A numerical study of pollutant entrainment and dispersion in a street network

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Why does entrainment matter?
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Buncefield fire, North of London in 2005

Enormous quantities of PM10 released
Hypothetical street-level release in a city centre

Aerial view of DAPPLE site (central London) - www.dapple.org.uk
Superimposed visualization in a wind tunnel scale model
Basic questions & approach

• When/where is entrainment important?

• What controls entrainment in an urban canopy?

• How can we model it in fast dispersion models?

Demonstrate entrainment using data from Direct Numerical Simulations (DNS)
Represent entrainment and other processes within a simple box–network framework
Explore qualitative and quantitative capabilities of the model
DNS results: ground vs. elevated source

Branford et al. (2011); Coceal et al. (2014)

0 deg simulation

Solid line: within/above canyons
Dashed line: within/above channel

Crosses denote source locations (blue within array at ground level; red above array at 2h).
Arrow denotes wind direction.

Continuous release of a passive scalar from an ensemble of point sources, advected by turbulent flow under neutral stability; periodic horizontal boundary conditions.
Lateral mixing is faster than vertical mixing

Both lateral and vertical mixing are quicker for ground sources

Material is entrained more gradually than is detrained

Entrainment starts quite soon after the release
DNS results: centreline concentration

Branford et al. (2011); Coceal et al. (2014)

45 deg simulation

Volume-averaged concentration

Cross denotes ground-level source location (within intersection)

Rapid decrease in concentration within array; slower decrease above.

By the third intersection concentration within and above are virtually equal.

Proportion of downward flux of material increases until equilibrium is achieved.
**DNS results: temporal concentration evolution**

Re-entrainment provides a shortcut pathway

Time scales match those estimated based on advection and vertical exchange velocities computed from the DNS data

Numbers indicate time for scalar to first reach relevant street (in non-dimensional units)
A box-network framework for dispersion

\[ \dot{C} V = q + \sum_k \Phi_k \]

\[ f_k = \Delta C E_k A_k \]

\[ \Phi_k = F_k + f_k \]

\[ F_k = C U_k A_k \]

\[ \dot{C} = Q - \frac{C}{\tau} \]

Total loss rate \( \tau_k \equiv \frac{l_k}{u_k} \)

Treat each street as a well-mixed box (Goulart et al., 2015)

Belcher et al. (2015)  Analytical solutions exist for a regular street network
Time evolution through a network

\[ \dot{C} = Q - \frac{C}{\tau} \]

Continuous release

\[ Q = \text{constant} \]

\[ C(t) = C(0) e^{-t/\tau} + C(\infty) (1 - e^{-t/\tau}) \]

\[ C(\infty) = Q \tau \]

Puff release

\[ Q = Q_0 \delta(t) \]
Comparison of mean concentrations with DNS

LEFT: Centreline and lateral profiles in array

CENTER: Profiles above array

Reproduces well the decay in mean centreline concentration within and above the array.

Magnitude and width of plume well captured by simple model.

Increasing the detrainment rate does not change concentration in far field.

Network model is (extremely) simple and (extremely) fast!

Circles: DNS. Asterisks: Network model
Conclusions

• Entrainment in a street network becomes important after the first few streets downstream of a release.

• Re-entrainment can provide a quicker pathway for material than advection through the street network.

• Enhanced initial detrainment is compensated by higher subsequent re-entrainment.

• Dispersion is governed by effective transfer time scales, which depend on the geometry and flow.

• A simple box-network model captures concentration pattern and evolution quantitatively/qualitatively.
Further questions

Explored in more detail in the DIPLOS project (Dispersion of Localised Releases in a Street Network: www.diplos.org)

• Pathways for entrainment

• Relative proportion of material via different pathways

• Effect of wake trapping and tall buildings

• Lagrangian simulations
References


[www.diplos.org](http://www.diplos.org)