REGULATORY MODELLING FOR ASSESSING AIR QUALITY IN STREET CANYONS IN THE U.K. – CURRENT PRACTICE AND FUTURE NEEDS

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INTRODUCTION

Under the Environment Act 1995, local authorities in the UK are required to review and assess air quality on a regular basis by comparing ambient concentrations of seven pollutants (NO_2, PM_{10}, SO_2, CO, Pb, benzene and 1,3-butadiene) against regulatory standards. Those areas where the prescribed objectives are not likely to be met by the relevant deadline have to be designated as Air Quality Management Areas (AQMA). In those cases, local councils have to produce action plans that set out specific measures for improving air quality. Over 130 local authorities in the UK have already declared AQMA mainly due to exceedences of the annual 40μg/m^3 NO_2 objective and (to a lesser extent) of the 24-hour 50μg/m^3 PM_{10} objective (Woodfield et al., 2003). Many of these exceedences were associated with localised pollution hotspots in urban streets, which may be classified as canyons. However, only in few cases were measurements taken on both sides of those streets in order to assess cross-road pollutant concentration gradients and/or wind recirculation patterns within the street.

The local air quality assessment process requires the use of a screening modelling tool based on the Design Manual for Roads and Bridges (DMRB), in order to predict air pollution levels at multiple roadside receptor locations in future years. If a street is classified as a canyon, then the CO and NO_2 roadside contributions predicted by DMRB need to be multiplied by an empirical factor of 2, which accounts for the model under-prediction. If the screening model shows that there is a risk of exceeding the air quality standards at a certain location, then a more advanced modelling tool should be used in combination with field measurements.

CURRENT MODELLING PRACTICE

The most widely used approach to regulatory street canyon modelling is based on the Danish OSPM model, which uses a simple formulation of the airflow in and above the street taken to be steady (Berkowicz et al., 2000). OSPM (Windows version) produces series of hourly pollutant concentrations at different heights on either side of a street canyon. It takes into account the contributions from: (i) the direct flow of pollutants from the car exhausts to the receptor, (ii) the recirculation of pollutants around a wind vortex generated within the canyon under certain wind conditions, and (iii) the urban background. The direct contribution is calculated applying Gaussian dispersion theory, while a simple box model is used to calculate the recirculation contribution. The UK Met Office has developed a suite of operational street canyon models that includes AEOLIUS Screen, Q and Full (in increasing order of complexity). AEOLIUS Screen and Q are screening tools that calculate hourly concentrations of regulated pollutants within a street canyon for only parallel and perpendicular (leeward) wind conditions. AEOLIUS Q has the option to replace default emission factors with user-defined inputs. AEOLIUS Full is a more advanced version (based on OSPM) that can handle a wider variety of wind conditions and traffic patterns (Buckland and Middleton, 1999). Another variation of the OSPM code is embedded in ADMS-Urban, a second generation Gaussian dispersion model which is widely used for regulatory purposes in the U.K. (Carruthers et al., 1994). Two other operational street canyon models, STREET-SRI and CAR

International, have been mainly used in the USA and continental Europe, respectively (Vardoulakis et al., 2003).

Operational street canyon models generally require input data that describe the street geometry, local road traffic and meteorology. Although OSPM, AEOLIUS Full, and ADMS-Urban are based on similar physical principles and mathematical techniques to simulate in-canyon pollutant dispersion, they have certain differences which are reflected on their input requirements (Table 1). For example, AEOLIUS Full uses a statistical relationship derived from roadside measurements to calculate NO_2 from NO_x (Derwent and Middleton, 1996). OSPM solves a simple system of three chemical equations, which requires background O_3 and global radiation data. Finally, ADMS-Urban uses a more complex chemistry scheme that requires O_3 and SO_2 background data (although it can also use the statistical relationship by Derwent and Middleton for the same purpose). In addition to the user-defined input parameters, there are several empirical parameters that are fixed inside the models. These parameters, which are generally inaccessible by the users, may be related to the size of the wind vortex within the street, the rate of the exchange of pollutants across the boundaries of the recirculation zone, the traffic induced turbulence, the wind profile within and above the urban canopy, etc. (Vardoulakis et al., 2002).

Table 1: Minimum input requirements for three dispersion models commonly used in regulatory street canyon applications in the U.K. (Y: Yes – N: No)

MODEL:	WinOSPM	ADMS-Urban	AEOLIUS Full
Canyon height	Y	Y	Y
Canyon width	Y	Y	Y
Canyon length	Y	Y	N
Street axis orientation	Y	Y	Y
Gaps / different building heights	Y	N	N
User-defined surface roughness	N	Y	Y
Wind speed	Y	Y	Y
Wind direction	Y	Y	Y
Cloud cover	N	Y	N
Height of recorded wind (at met. site)	N	Y	N
Surface Roughness (at met. site)	N	Y	N
Air temperature	Y	Y	Y
Atmospheric pressure	N	N	Y
Global radiation	Y	N	N
Vehicle emission factors	Y	Y	Y
Vehicle categorization	Y	Y	Y
Vehicle counts	Y	Y	Y
Average vehicle speed	Y	Y	Y
Background concentrations	Y	Y	Y
Receptor height	Y	Y	N
Receptor distance from kerb	N	Y	N

CASE STUDIES

Three operational dispersion models (WinOSPM, AEOLIUS Full and ADMS-Urban 2.0) of comparable complexity were used in the present study in order to illustrate the advantages and shortcomings of the current regulatory street canyon modelling practice in the U.K. They were used to calculate hourly NO_2, CO and PM_{10} concentrations in two heavily trafficked road axes within designated AQMA in Birmingham and London during one year (2003).

(a) Stratford Road (Birmingham) is a busy street passing through a shopping area, with residential properties over some of the shops. Low-rise (three to four-storey) buildings line up almost continuously on both sides of the street. There is one traffic lane in each direction and one parking lane only on the west side. The total width of the street is 22m, the average building height is 12-14m, and the street axis bearing from the north is 153°. The annual average daily traffic flow (AADT) is around 29,000 vehicles/day. Due to congestion, the average vehicle speed is only 10-20km/h, with many stop-starts. Birmingham City Council operates an air quality monitoring station in Stratford Road since April 2002. CO, PM_{10} and NO_x concentrations are continuously recorded at 3 m height on the east side of the street.

(b) Marylebone Road (London) is an extremely busy dual carriageway in central London that runs through an area made up of education buildings, tourist attractions, shops and housing. There are up to seven lanes of traffic in some places (including bus lanes) and traffic flows in both directions. The total road width is approximately 40m, the average building height is about 25m and the street axis bearing from the north is 70°. The annual average daily traffic flow (AADT) is around 76,000 vehicles/day. Due to severe congestion, the average vehicle speed is only 10-20km/h, with many stop-starts. An automated air quality monitoring station (sponsored by DEFRA) is located on the south side of Marylebone Road since May 1997, recording continuously CO, O_3, NO_x, SO_2, $PM_{2.5}$, PM_{10} and a wide range Volatile Organic Compounds (VOC) at 3 m height above the ground.

RESULTS AND DISCUSSION

The agreement between calculated and observed NO_2, CO and PM_{10} values was generally good. Although the three models appeared to underestimate the roadside concentrations in most cases, 63-93% of the predictions were within a factor of two of the observed values and correlation coefficients ranged from 0.30 to 0.84 for all modelled pollutants. A summary of model performance statistics for each location, including annual mean concentrations, correlation coefficients, fractional bias, normalised mean square error (NMSE), and percentage of predictions within a factor of two (FAC-2), are presented in Tables 2-3.

The model under-predictions observed in this study were not entirely unexpected. Buckland (1998) and Manning et al. (2000) tested AEOLIUS Full using air quality data from Birmingham, London and Leek (Staffordshire). They also found that the model under-predicted the observed NO_x and/or CO concentrations, especially when airport wind data were used. In general, dispersion models have an inherent tendency towards average behaviour, failing thus to reproduce extreme pollutant concentrations. In the present study, the model underestimations for Stratford Road and Marylebone Road are thought to be mainly due to: (a) the use of remote wind data (from Coleshill weather station and Heathrow Airport, respectively), (b) the impact of major intersecting streets which were not explicitly modelled (Warwick Road and Baker Street, respectively), (c) the large impact of congested traffic during rush hours, and (d) the low aspect ratio of the two canyons (height/width$\approx$0.5). It should be also noted that the vehicle emission factors, which were calculated with the Emission Factor Toolkit (EFT2f), did not account for non-exhaust particle emissions (e.g. from brake and tyre wear) and road dust re-suspension, which may have a significant impact on kerbside PM_{10} concentrations (AQEG, 2005). There is evidence that the primary NO_2

fraction of total NO_x exhaust emissions may have also been underestimated (AQEG, 2004). Cold start emissions were taken into account in all cases.

Table 2: Model performance statistics for Stratford Road (Birmingham)

Stratford Rd	Observed	WinOSPM	ADMS-Urban	AEOLIUS Full
			NO_2	
Annual Mean (μg/m^3)	61.50	46.44	45.09	63.00
Correlation Coef. (ideal value: 1)		0.77	0.75	0.84
Fractional Bias (ideal value: 0)		0.28	0.31	-0.02
NMSE (ideal value: 0)		0.30	0.38	0.12
FAC-2 (ideal value: 100%)		85	81	90
			CO	
Annual Mean (mg/m^3)	1.07	0.81	0.62	0.74
Correlation Coef. (ideal value: 1)		0.76	0.70	0.76
Fractional Bias (ideal value: 0)		0.28	0.52	0.37
NMSE (ideal value: 0)		0.47	0.93	0.61
FAC-2 (ideal value: 100%)		82	63	77
			PM_{10}	
Annual Mean (μg/m^3)	30.67	27.78	26.22	27.20
Correlation Coef. (ideal value: 1)		0.68	0.66	0.68
Fractional Bias (ideal value: 0)		0.10	0.16	0.12
NMSE (ideal value: 0)		0.56	0.63	0.59
FAC-2 (ideal value: 100%)		93	92	93

Table 3: Model performance statistics for Marylebone Road (London)

Marylebone Rd	Observed	WinOSPM	ADMS-Urban	AEOLIUS Full
			NO_2	
Annual Mean (μg/m^3)	104.78	82.74	77.34	112.62
Correlation Coef. (ideal value: 1)		0.54	0.38	0.54
Fractional Bias (ideal value: 0)		0.24	0.30	-0.07
NMSE (ideal value: 0)		0.28	0.40	0.18
FAC-2 (ideal value: 100%)		85	76	88
			CO	
Annual Mean (mg/m^3)	1.30	1.22	1.00	1.10
Correlation Coef. (ideal value: 1)		0.54	0.30	0.52
Fractional Bias (ideal value: 0)		0.07	0.26	0.17
NMSE (ideal value: 0)		0.29	0.54	0.34
FAC-2 (ideal value: 100%)		83	68	80
			PM_{10}	
Annual Mean (μg/m^3)	48.34	35.94	33.60	35.09
Correlation Coef. (ideal value: 1)		0.74	0.68	0.74
Fractional Bias (ideal value: 0)		0.29	0.36	0.32
NMSE (ideal value: 0)		0.24	0.32	0.25
FAC-2 (ideal value: 100%)		86	79	84

CONCLUSIONS AND FURTHER WORK

Urban canyons have been associated with exceedences of air quality standards in the U.K. and abroad. Commonly used operational models that are able to reproduce time series of pollutant concentrations within street canyons were critically reviewed in this study. These models require a relatively small amount of input information and computational resources, which make them an attractive alternative to more advanced techniques such as CFD and wind tunnel modelling. Three operational models, WinOSPM, AEOLIUS Full and ADMS-Urban 2.0, were applied to two busy low-rise canyons in Birmingham and London, with corresponding assumptions and definition of input data. Although the models reproduced reasonably well the NO_2, CO and PM_{10} concentration patterns, they underestimated the annual mean concentrations in most cases. That reveals the importance of empirical model assumptions, as well as certain inadequacies of the selected input datasets (e.g. airport wind data, emission factors that do not account for non-exhaust particle emissions, etc.). Therefore, street canyon models should be used with caution in regulatory applications when relevant monitoring air quality data are not available. Further work is needed in order to fully evaluate the above models for a variety of urban canyon configurations, traffic and meteorological conditions. Finally, novel features enabling dispersion models to simulate particle re-suspension, traffic induced turbulence during congestion, urban vegetation effects, and thermal effects due to solar heating should be developed.

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