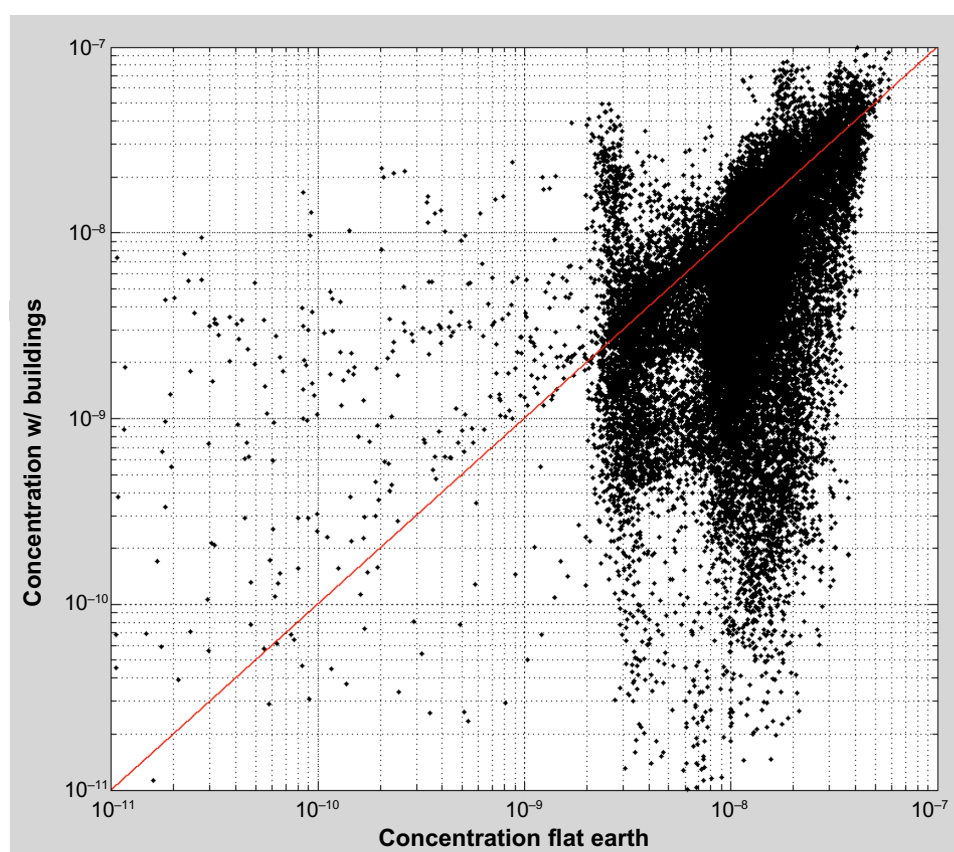


Figure 7. Point-by-point comparison of the QUIC model-computed near-surface gas concentrations for the case of buildings versus no buildings (ie, the flat-earth case).

buildings are extremely tall (176, 213, and 223 m, respectively) and stick up into cleaner regions of the air, ie, as shown in Figure 5, concentrations near the building top are 2–3 orders of magnitude lower than the concentrations at the street level. Since we treat the tall buildings as one large well-mixed volume, the contaminated air near the street level is being mixed with relatively clean air from the upper regions of the building. In reality, the building will likely show variations floor-by-floor and will depend on the specifics of the air handling units.

Summary

Using downtown Philadelphia as a test case, the impact of buildings on the street-level concentrations was assessed by

Table 2. Differences in model-computed near-surface gas concentrations for the domain with and without buildings.

DIFFERENCE IN CONCENTRATIONS	PERCENT OF POINTS
<25%	25.6
25–50%	11.4
50–100%	13.7
100–500%	25.6
500–1000%	10.7
>1000%	12.9

running the QUIC transport and dispersion model with and without buildings. In a point-by-point comparison, the concentrations in the streets with vehicle emissions were typically higher for the case with buildings on both sides of the street, owing to the increased residence time of the pollution within the street canyon vortex. However, in general, the concentrations in the entire domain were lower on average for the case with buildings because of increased vertical mixing, mainly a result of vehicle emissions getting lofted to building height in the updraft that develops on the lee-side of buildings in the downwind cavity. Note that these generalizations may be different in other cities and may vary from neighborhood-to-neighborhood depending on building shape, height, and plan area; the spacing between buildings; the relative heights of nearby buildings; the layout of the roads; and the wind direction.

Rough estimates of particle infiltration into buildings and the subsequent time evolution of indoor concentrations were also computed for a special case, only considering the emissions from the Vine Street Expressway. As expected, wide differences in indoor concentration levels were found based on differences in building leakiness, filtration systems, and air handling unit volume exchange rates. Furthermore, buildings with similar building ventilation characteristics were found to have different indoor concentrations based

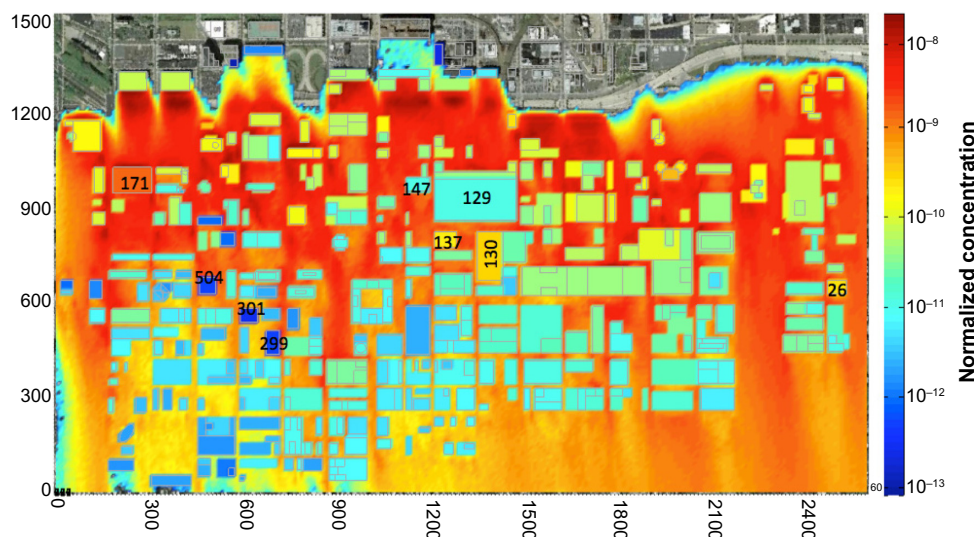


Figure 8. Four-hour-averaged outdoor and indoor concentrations of 2 μm particulates at 15 m above ground level because of vehicle emissions from just the Vine Street Expressway. Prevailing winds are from the north, with a $\pm 10^\circ$ oscillation over the four-hour period. Building numbers are referenced in the text.

on whether or not they were sheltered from the prevailing wind by a building immediately upwind, especially for buildings without mechanical ventilation systems. Sheltering results in lower winds around the building, thus reducing the natural leakage into the building. We also found that tall buildings generally had lower indoor concentrations with respect to street-level outdoor concentrations as a result of pulling in cleaner air from inlets high on the building. Floor-to-floor variations in the indoor concentrations are not considered in these QUIC modeling calculations, however.

The simulations presented in this paper used a constant vehicle-emissions rate in order to isolate the effects of buildings on the concentration levels. In reality, emissions vary as a function of vehicle fleet mix, engine conditions, traffic density, and acceleration history. Utilizing a spatially and temporally resolved vehicle-emissions model with the QUIC building-aware transport and dispersion model would provide a powerful method to study air quality and health impact issues related to CO and particulates in cities. Air quality assessments of at-risk population, highway construction projects, sound barrier installations, traffic signaling changes and other traffic management measures, fleet mix modifications, and new building constructions could be assessed in a systematic fashion in dense built urban areas. Incorporation of a photochemical model would allow for assessments of NO_x, ozone, and other reactive gases.

Author Contributions

Conceived and designed the experiments: MJB, MAN, MDW, KAW. Analyzed the data: MJB. Wrote the first draft of the manuscript: MJB. Contributed to the writing

of the manuscript: MJB, MAN, MDW, KAW. Agree with manuscript results and conclusions: MJB, MAN, MDW, KAW. All authors reviewed and approved of the final manuscript.

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Appendix

Indoor concentration equations. The differential equation below governs the time-rate-of-change of the indoor concentration due to infiltration of the outdoor plume into a well-mixed indoor volume (eg, Ref. 43):

$$\frac{\partial C_i}{\partial t} = q_0 C_o + q_3(1-F)C_o - q_1 C_i - q_2 F C_i - \frac{av_d}{V} C_i - q_e C_i$$

where C_i is the indoor concentration, C_o is the outdoor concentration, the q 's are volumetric air flow rate per unit volume [$1/t$], the term on the left is the change in the indoor concentration per unit time, the first term on the right-hand side represents the infiltration of the outdoor pollutant, the second term is the HVAC intake with F being the fraction of particle mass captured by the filters, the third term is the exfiltration (ie, the amount of indoor contaminant emitted to the outside), the fourth term is the HVAC-recirculated contaminant, the fifth term is the indoor deposition (where v_d is the deposition velocity, a is the indoor surface area, and V is the indoor

volume), and the last term is a radiological or UV decay sink term. Note that F is a function of the filter type and the particle diameter.

The general solution to the differential equation above is:

$$C_i(t) = A e^{-Bt} \int_0^t C_o(t) e^{Bt} dt$$

where

$$A = q_0 + q_3(1-F)$$

$$B = q_1 + q_2 F + av_d/V + q_e$$

The solution can be solved numerically via a recursion relationship:

$$C_i(t + \Delta t) = \frac{A}{B} C_o(t + \Delta t) + \left\{ C_i(t) - \frac{A}{B} C_o(t) \right\} e^{-Bt} - \frac{A}{B^2 \Delta t} \{ C_o(t + \Delta t) - C_o(t) \} \{ 1 - e^{-Bt} \}$$