Manchester Metropolitan University

Passive Mitigation of a Surface-Based Source – the Application of an Aerofoil Array

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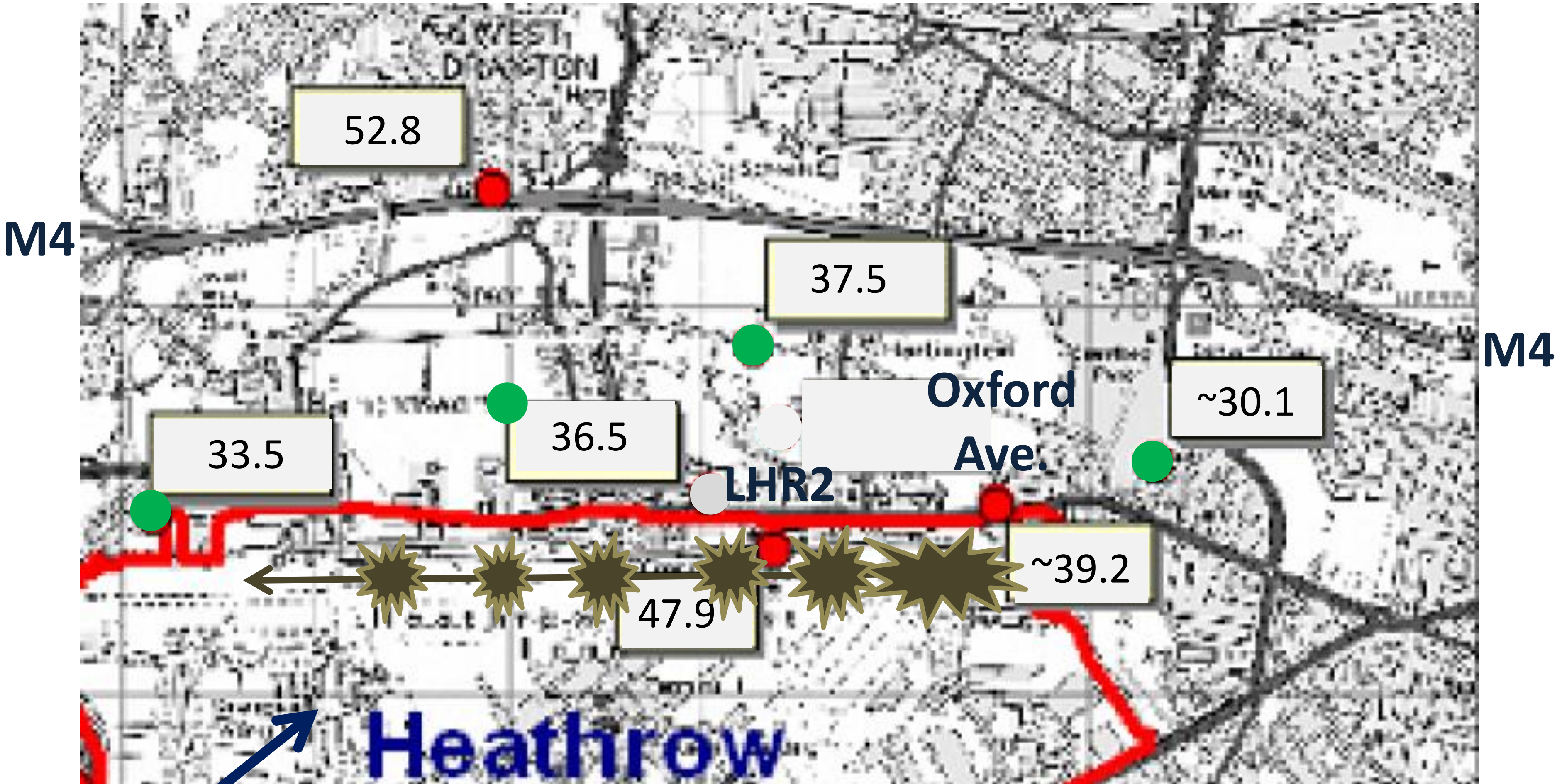
The Problem – such as it remains….



Prevailing wind

NO_2 concentrations, 2013.
(We're allowed 40 µg m^{-3}.)

Two phases to exhaust dispersion:-

Initial phase (Oxford Ave)
Source is near-stationary. Dispersion is initially dominated by the momentum of the emission and later by its buoyancy.

Late phase (LHR2)
Source is moving rapidly (~70 m s^{-1}). Exhaust is thus extended longitudinally but also initially forced to the ground by the lift on the wings.

At some speed close to 70 m s^{-1}, the pilot increases the angle of attack of the aircraft ("rotation"). This increases its lift and allows it to take of at ~90 m s^{-1}. Of course, it also directs the exhaust at the ground even more strongly.

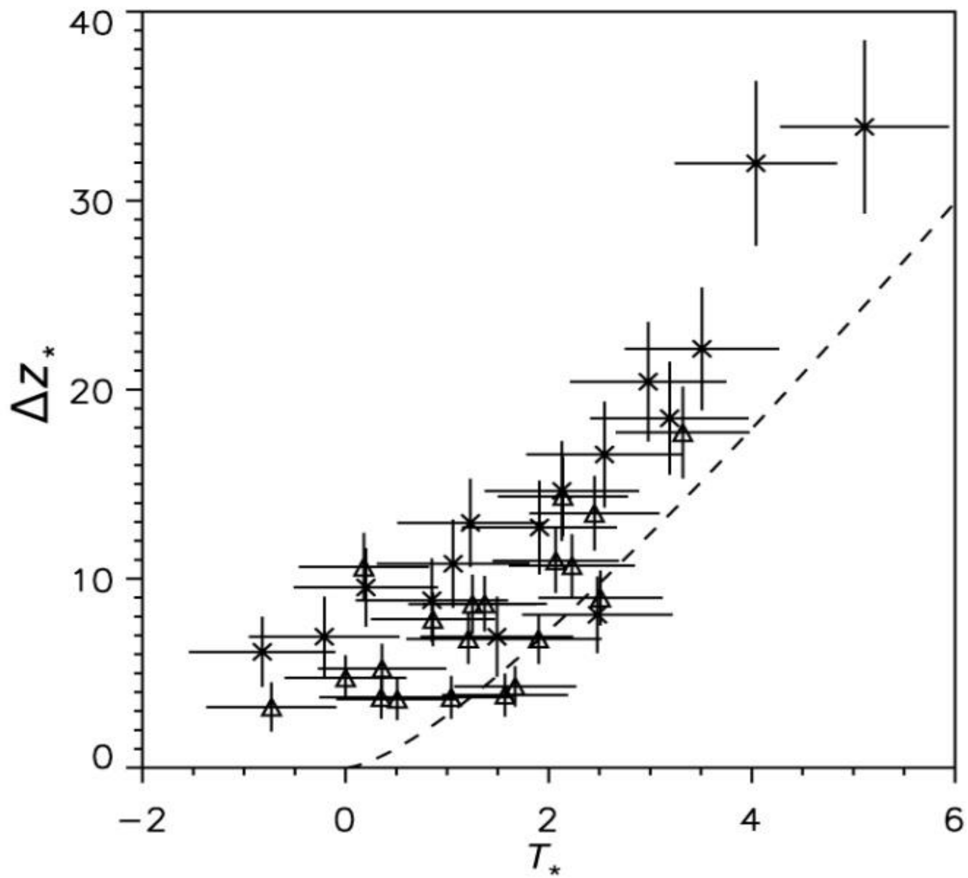
In both phases, the emission is dispersed laterally as a wall jet, but also advected to the airport boundary by any S component to the wind.

Initial phase (Oxford Ave.)

Great deal of experimental (Lidar) and theoretical (PDEs) work,

e.g. for height of head of wall jet against travel time (both non-dimensionalized):-

This work was funded by the EPSRC with a view to improving airport AQ modelling.



Graham A *et al.*., 2008, Representing the dispersion of emissions from aircraft on runways, *Proc. 12th Int. Conf. on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes.* 6-9 October 2008, Cavtat, Croatia.

Mitigation Measures (initial phase) – Baffles!

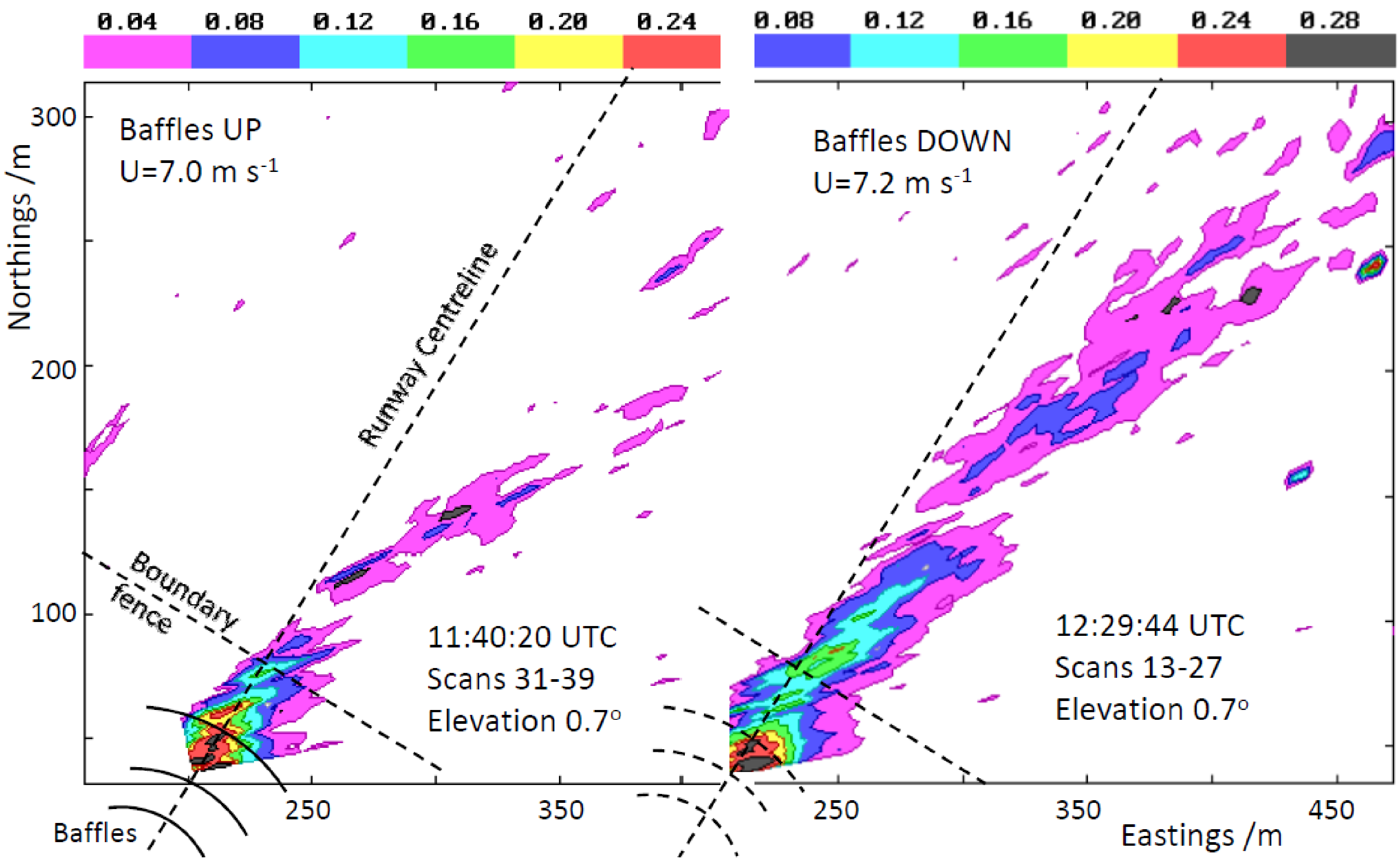
Cranfield,
Sept. 2011

EPSRC funded

By breaking the Coanda effect – which glues the exhaust plume to the surface for 50-80 m from the source – we allow the plume to follow its natural tendency to rise.   The baffles form a **virtual chimney**.

Lidar maps of exhaust plume (initial phase)

(Essentially, time-integrated PM concⁿ just above hedge height.)



Bennett, M, *et al.*, 2013: Abatement of an aircraft exhaust plume using aerodynamic baffles. *Environ. Sci & Technol.* **47,** 2346–2352. DOI: 10.1021/es303586x.

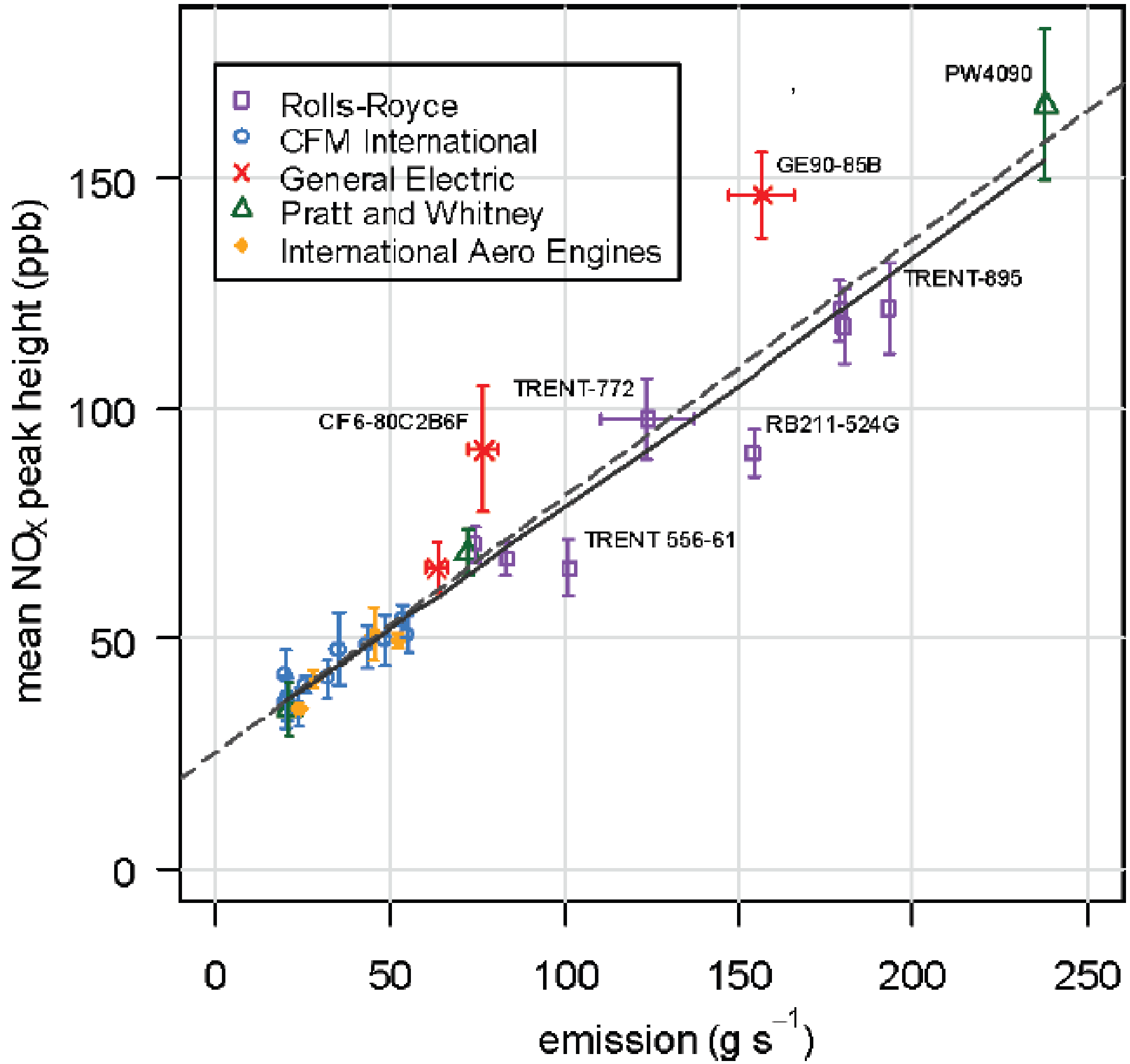
Late phase (LHR2)

The exhaust trail is advected laterally across the monitor. Best-fit line implies that emission is dispersed vertically by $\Delta z \approx 95$ m by the time it reaches the LHR2 monitor.

Buoyant rise is also important, so really we have:-

$$\frac{1}{\Delta z} = \sqrt{\frac{2}{\pi}}\frac{1}{\sigma_z}\exp\left\{-\frac{h^2}{2\,\sigma_z^{\,2}}\right\}$$

$= 1/95 \ \text{m}^{-1}$



Carslaw, D.C, *et al.*, 2008: Near-field commercial aircraft contribution to nitrogen oxides by engine, aircraft type, and airline by individual plume sampling. *Environ. Sci. & Technol.*, **42,** 1871–1876.

Baffles cannot usefully mitigate late phase dispersion!

1) At the side of the runway, the jet blast is no longer available.

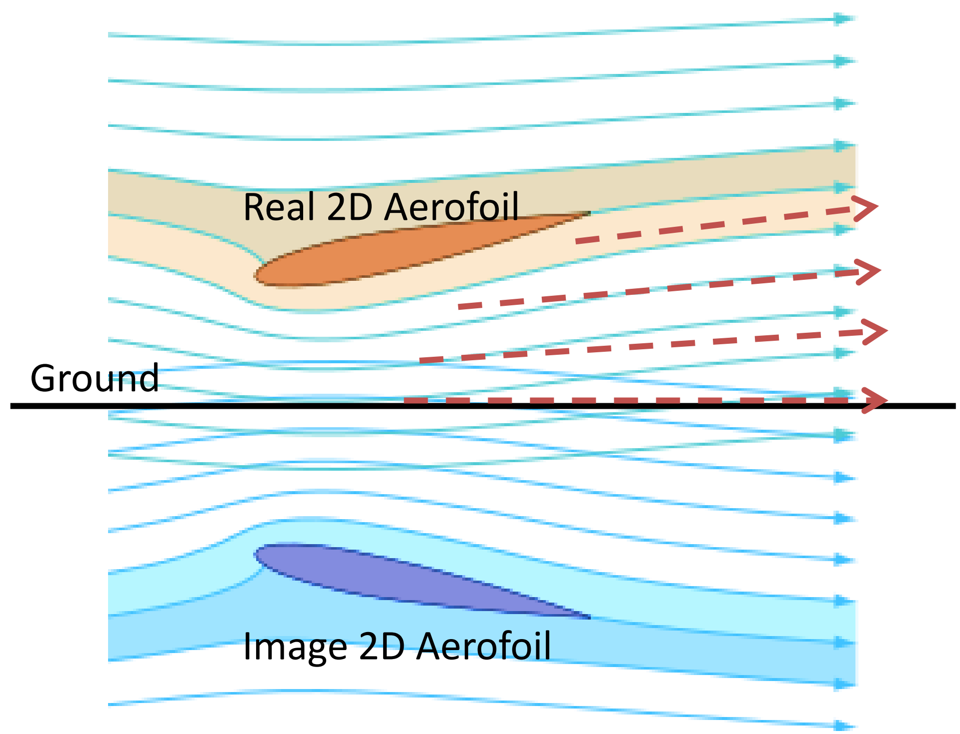
2) If we use the ambient wind (and the advance of the wall jet) to deflect the emission upwards, where is the clean air to replace it to come from?

Fundamentally, the problem is that:

behind the starting jet (initial phase), we have a 3D flow, which we can lift from the ground, while

beside the runway we have a quasi-2D ground-based exhaust – this cannot all be lifted simultaneously.

The flow may be slowed and deepened but remains ground-based.

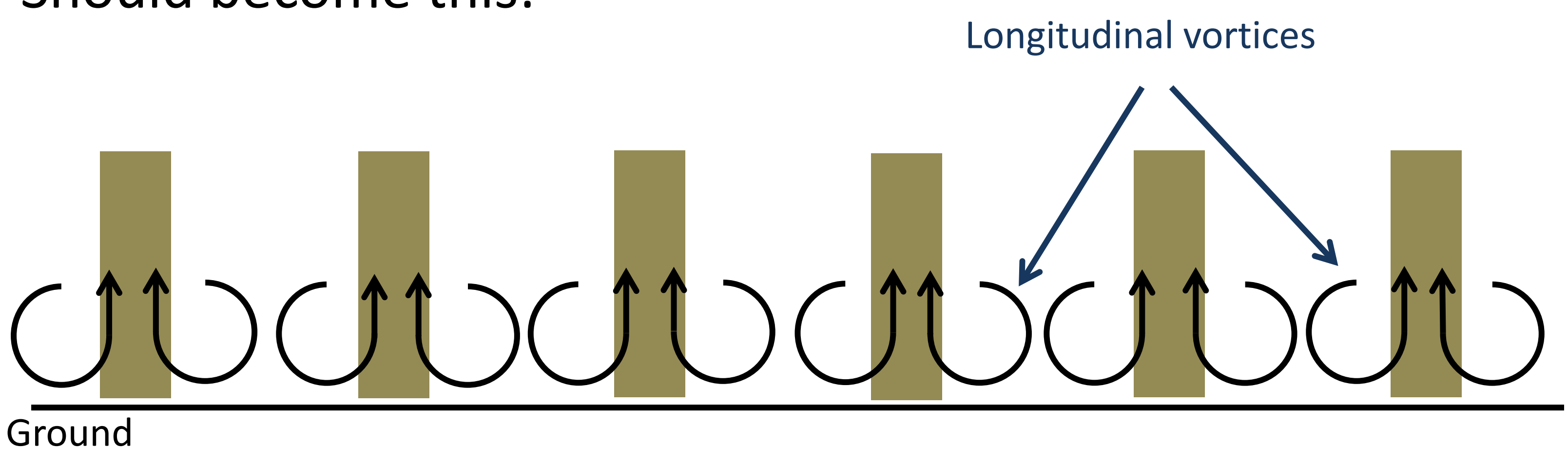


On the other hand….

We could break the exhaust into segments and encourage a substantial fraction to leave the ground.

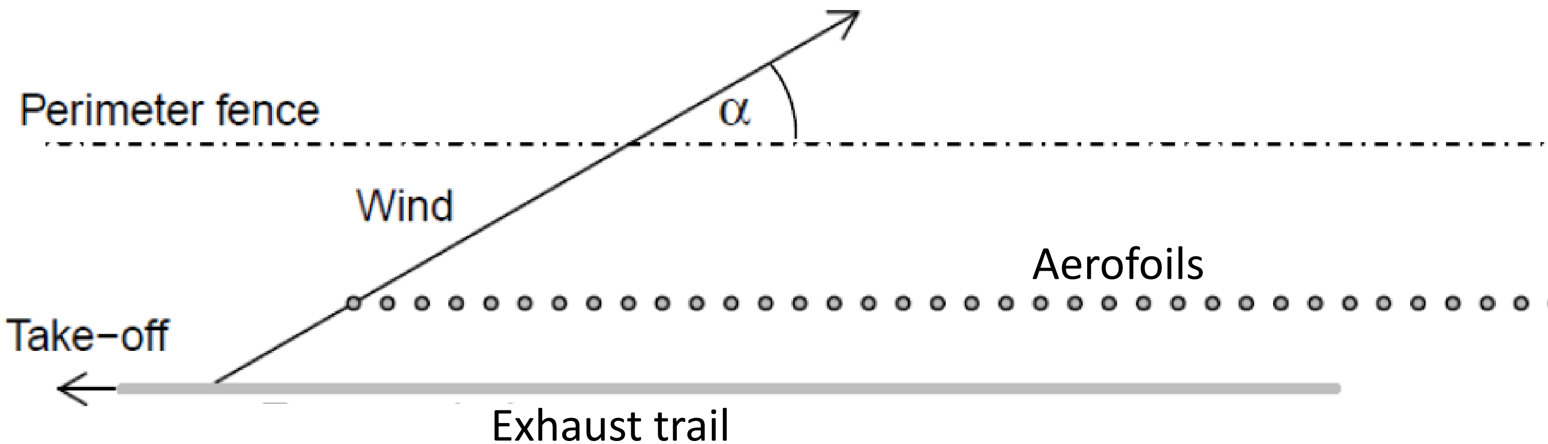
Thus:-

Should become this:-



We can achieve this by installing a row of aerofoils between the runway and the perimeter fence.

Thus:-



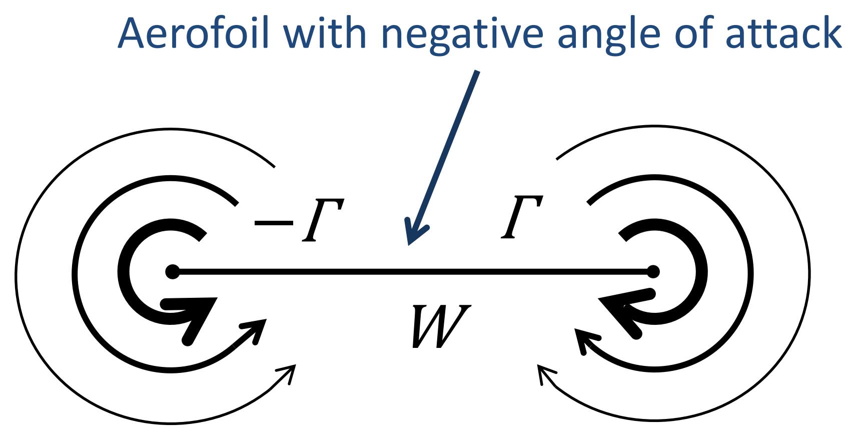
If the aerofoils are given a <u>negative</u> angle of attack, then they apply <u>upwards</u> momentum to the ambient crosswind.

Piecewise, they thus displace the exhaust trail upwards.

Zhukovski's theorem

Chord

Lift on long aerofoil ($W \gg B$)



$$F_{L\infty} = ½\, C_{L\infty}\, \rho\, B W u^2$$

$$= \rho\, \Gamma_\infty\, W\, u$$

Hence, <u>vorticity</u> $\Gamma_\infty = ½\, C_{L\infty}\, B\, u$

For finite W, an elliptical aerofoil is optimal and hence

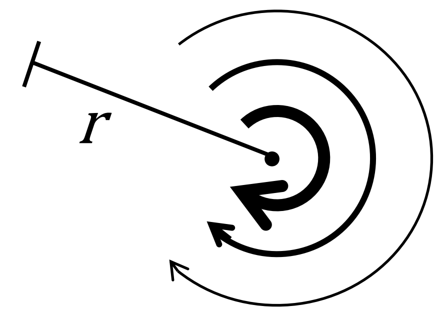
$$\Gamma_e = {}^{\pi}/_{8}\; C_{L\infty}\, B\, u$$

For a flat plate, the maximum value of $C_{L\infty}$ is 0.88

— values of >1.5 are obtainable with standard aerofoils.

Vortex flows

Vorticity, Γ is related to tangential velocity by $\Gamma = 2\pi r u_t$ and is conserved in inviscid flow.



Thus $u_t = {}^{1}/_{16}\, C_{L\infty}\, B\, {}^{u}/_{r}$

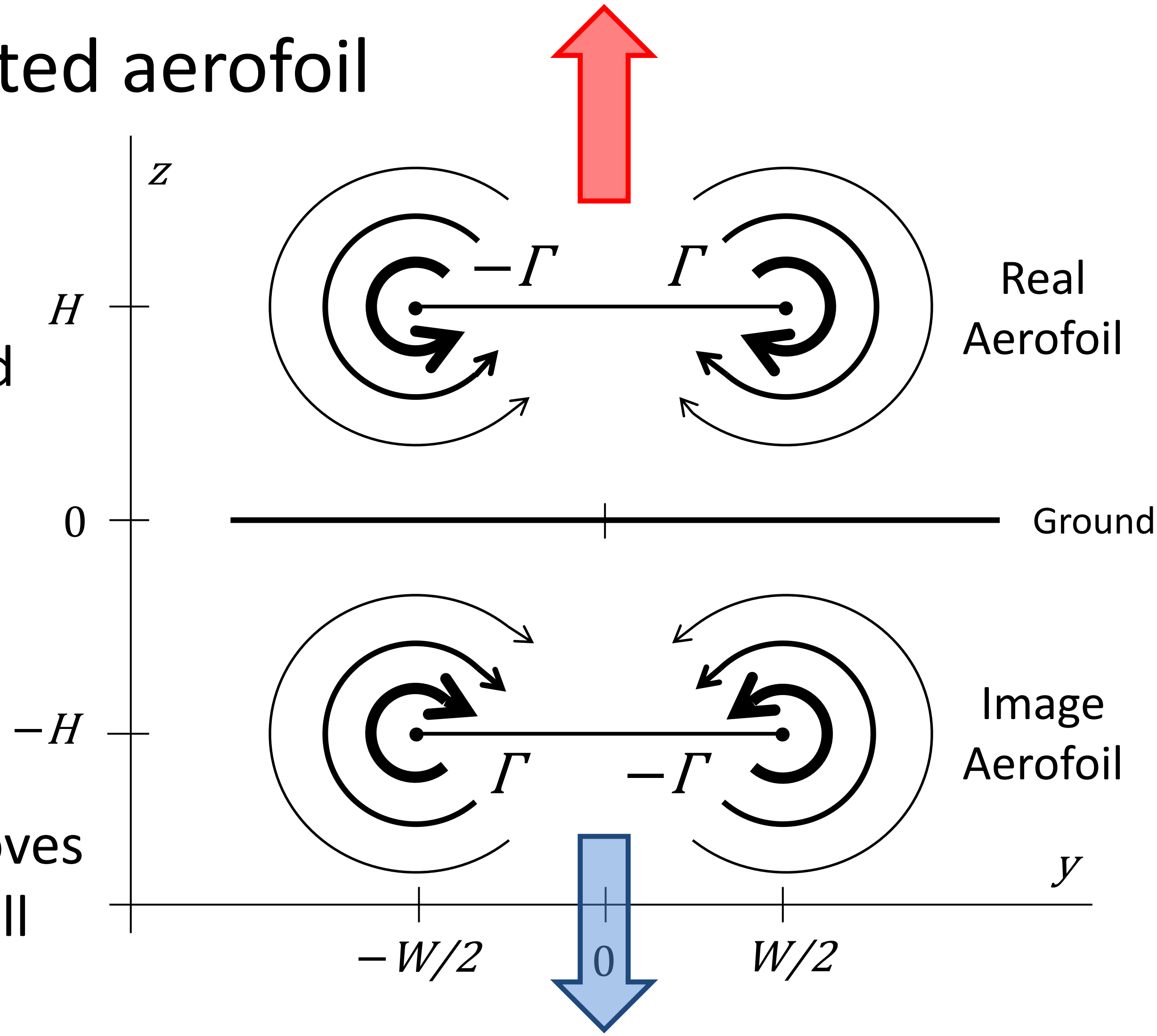
Setting the system in Cartesian coordinates with x downwind, y cross-wind and z vertical, we can see flows evolve geometrically in the y-z plane as

$$\frac{\Delta y}{\Delta x} = {}^{1}/_{16}\, C_{L\infty}\, B\, {}^{z}/_{r^2} \quad \text{and} \quad \frac{\Delta z}{\Delta x} = -\,{}^{1}/_{16}\, C_{L\infty}\, B\, {}^{y}/_{r^2}$$

where $r^2 = \Delta y^2 + \Delta z^2$.

Surface-mounted aerofoil

Neglecting boundary-layer effects, we must add a pair of image vortices below ground to ensure zero vertical flow at $z = 0$.



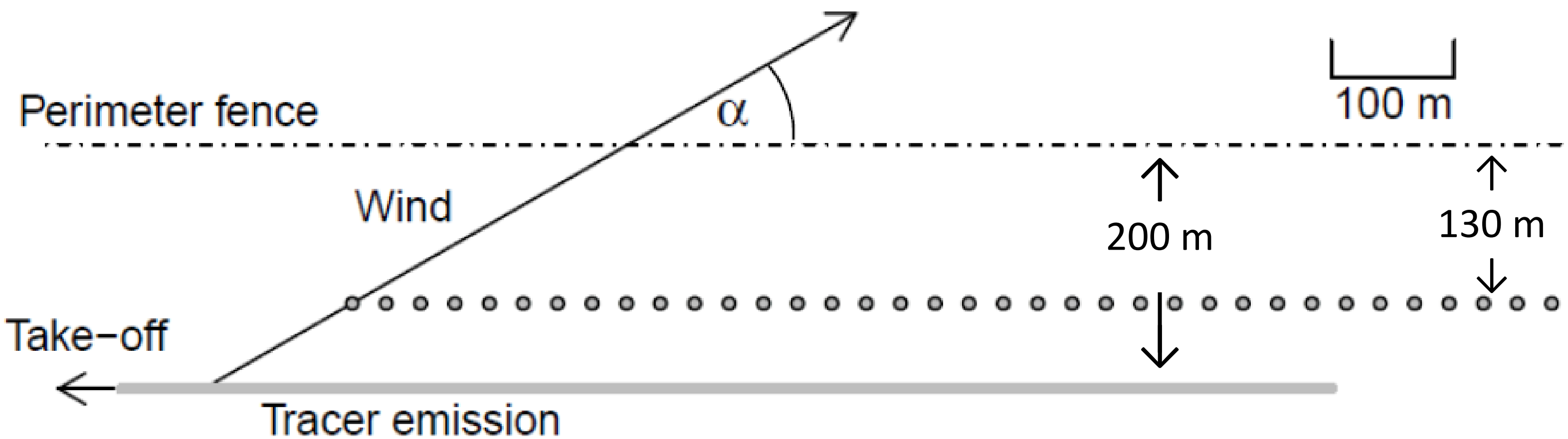
Each vortex core moves in the flow-field of all the <u>other</u> vortices.

In the absence of other flows, both real and image vortices thus move away from the surface.

Calculations

We can now model numerically the flow field downstream of our row of aerofoils. These are treated as 36 inclined circular flat plates, of diameter 10 m and spacing 28 m between centres.

The use of circular plates minimizes W and maximizes Γ.



Exhaust trail is modelled as particles released on a 1 m × 2 m grid up to a height of 5 m above the runway centreline.

These move passively in the flow fields of all 144 vortices.

Effect on tracer plume

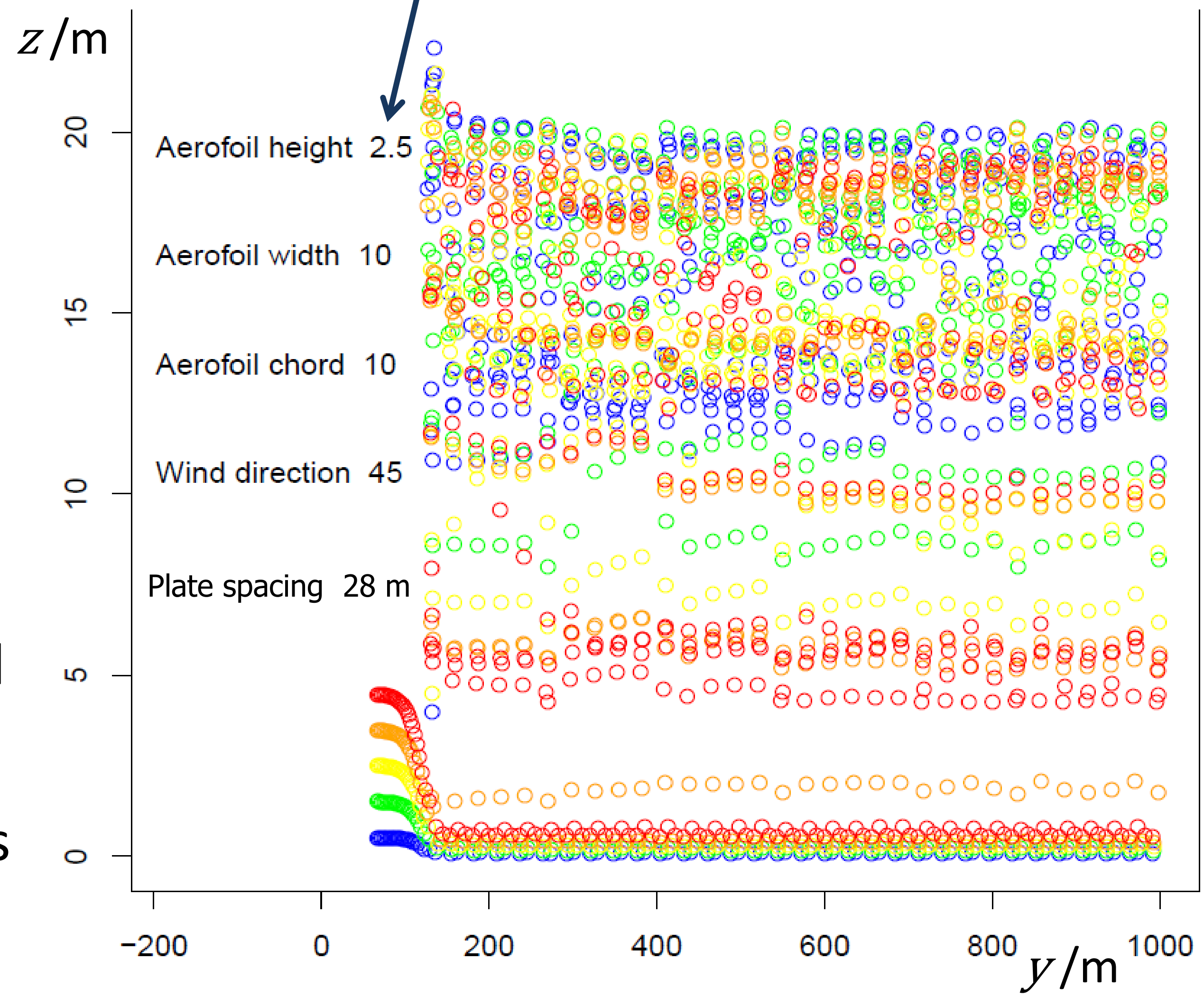
$\alpha = 45^o$

At the distance of the fence, the aerofoils have split the tracer into:

a) A ground-hugging component; and

b) A diffuse cloud between heights of 5 and 20 m.

Aerofoils must be at a height comparable to the release height of the tracer.

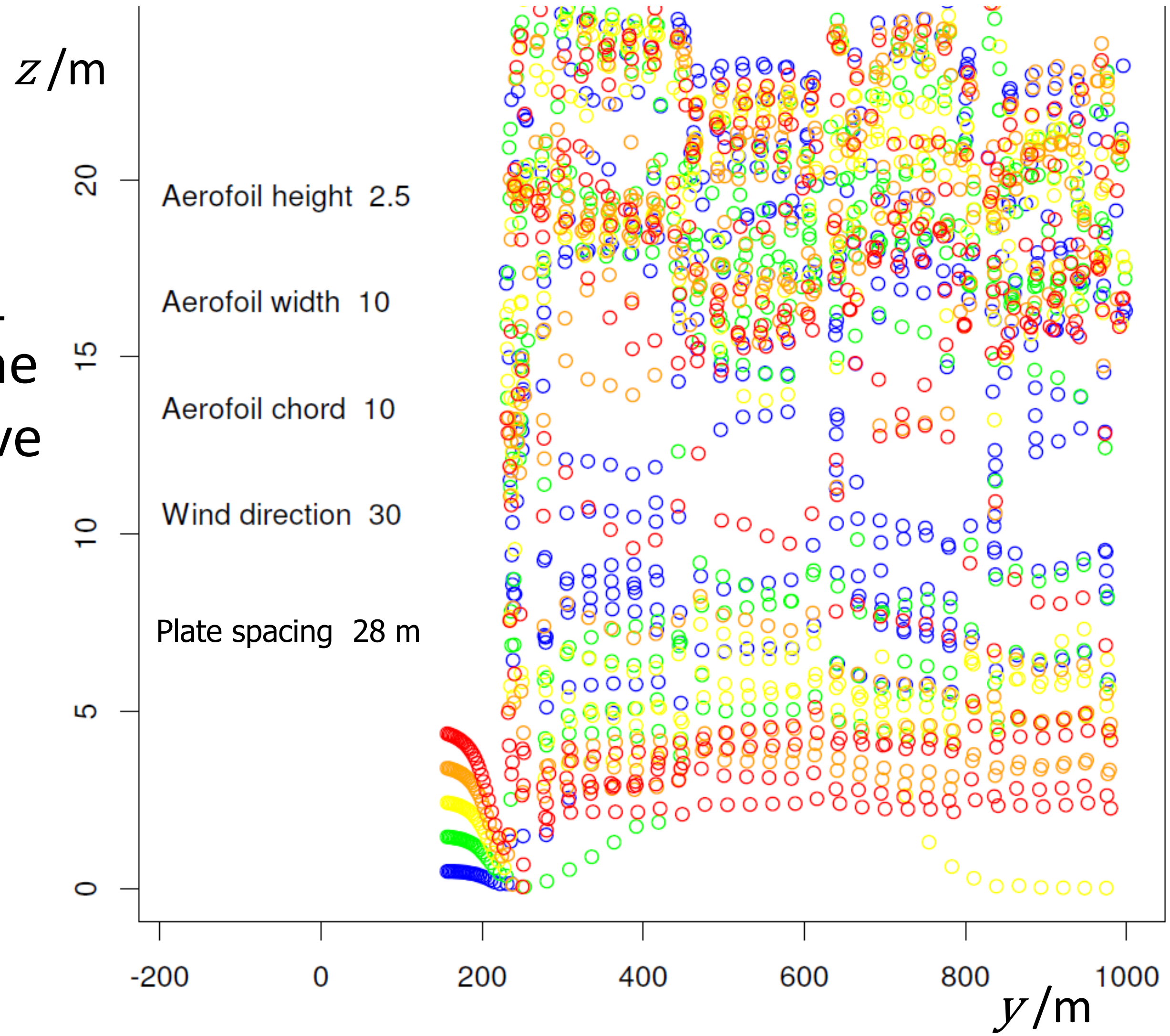


For these parameters, the mean height gain is 9.5 m.

Effect on tracer plume

$\alpha = 30^o$

With a <u>longer fetch</u> to the boundary, the trailing vortices have been able to lift all the exhaust off the ground.



For these parameters, the mean height gain is 11.7 m.

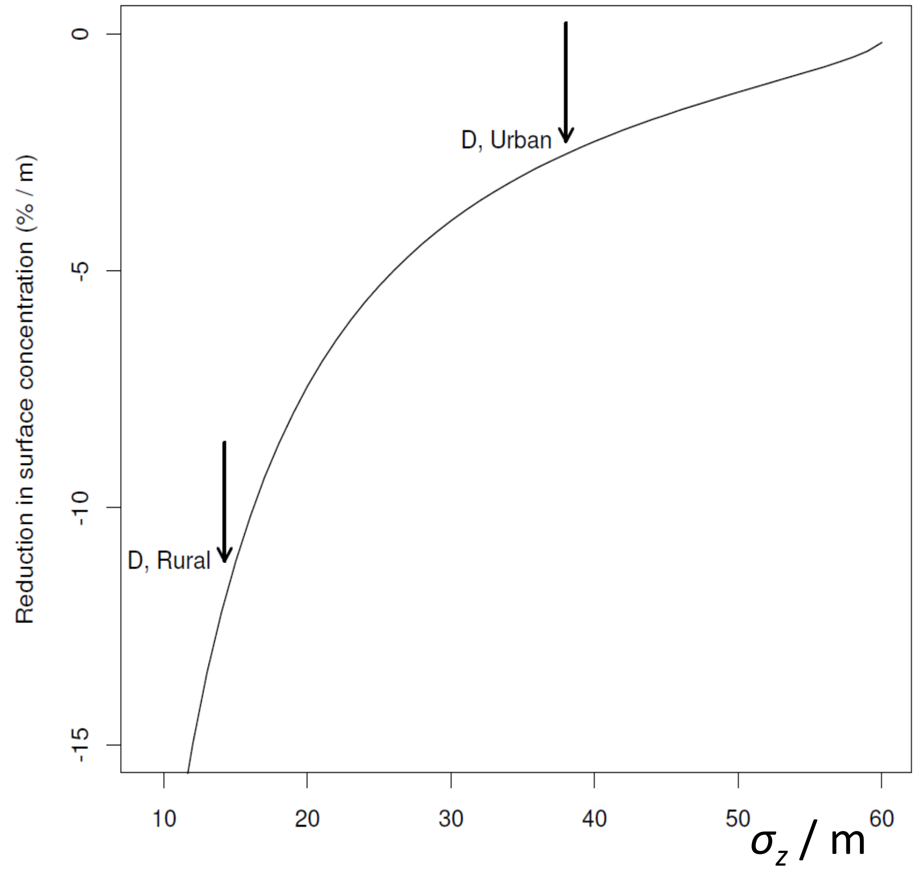
Impact on surface concentration at the fence

We treat each tracer particle as dispersing independently from the runway centreline to the boundary fence at a travel distance of 283 m ($\alpha = 45^{o}$).

What is the impact of a few extra m of particle height?

Gaussian formula gives:-

$$\frac{1}{\chi}\frac{\partial \chi}{\partial h} = -\frac{1}{\sigma_z}\sqrt{2\ln\frac{2\,\Delta z}{\pi\,\sigma_z}}$$



Carslaw *et al.* give $\Delta z \approx 95$ m, while Pasquill-Gifford give $\sigma_z \approx 38$ m downstream of the terminal buildings .

Assuming linearity, we have thus abated surface concentrations by ~24% for these aerofoil parameters. More should be possible with better aerofoils.

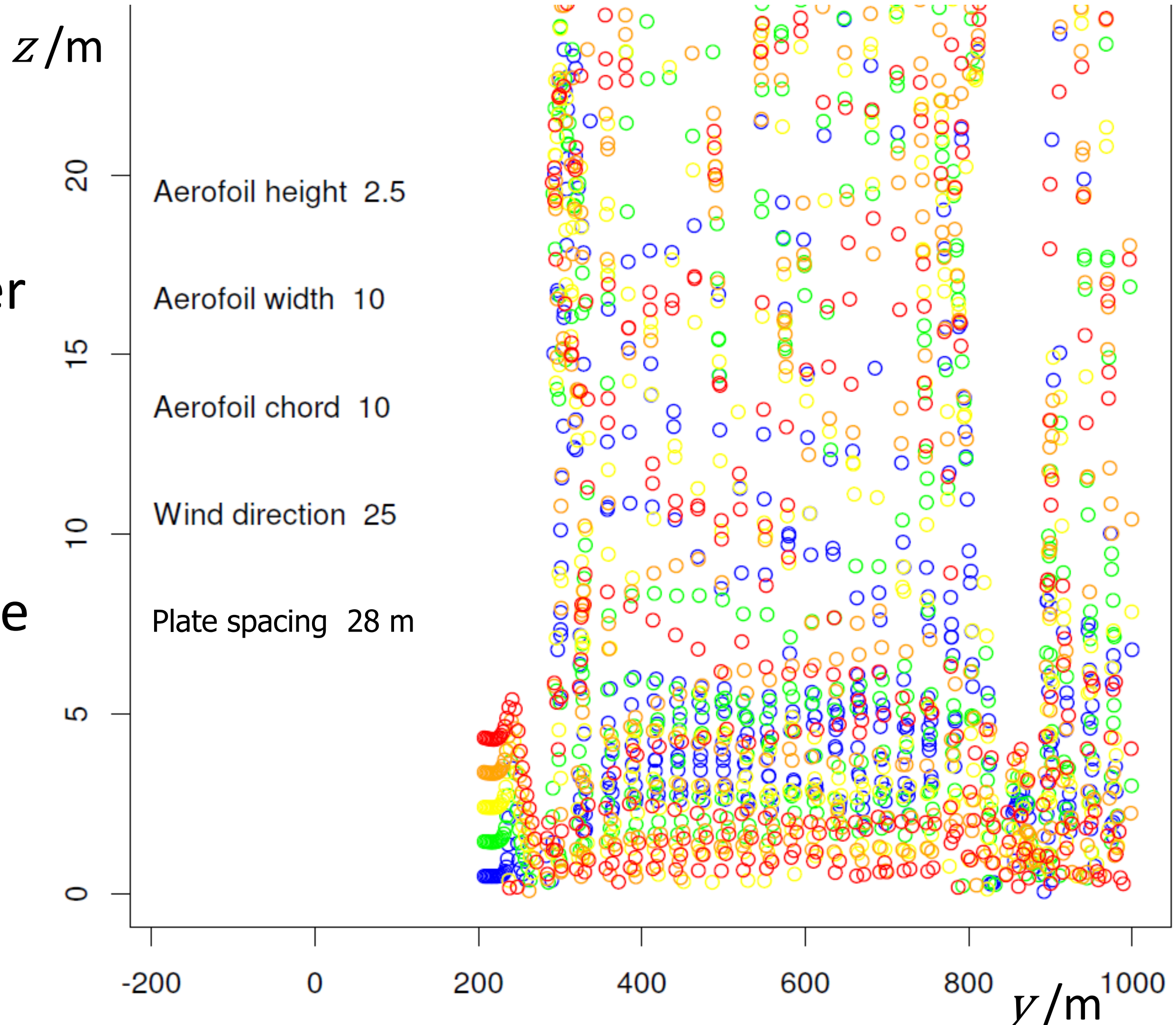
Chaotic behaviour

$\alpha = 25^{o}$

If the aerofoils are close enough together for vortex pairs to overlap, the flow becomes chaotic.

Calculated outputs are then essentially stochastic.

Height gain: 8.6 m



Great care must be taken with the numerics if physically realistic outputs are to be obtained.

Conclusions

- This relatively simple intervention could significantly reduce the local impact of an extended ground-level source.
- Serious modelling (wind tunnel and CFD) is needed – in particular to include the effects of the boundary layer.
- At an airport, safety considerations are paramount, so serious engineering calculations would also be required.
- The method could apply equally to (e.g.) reducing ground frosts.