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The Application of CFD to the Estimation of Motor Vehicle Pollution in Urban Environments

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Topics to be covered

- Introduction
- Rationale for air quality modelling
- Main pollutants and their health effects
- Advection/diffusion models
- Two-dimensional CFD models
- Three-dimensional CFD models
- Conclusions

Introduction

- Polluted air can adversely affect humans, plants, animals and buildings.
- Major pollution events can cause illness and death
- Chronic pollution, even at low levels can cause and exacerbate respiratory illness.
- Pollution may arise from industry, domestic and commercial heating, agriculture and transport.
- Major problems are now being created by motor vehicles, despite technological improvements.

Glasgow Street Canyon

Glasgow Urban Motorway

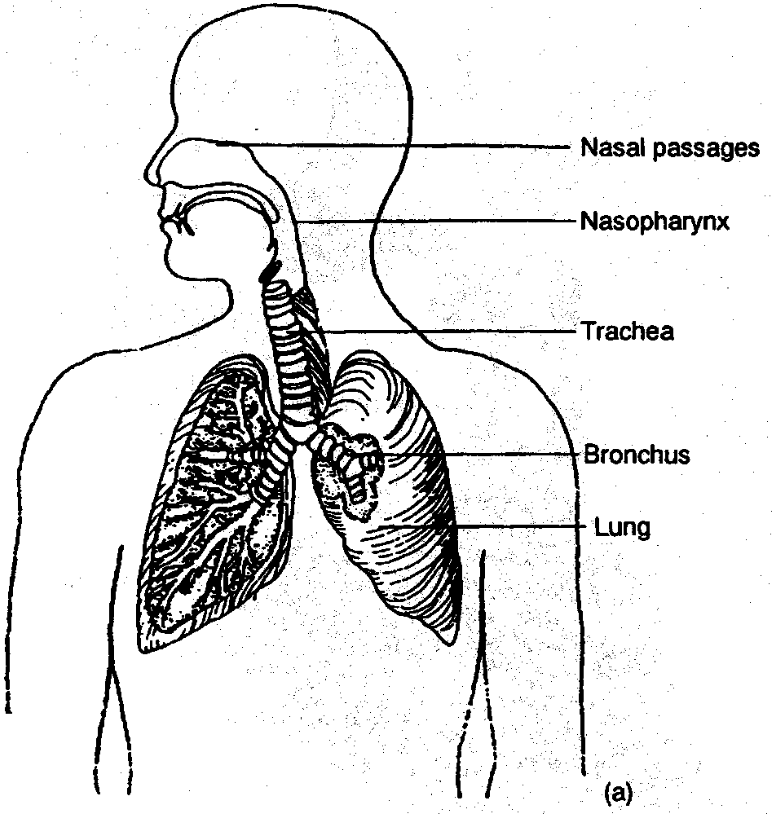
Rationale for Air Quality Modelling

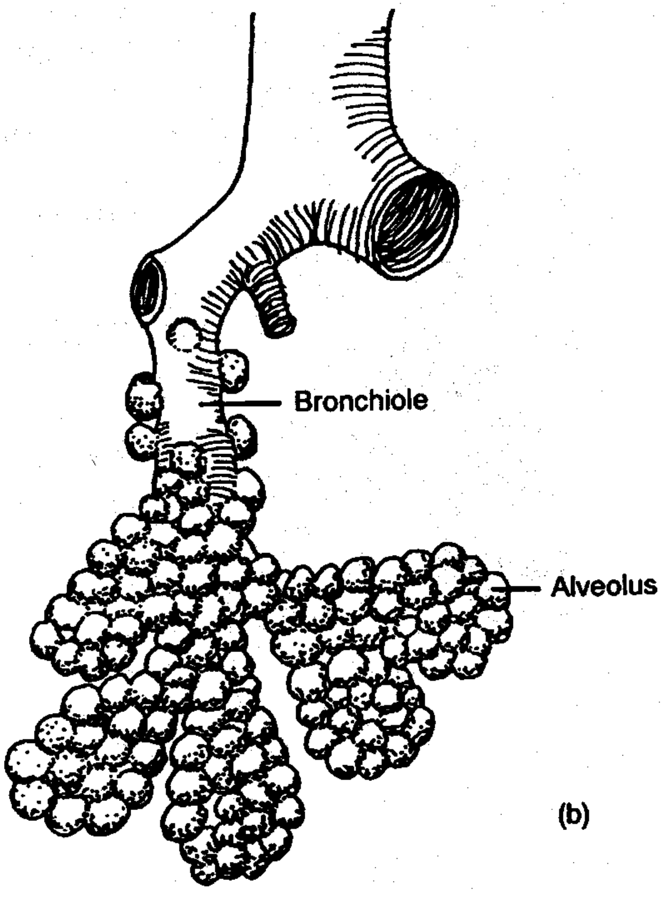
- Establishing emission control legislation
- Evaluating emission control strategies
- Locating future sources
- Planning control of pollution episodes
- Assessing responsibility for pollution
- Spatial and temporal interpolation of data

Main Air Pollutants

- Carbon monoxide
- Sulphur dioxide
- Nitrogen dioxide
- Particulate Matter
- Lead
- Benzene
- 1,3-butadiene
- Heavy metals (Hg, Cd, Ni, Cr)
- Arsenic
- Poly-aromatic hydrocarbons (PAH)
- Ozone
- Peroxyacetyl nitrate (PAN)

Air Pollution Targets the Eyes, Respiratory System and Nervous System





Carbon monoxide

- Caused by incomplete combustion of carbon in the fuel
- Internal Combustion engine is primary source in urban areas
- Combines with haemoglobin in the blood and affects nervous system
- Relatively long lifetime in atmosphere: 50 days
- Effectively a conserved tracer

Air Quality Models

- Air quality models attempt to simulate the concentrations of air pollutants in the real world.
- Mathematical models use analytical and numerical formulations, usually implemented on computers.
- Models may be deterministic or statistical.
- Models may be based on first principles or be empirical.

Eulerian Advection/Diffusion Models

- Wind speeds and concentrations are specified in a stationary co-ordinate system (i.e. as "fields")
- Wind speed field is found using computational fluid dynamics (PHOENICS CFD or from measurements)
- Advection diffusion equation solved for concentration field.

Advection Diffusion Equation (e.g. in PHOENICS)

$$\frac{\partial C}{\partial t} = -\left(U.\nabla\right)C + K_D \nabla^2 C + S$$

$C(x,y,z,t)$ = concentration of pollutant

$K_D(x,y,z,t)$ = atmospheric turbulent diffusion coefficient

$U(x,y,z,t)$ = windspeed vector

$S(x,y,z,t)$ = source/sink for pollutant

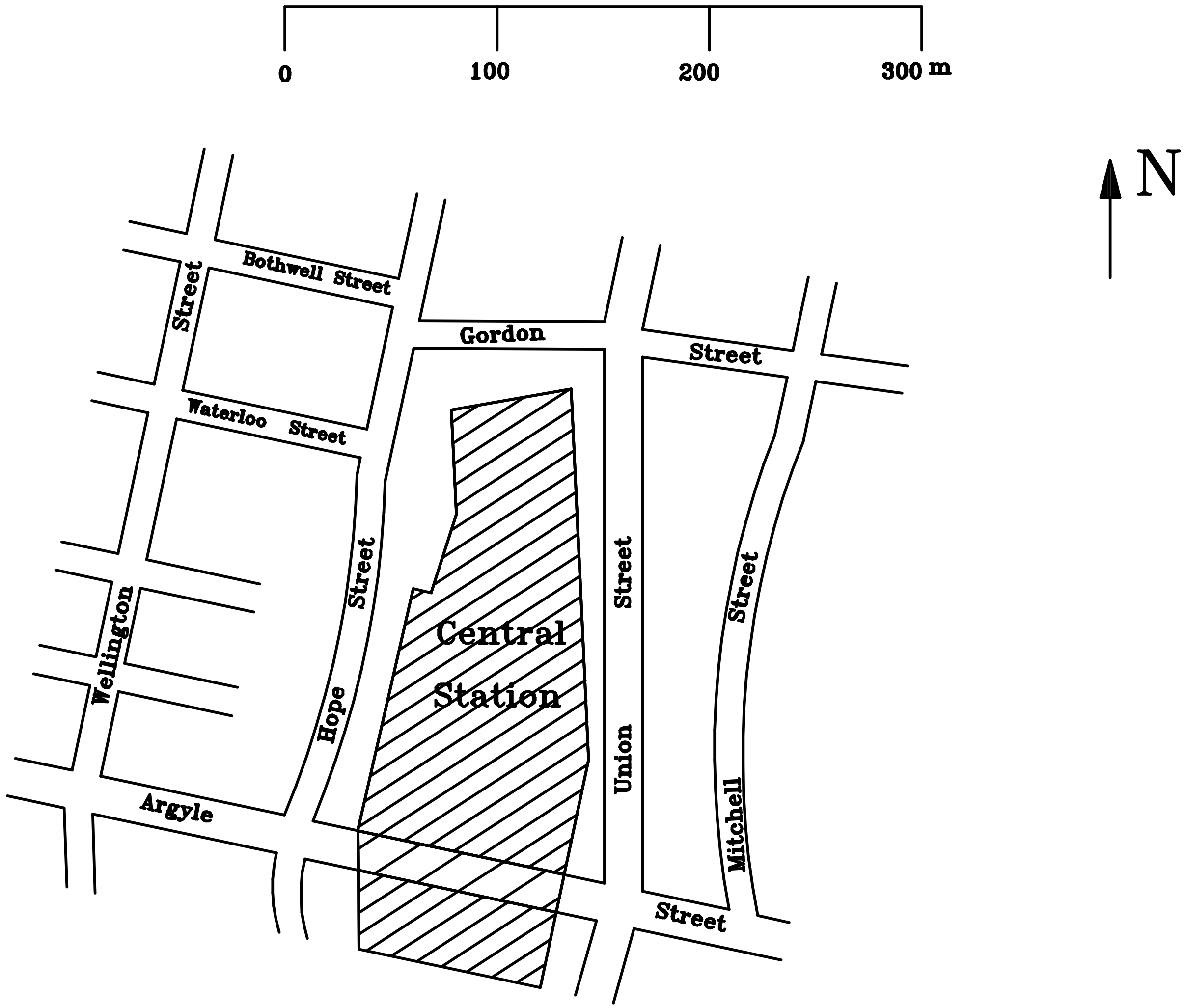
∇= gradient operator

∇^2 = Laplacian operator

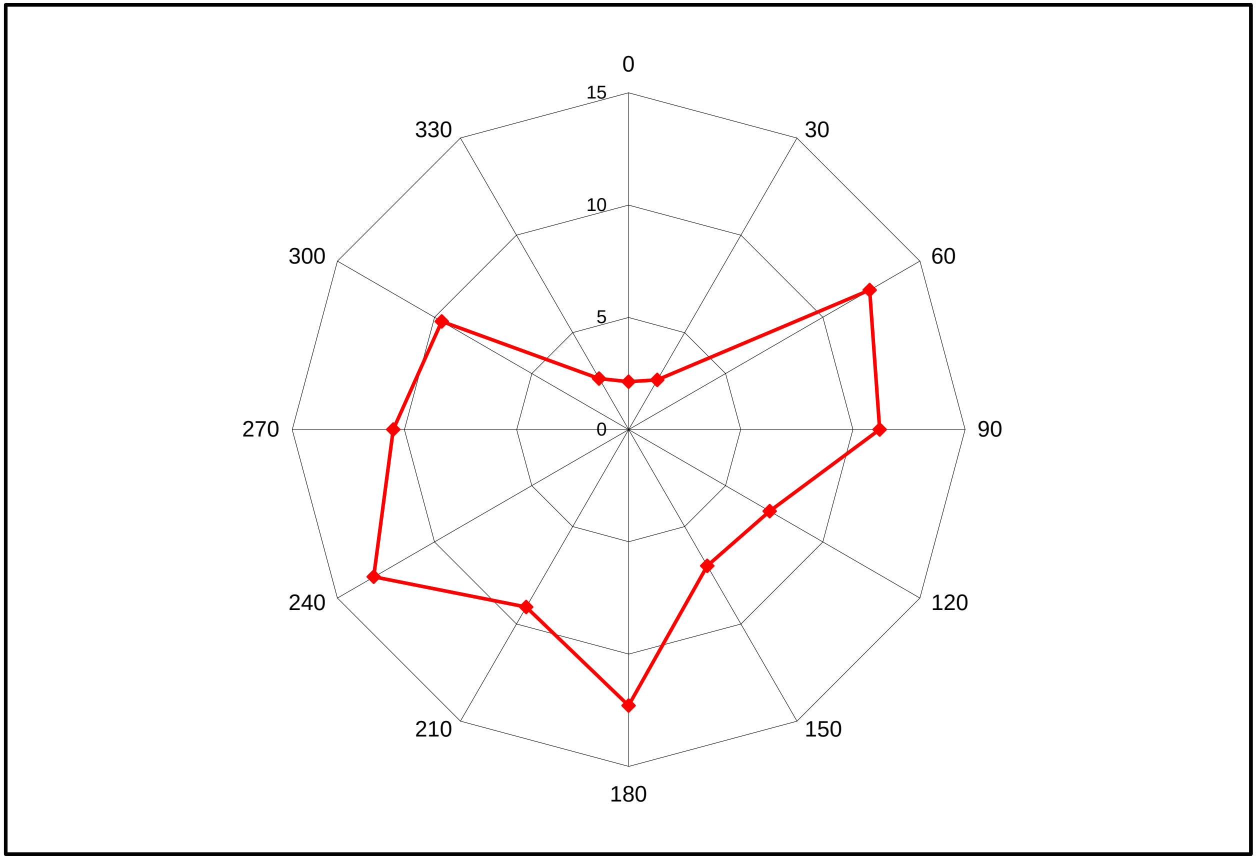
PHOENICS CFD Modelling

- Two-dimensional, infinitely long street canyon
- Cartesian coordinates
- Standard k-ε turbulence model
- Steady State

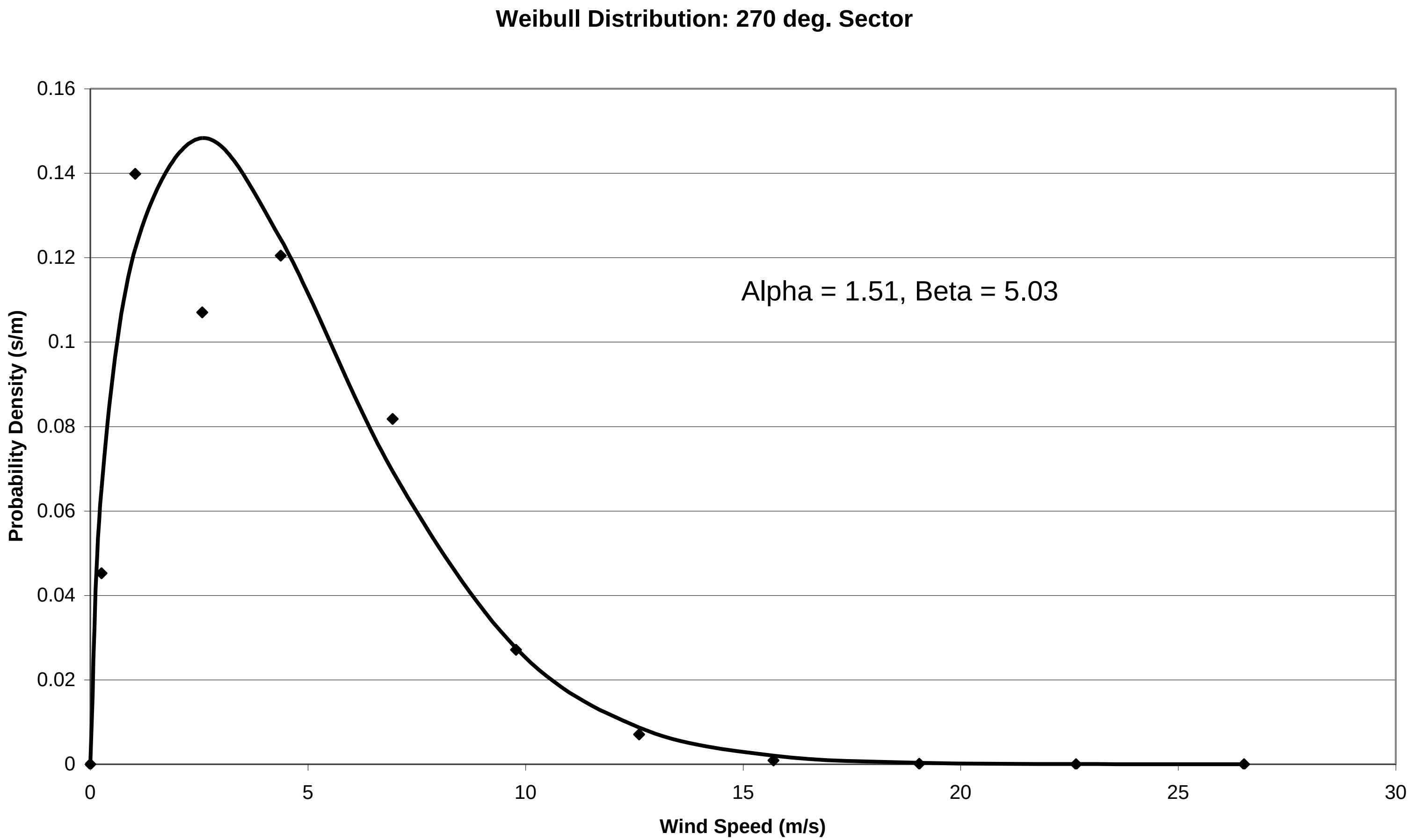
Hope Street, Glasgow



Wind Rose for Meteorological Office Weather Station at Bishopton



Typical Wind Speed Distribution for Bishopton Weather Station



Standard k-ε Turbulence Model

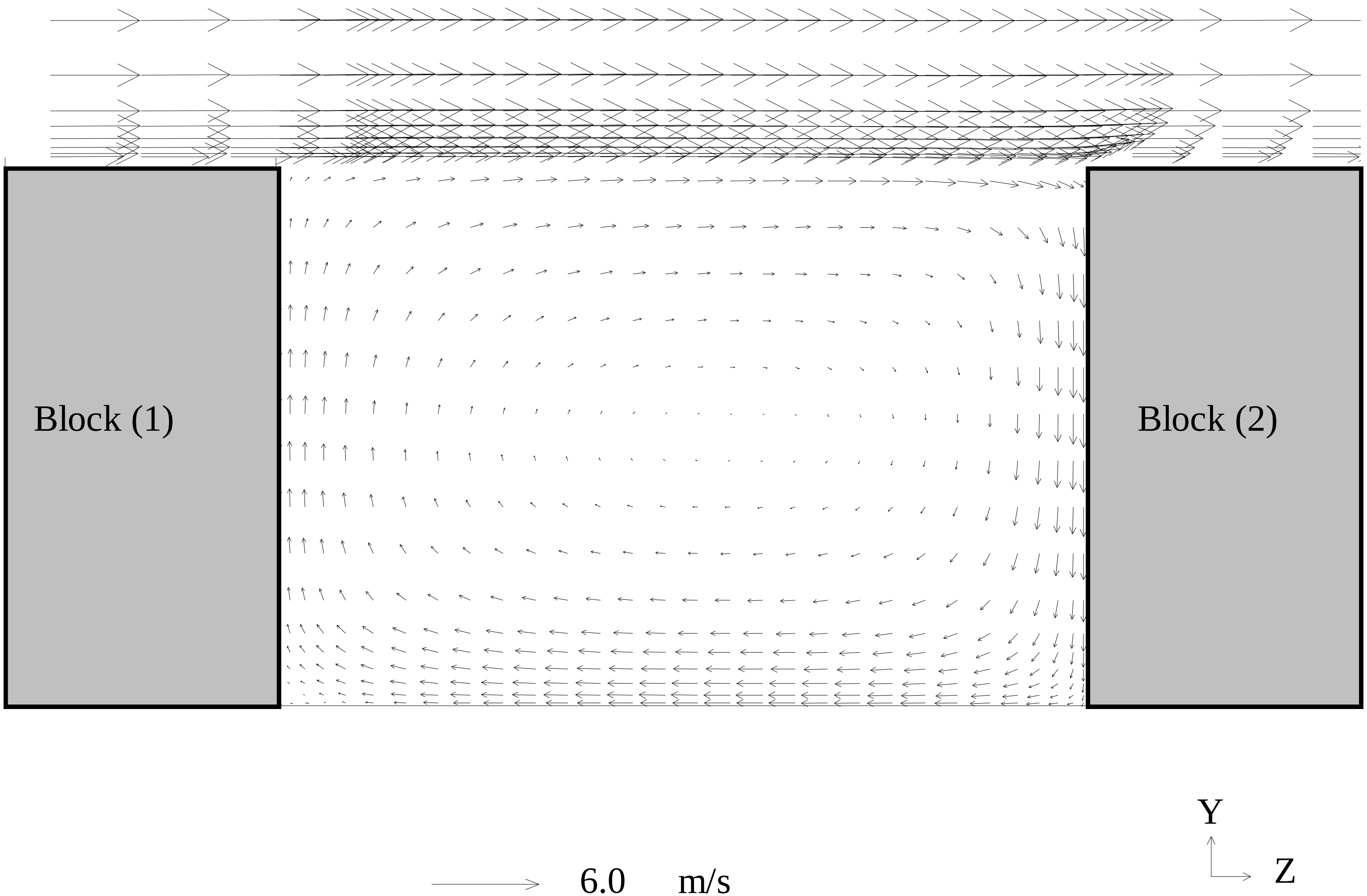
Equation	Φ	Γ_Φ	S_Φ
Turbulent Kinetic Energy	k	ν_t/σ_k	$\rho(G-\varepsilon)$
Dissipation Rate	ε	ν_t/σ_ε	$\rho(\varepsilon/k)(C_{\varepsilon 1}G - C_{\varepsilon 2}\varepsilon)$

$$G = \nu_t (\partial_k U_i + \partial_i U_k) \partial_k U_i$$

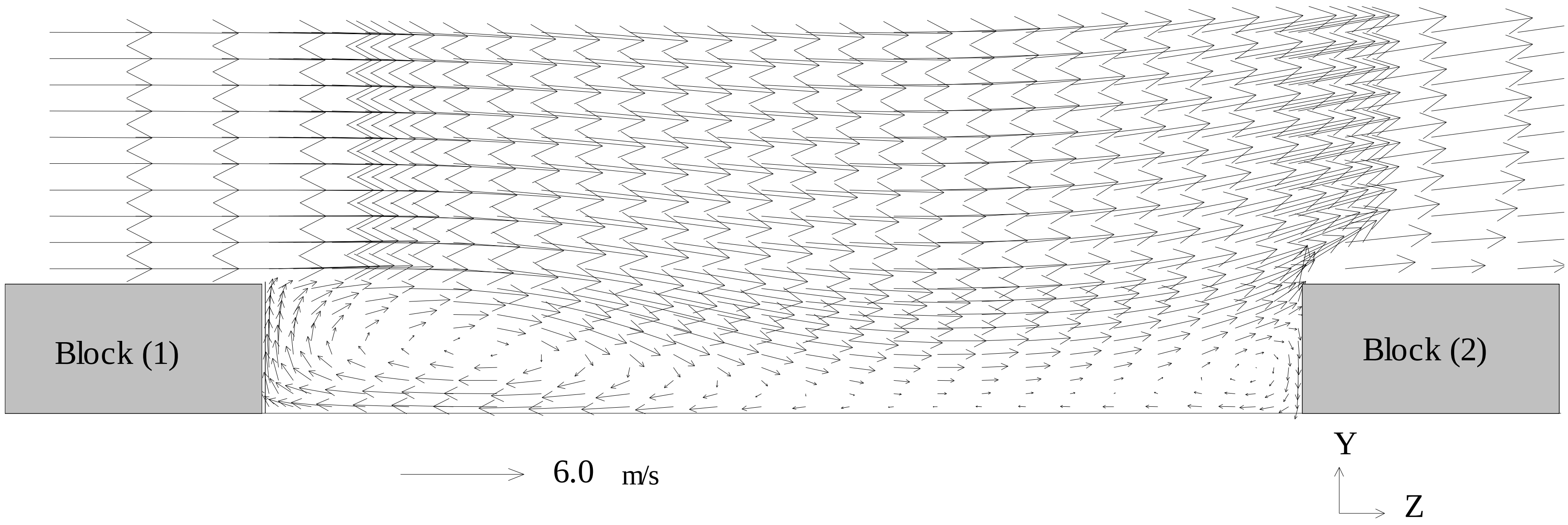
$$\nu_t = C_\mu k^2 / \varepsilon$$

σ_k=1.0, σ_ε=1.314, $C_{\varepsilon 1}$=1.44, $C_{\varepsilon 2}$=1.92, C_μ= 0.09

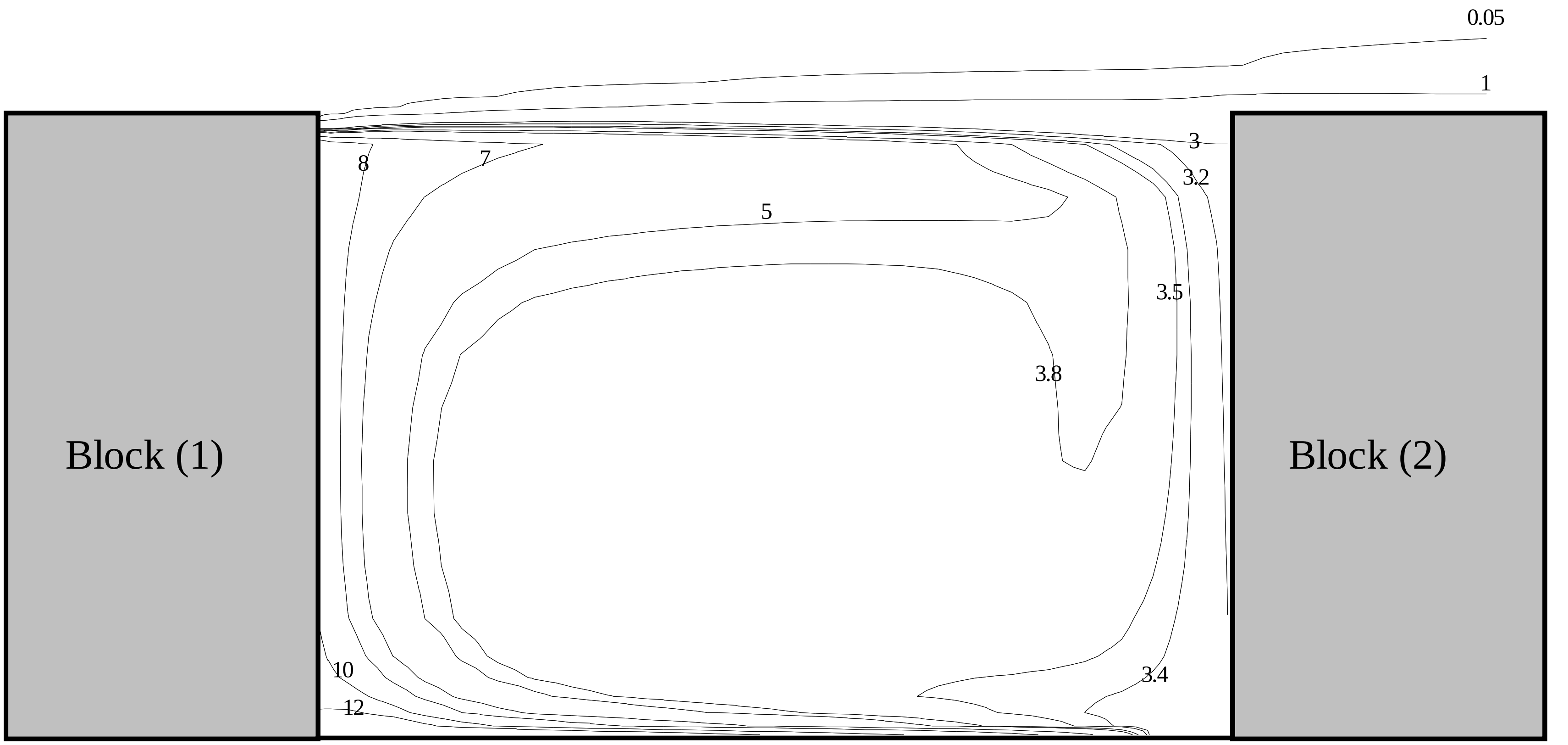
PHOENICS two-dimensional simulated wind flow in a street canyon for W=30 m H=20 m



PHOENICS two-dimensional simulated wind flow in a street canyon for W=40 m, H=5 m



PHOENICS CO contours (ppm) for a wind speed above building U=5 m s^{-1}, W=30 m H=20 m



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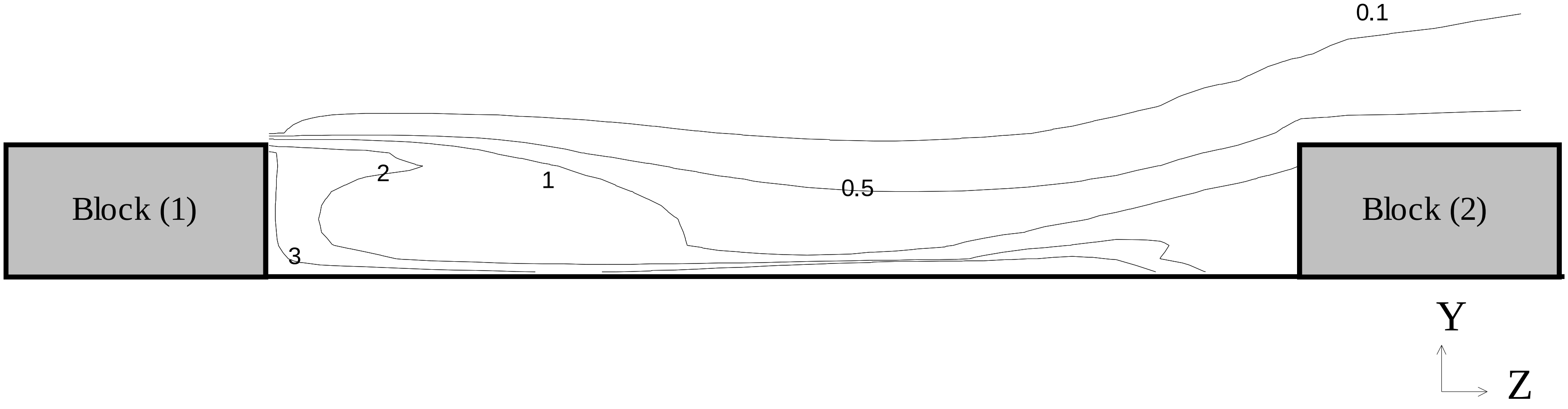
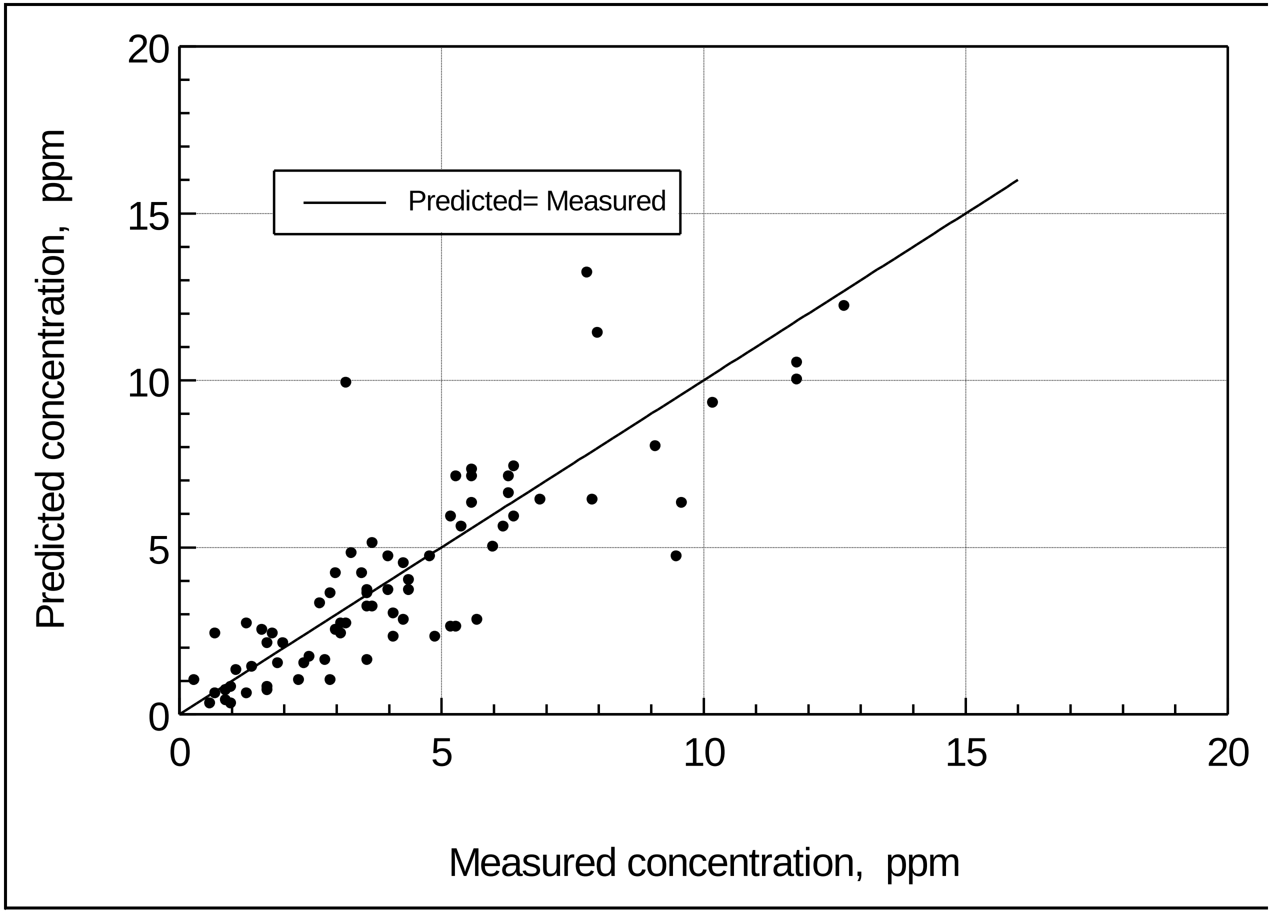
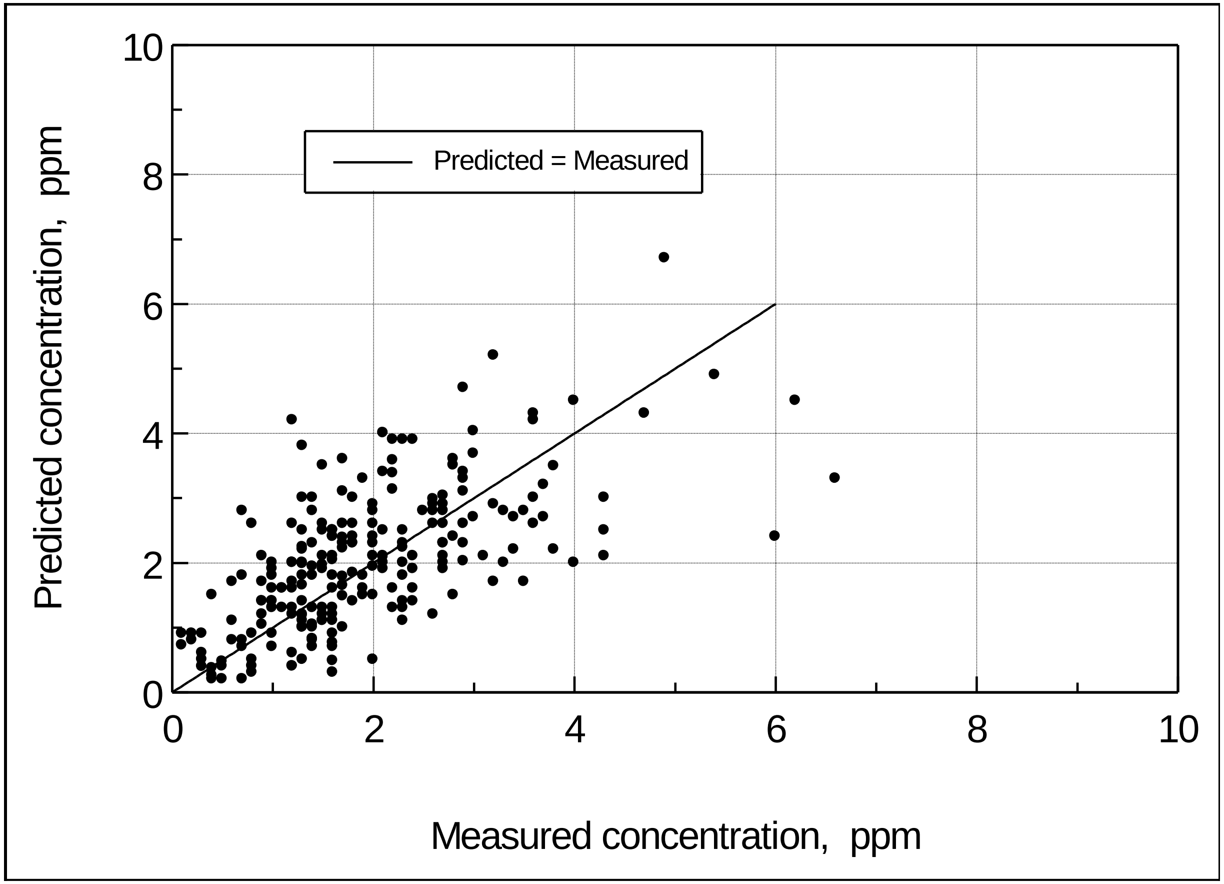


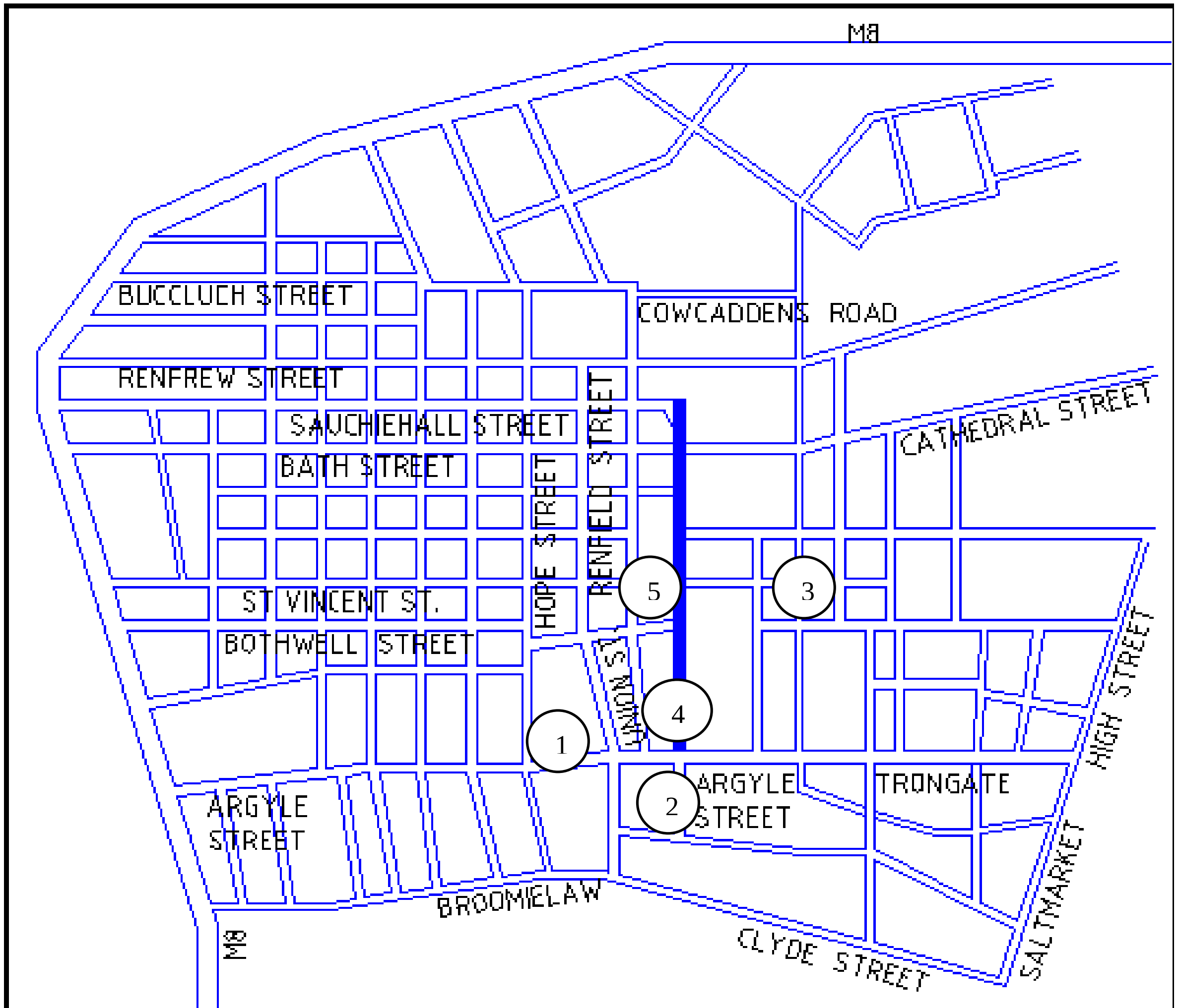
Comparison between predicted and measured CO for leeward face of upwind building, Hope Street, Glasgow



Comparison between predicted and measured CO for wind-ward face of downwind building, Hope Street, Glasgow



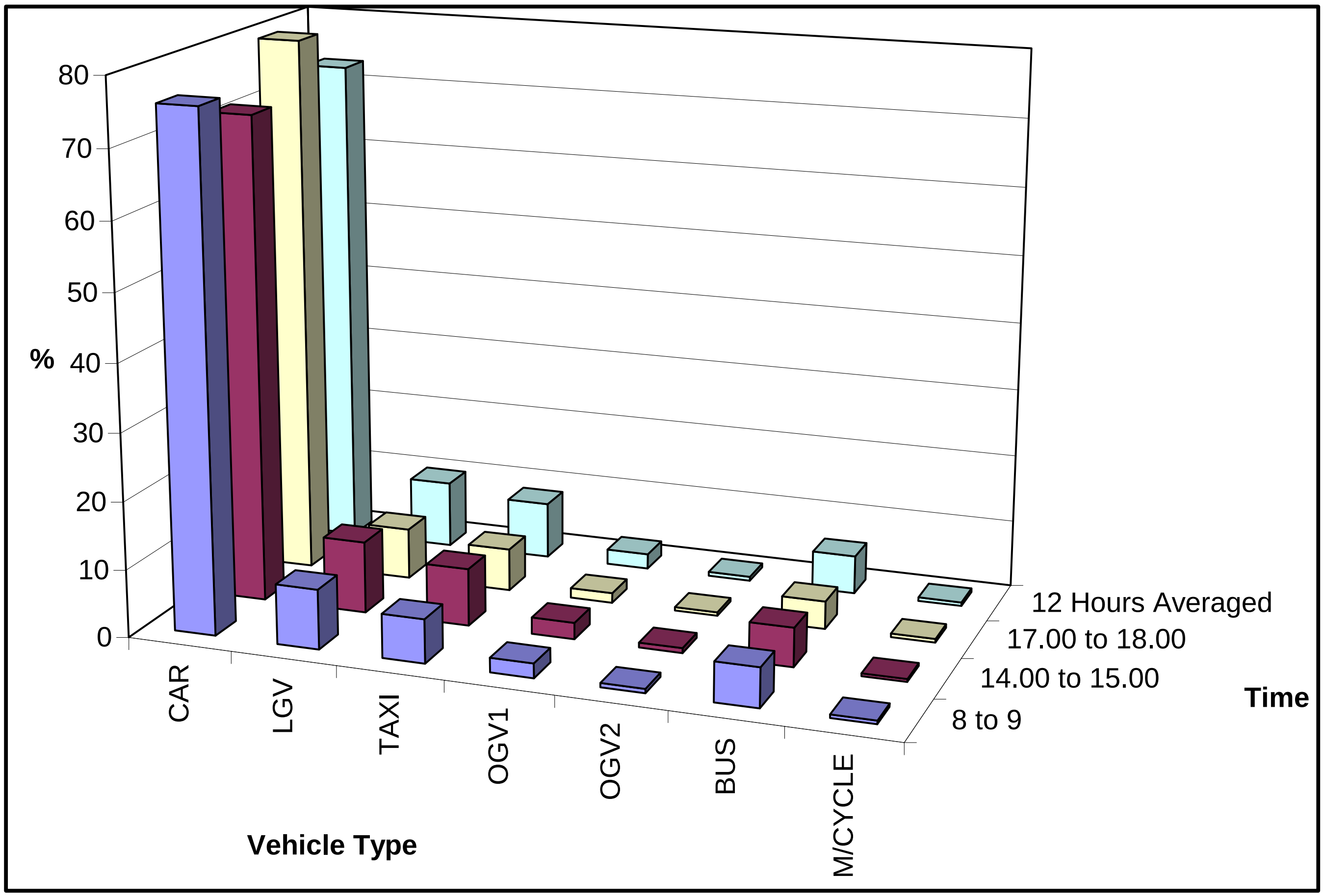
Glasgow Integrated Air Quality Model



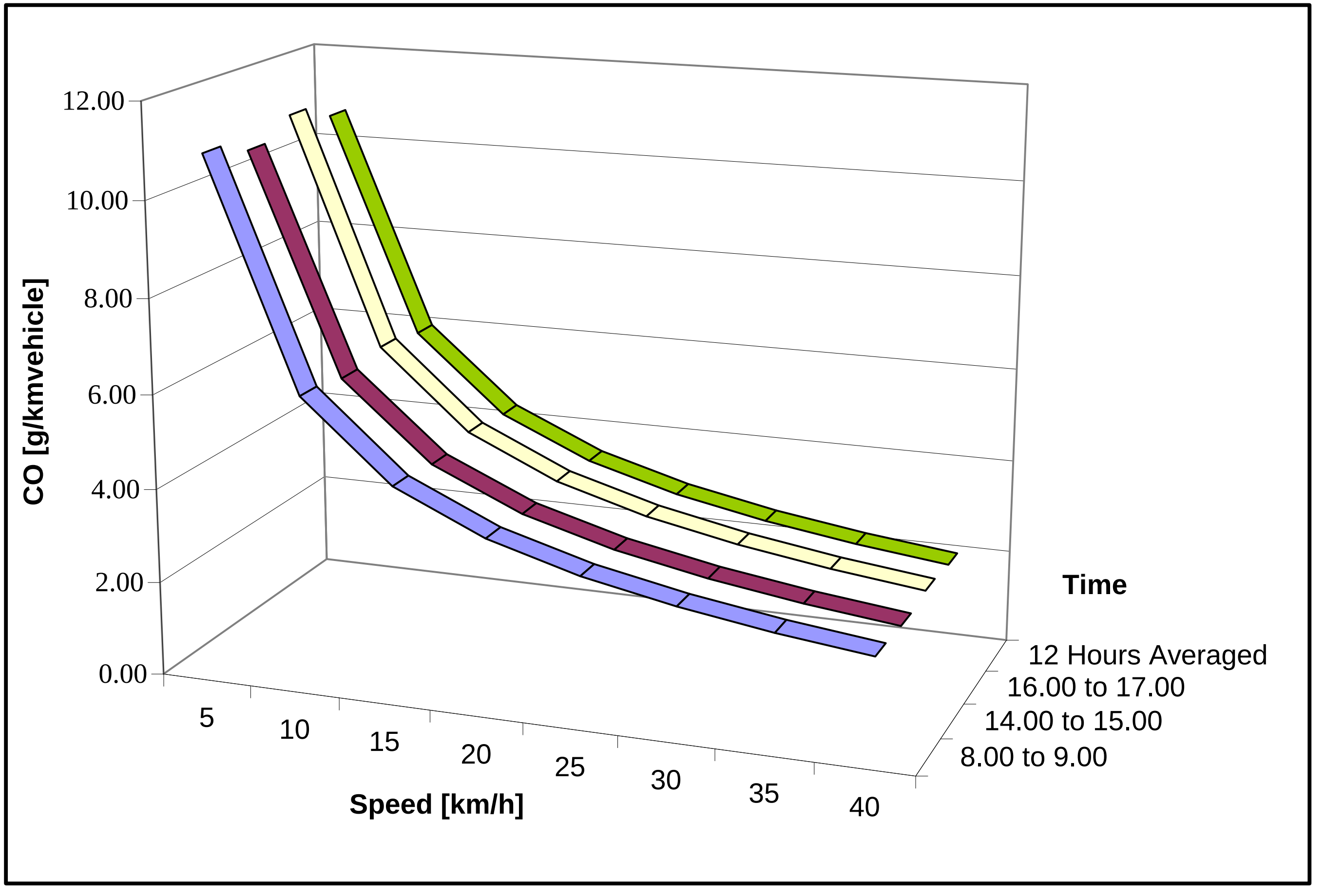
Traffic Simulation

- SATURN: **S**imulation and **A**ssignment of **T**raffic in **U**rban **R**oad **N**etworks
- Network analysis software developed by the Institute of Transport Studies, University of Leeds
- Commercial Distributor, W S Atkins of Epsom, UK, from 1981

Calculated Fleet Composition



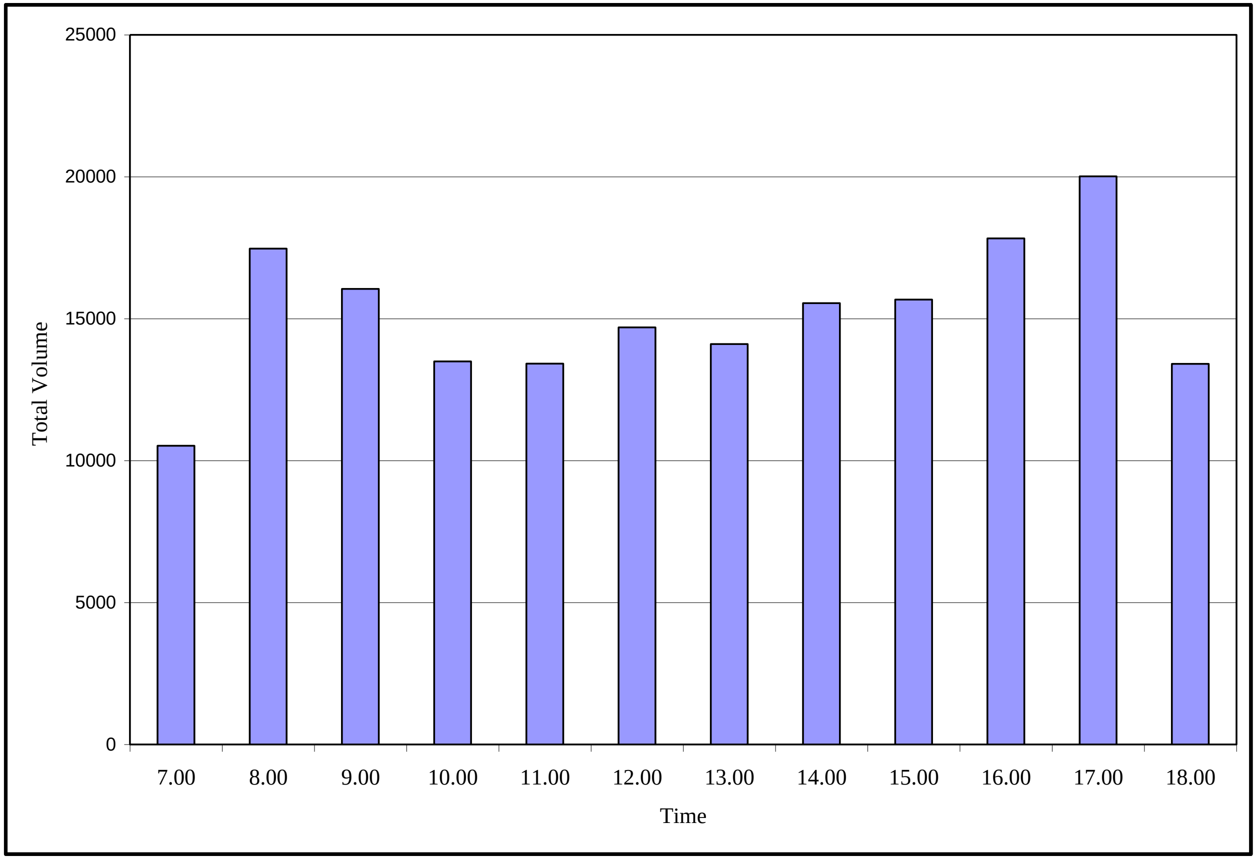
Estimated CO Emission Factors (Casella Stanger EFT 2e)



Carbon Monoxide Emissions

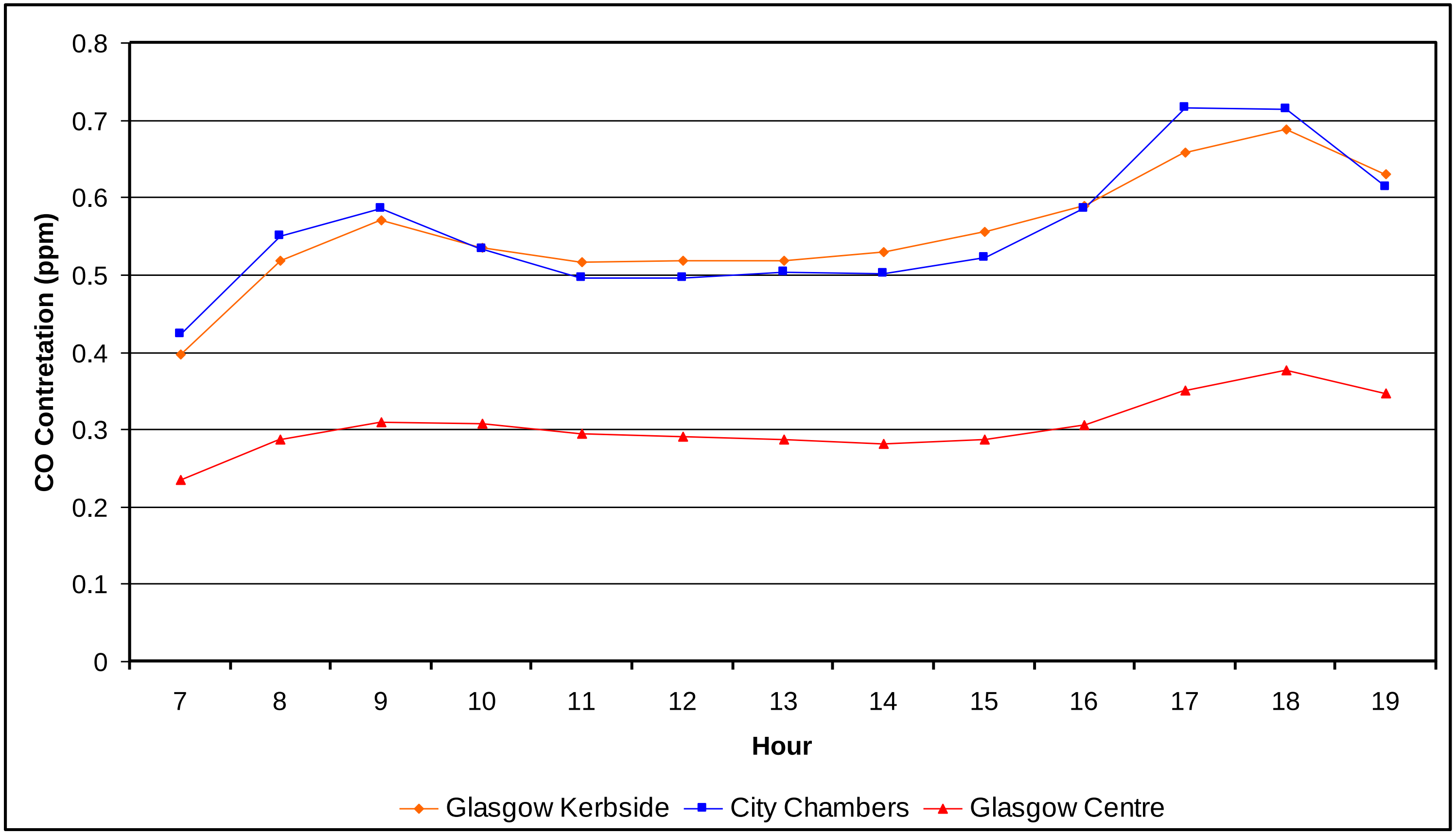
Speed (km/h)	Emission (g/veh. km)	Speed (km/h)	Emission (g/veh. km
0	2.15	25	2.93
5	10.6	30	2.55
10	5.98	35	2.26
15	4.33	40	2.03
20	3.47		

Diurnal Variation of Traffic Volume



Monitoring Trailer in Renfield Street

Hourly Averaged Carbon Monoxide Concentrations for Fixed Monitors



PHOENICS CFD, 3-D Modelling

- Cartesian coordinates
- Renormalisation Group (RNG) k-ε turbulence model
- PARSOL Algorithm (Partial Solution)
- Linearisation of minor irregularities in street directions
- Rotation of axes to align with streets

RNG k-ε Turbulence Model

Equation	Φ	Γ_Φ	S_Φ
Turbulent Kinetic Energy	k	ν_t/σ_k	$\rho(G-\varepsilon)$
Dissipation Rate	ε	ν_t/σ_ε	$\rho(\varepsilon/k)(C_{\varepsilon 1}G - C_{\varepsilon 2}\varepsilon) - \alpha\varepsilon$

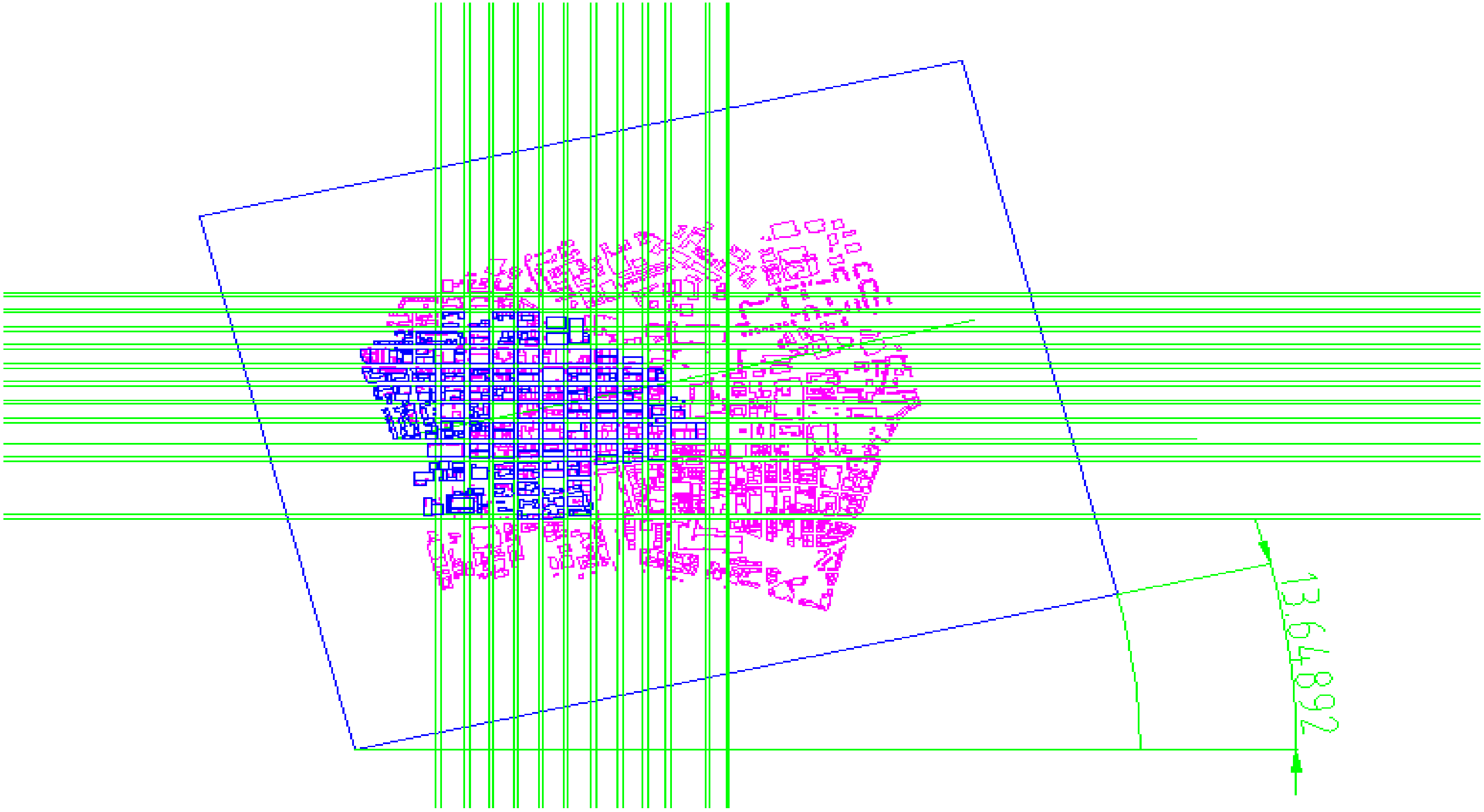
$$G = \nu_t\,(\partial_k U_i + \partial_i U_k)\,\partial_k U_i \qquad \nu_t = C_\mu\,k^2/\varepsilon$$

$$\alpha = C_\mu \eta^3 (1-\eta/\eta_0)/(1+\beta\eta^3) \qquad \eta = Sk/\varepsilon$$

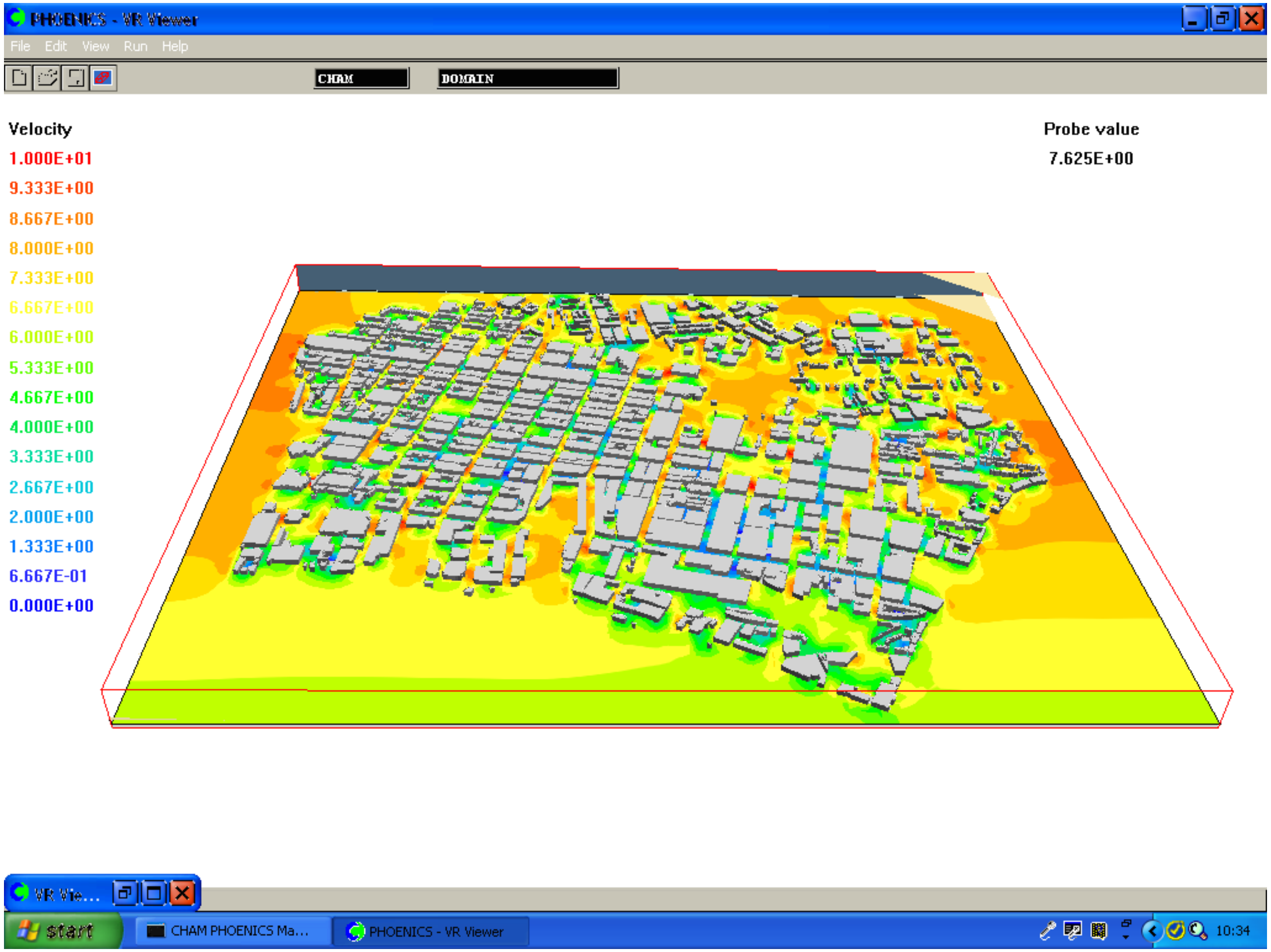
$$S = \sqrt{2S_{ij}S_{ij}} \qquad S_{ij} = 0.5(\partial_j U_i + \partial_i U_j) \qquad \eta_o = 4.38,\ \beta = 0.012$$

σ_k=0.7914, σ_ε=0.7914, $C_{\varepsilon 1}$=1.42, $C_{\varepsilon 2}$=1.68, C_μ= 0.0845

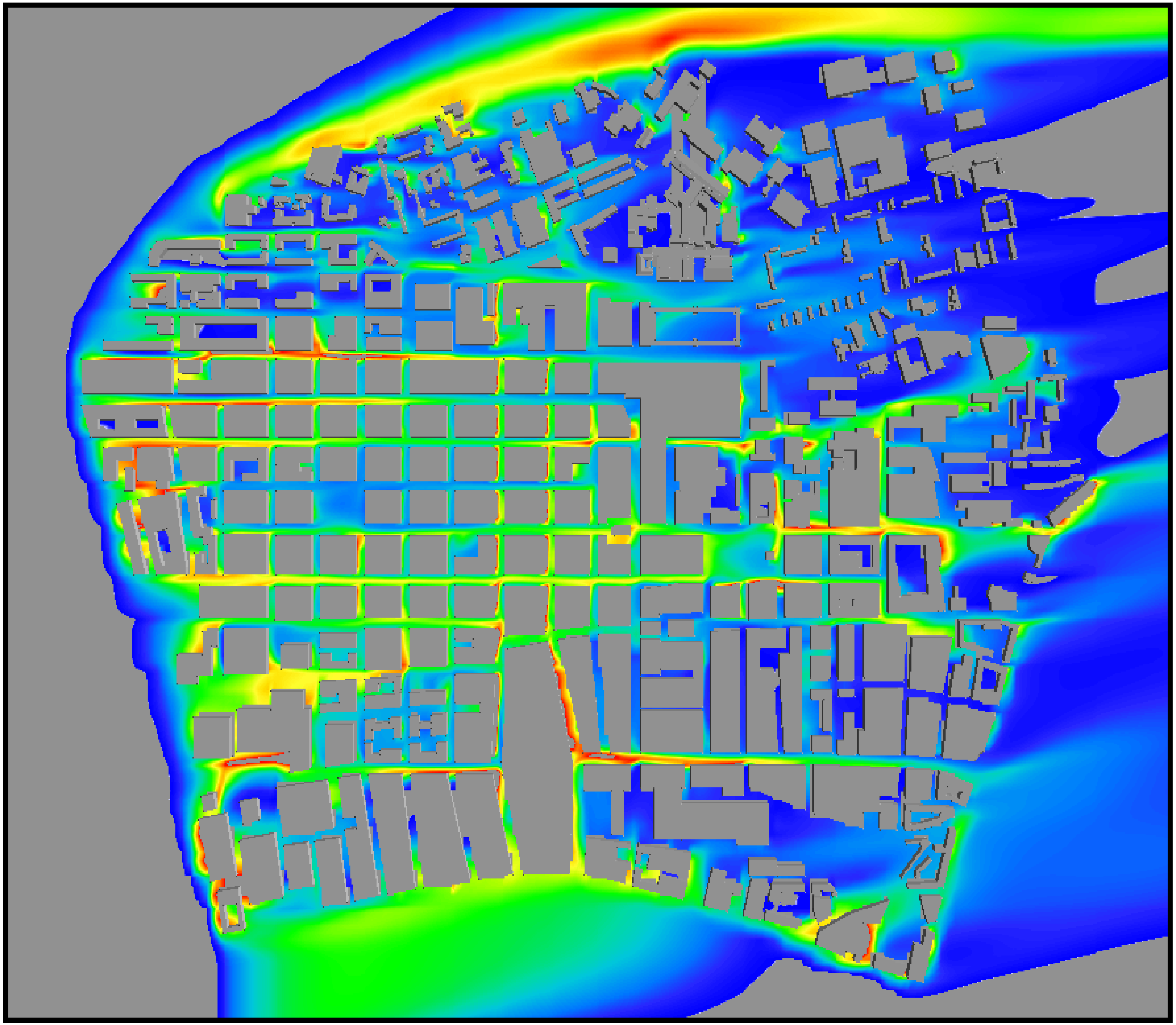
Rotation of the AutoCAD Supporting Plate



Wind Field for AutoCAD Solid Model of Glasgow LAQM Area



Typical
CO
Conc.
Field,
Red=High
Blue=Low



Results (ppmv of CO)

Westerly 2 m/s	Predicted	Measured
Hope St. (1)	1.0	1.2
St. Enoch Sq. (2)	0.1	0.4
Cochrane St. (3)	0.5	0.7
Union St. (4)	1.4	1.3

Results (ppmv of CO)

Westerly 5 m/s	Predicted	Measured
Hope St. (1)	0.46	0.5
St. Enoch Sq. (2)	0.11	0.1
Cochrane St. (3)	0.43	0.5
Renfield St. (5)	1.4	0.8

Conclusions of Glasgow Study

- Predicted and measured CO concentrations are in reasonably good agreement, with average errors of 20 to 30 percent
- Ideally monitoring stations should be in regions of small concentration gradients, otherwise comparison may be difficult
- CFD models can form the basis of an integrated air quality management tool

Existing UK Air Quality Models

- R-91, R-157 (Gaussian Plume Models from UK Atmospheric Dispersion Modelling Working Group)
- ADMS (CERC commercial code, taking account of vertical profiles of windspeed and turbulence and with integral plume rise model)
- ADMS Urban (CERC development including mobile sources and complex topography)

General Conclusions

- Large variety of model types and packages.
- Choose simplest for the purpose!
- Models need to be calibrated and validated.
- Accuracy of models may be limited (perhaps to within only a factor of 2!)
- CFD models may soon displace simpler Gaussian plume models!

References

- A A Hassan & J M Crowther, Env. Mon. & Assessment, **52**, 281-297, 1998
- J M Crowther & A A Hassan, Water, Air & Soil Pollution: Focus **2**, 279-295, 2002
- D Mumovic, J M Crowther & Z Stevanovic, Building & Environment, **41**, 1703-1712, 2006

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