MODELLING THE CAUSES OF VEHICLE EXHAUST EXPOSURE MICRO-EPISODES

Hongbin Wang[1], Roy Colvile[1], Elsa Aristodemou[1], Christopher Pain[2]
[1]Department of Environmental Science & Technology, Imperial College London, UK
[2]Department of Earth Science & Technology, Imperial College London, UK

INTRODUCTION

Future regulatory models will be required to predict personal exposure, which is defined as pollutant concentration at a person's breathing zone, more realistically than the current focus on fixed monitoring locations. This includes not only daily and longer-term averages, but also short "microepisodes" where average exposure over a minute or less are an order of magnitude higher than hourly averages. Measurements of exposure of pedestrians and other road users to vehicle exhaust near the intersection of Marylebone Road and Gloucester Place in Central London, showed that these microepisodes are sufficiently frequent and intense to dominate the exposure of those individuals who breathe the highest pollutant concentrations.

In order to figure out causes of these microepisodes, exposure of a pedestrian crossing west Marylebone Road at the intersection of Marylebone Road and Gloucester Place is modelled using the adaptive mesh FLUIDITY CFD code. The intersection is formed by four parallelly aligned buildings; traffic emission sources are time-varying according to traffic light status. Exposure of a pedestrian crossing the street is obtained from the concentration values at the person's positions along the walking path. This research applies time-dependent large eddy simulation (LES) CFD to an exposure study and is the first of its kind.

METHODOLOGY

Large eddy simulation

In the vicinity of the intersection of Marylebone Road and Gloucester Place, the timescales of movement of air and movement of people through the domain are comparable, and the emissions change under the influence of traffic signals with similar time period. A time-dependent CFD model is therefore required. FLUIDITY, developed at Imperial College, is a general CFD code, in which the computational mesh is refined every timestep or some multiple of timesteps to ensure transient as well as permanent areas of steep gradients in velocity or concentration are resolved. Implementation of LES in FLUIDITY uses an anisotropic sub-filter scale Smagorisnky-type model which was found to perform better with the adaptive mesh than an ordinary sub-filter scale model for flow past a surface-mounted cube (Bentham et al., 2003). The model has since been evaluated also for mean and time-varying flow parameters between a group of four blocks by Aristodemou et al. (2005). Here, we study a very similar four-building configuration, building heights and street widths the same as those in the DAPPLE street canyon intersection in London, with time-varying emissions and compute pollutant concentrations at moving receptors.

Sources in the vicinity of the intersection

A. Emission location

Traffic emission at the intersection of Marylebone Road and Gloucester Place is very complex and therefore some simplifications are made to describe the emission sources, basically following the strategy taken by Colvile et al. (2003). Marylebone Road is a busy dual carriageway. The north side of the road is a three-lane street with traffic going east whilst its south side has four lanes with traffic going west. Gloucester Place is a one way three-lane road, only allowing the vehicles going north. Seven traffic sources are defined around the Marylebone-Gloucester intersection (see Fig. 1). At each side of the intersection, on the Marylebone Road, two sources were defined. At each side of the intersection on the Gloucester Place, only one source was defined. The sources are assumed to be homogeneous cuboid volume sources, whose length is taken as the length of the queue and the width of the sources taken as the width of the roads. Furthermore, it is assumed the height of the sources is 3 m, below which pollutants are sufficiently mixed so that the volume sources are vertically homogenous, due to the mixing caused by traffic motion.

B. Emission time

Except for the continuous source within the intersection (Source VII in Fig. 1), the sources on both Marylebone Road and Gloucester Place (Source I to Source VI in Fig. 1) are considered as time-varying traffic emissions, according to traffic light changes (see Fig. 2 and Fig. 3). On average, Green light of a period of 47.5 seconds is given to traffic on Marylebone Road, and a period of 42.5 seconds to traffic on Gloucester Place. It is further assumed that vehicles only give off pollutants immediately from the time traffic lights turn from red to green until vehicles reach a cruising speed, ignoring the comparatively small emission during vehicle deceleration and cruising. Fig. 2 is a schematic graph of the traffic emissions at Marylebone-Gloucester intersection that are approximated by top-hat functions.

C. Emission strength

Based on both traffic flow and acceleration of vehicles, a tentative emission strength scheme is used. In terms of unit emissions per unit volume, the strength for Source I, Source IV, and Source VI is 1, for Source II and Source III is 0.5, and for Source V is 0.25. The emission strength of the continuous Source VII is 0.5.

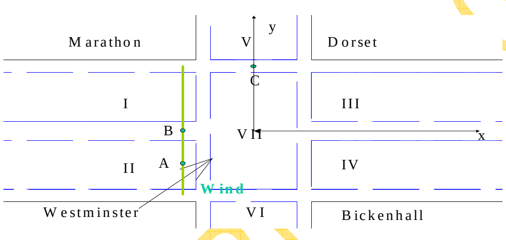


Fig. 1 Model set-up of the intersection of Marylebone Road and Gloucester Place. The thick line connecting AB is the path pedestrians take to cross west Marylebone Road.

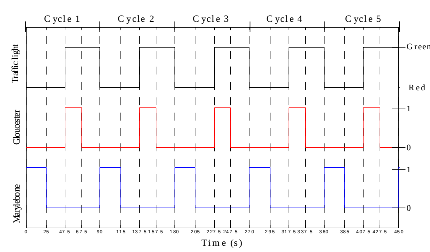


Fig. 2 Traffic sources changes according to change of traffic light. In the graph, the traffic light is for Marylebone Road. Emission is unity when a source is on and zero when it is off.

Pedestrian walking path and speed

Pedestrians follow designated routes crossing streets at the intersection during green pedestrian light or red traffic light of the road they cross (see Fig. 3). Modelled pedestrian walking paths are simplified as shown in Fig. 1 and 1.25 m s^{-1} is used as a standard pedestrian walking speed for calculation of pedestrian exposure.

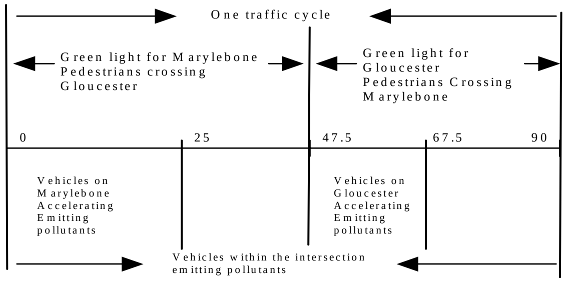


Fig. 3 Simplified diagram of activity of vehicles and pedestrians at the intersection of Marylebone road and Gloucester place.

RESULTS AND DISCUSSION

Flow patterns

Fig. 4 shows wind velocity vectors at horizontal sections at t = 384 s of z = 2 m and z = 7.5 m. It can be seen that wind at the level of 2 m is generally lower than at 7.5 m and flow patterns at the two different heights are not exactly the same. It seems that bulk airflows from south Gloucester Place turn east into east Marylebone Road, and bulk airflows from west Marylebone Road turn north to north Gloucester Place. Flow animation, made by visualising concentration field due to Source VII, a continuous source within the intersection, suggests that airflows enter between east Marylebone Road and north Gloucester Place quite randomly.

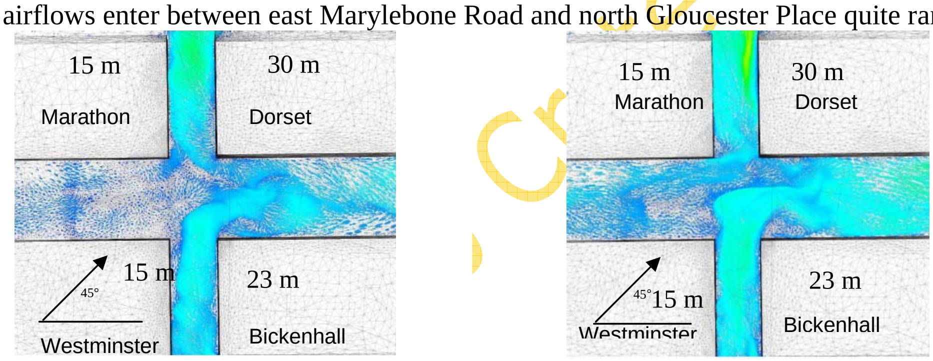


Fig. 4 Wind velocity vector at horizontal sections at t = 384 s. arrows point to wind direction and length of vector indicate wind speed. left – z = 2.0m, right – z = 7.5 m. The incident wind above roof level blows at 45^o from the direction of Marylebone Road as shown. Note the widths of Marylebone Road and Gloucester Place are 45m and 25 m respectively.

Concentration distribution

Two snapshots for Source I at times in traffic cycle 6 are presented in Fig. 5. Comparison with Fig. 3 shows the left graph in Fig. 5 is 20.67 s after the source starts to emit and 4.33 s before it ceases. The graph shows that high concentrations occur within Source I and the maximum of about 500 concentration units is found at the north side of Marylebone Road, close to the intersection. The concentration drops dramatically some distance away from the source, and more so closer to the source. On the west side of Gloucester Place close to the intersection less than 20 m away from the source, the concentration is around 50, about 10% of the maximum concentration. The right graph of Fig. 5 is concentration distribution 55.67 s after the source ceases and 9.33 s before the source begins to emit again in the next traffic cycle. Compared with the left graph, high concentration within the source decreases from 500 down to 300, reduced by about 40%, and the fall in concentration with distance away from the edge of the source is less. Similar patterns can be seen for the other five time-varying sources.

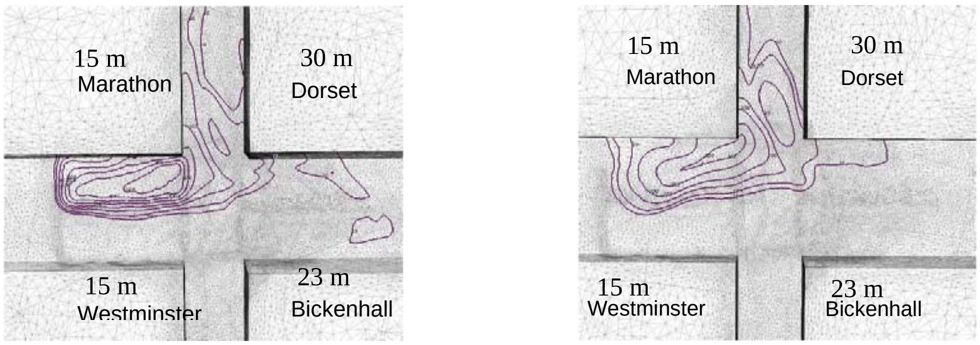


Fig. 5 Concentration distributions due to Source I at horizontal section z=2.0 m from the ground. left – t = 470.67 s , right – t = 530.67 s.

Relationship between wind direction and concentration at fixed receptor

Fig. 6 shows horizontal wind direction measured at receptor B and concentrations due to Source II measured at receptors A and B (different points a few metres apart on the crossing of the western part of Marylebone Road). It can be seen that the concentration at receptor A change nicely with the emission change of Source II because the receptor is within the source (see Fig. 1). For example, concentration at receptor A begins to increase at the onset of Source II emissions (e.g., at 0 s, 90 s and 180 s) and reaches maxima at the end of the emissions (e.g., at 25 s, 115 s and 205 s), regardless of the wind direction. However, for concentration at receptor B, concentration mainly peaks when the wind is from the favourable direction (between 0° to 100°) and when Source II emission is at the end or soon after it finishes. The concentration troughs around t=655 s and 745 s demonstrate that if the wind comes from the non-favourable direction (between 0° to -50° in this case), even if the source emission is at the end of emission, there can be a low concentration. It is not surprising that the concentration troughs are observed around t = 90 s, 180 s, 540 s and 900 s when after the emission has ceased for 65 s even though the wind blows from the source.

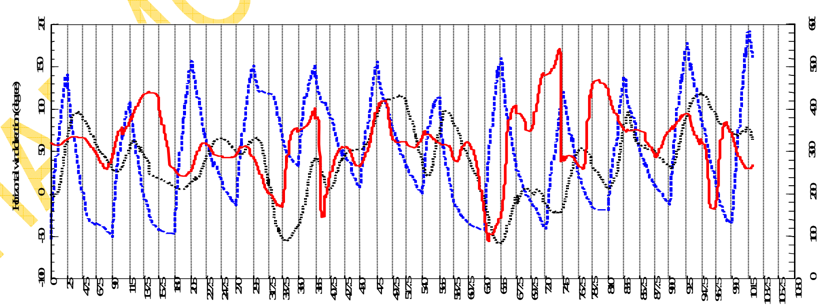


Fig. 6 Horizontal wind direction measured at B and concentration due to source II measured at receptor A and B (locations of the source and receptor see Fig. 1). Solid line – horizontal wind direction at B, dash line – concentration at A, dot line – concentration at B.

Pedestrian exposure

A. Exposure samples within one traffic cycle

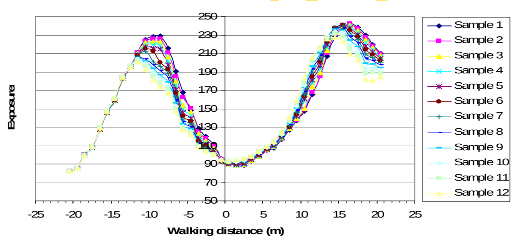
A pedestrian may arrive and leave the kerbside of south Marylebone Road at different times. Fig. 7 presents exposure samples of a pedestrian supposedly crossing west Marylebone Road at different times with 0.8 s apart within traffic cycle 4. It can be seen that the 12 exposure curves show two peaks, each associated with time spent close to one of the source regions. All the timeseries are very similar. Fig. 8 shows average exposure of a pedestrian supposedly crossing west Marylebone Road at different times within a traffic signal cycle, which shows the average exposure decrease monotonically by 5% within 9.6 s, implying that the crossings within the same traffic cycle do not experience exposure of significant difference.

B. Exposure samples between traffic cycles

In order to investigate to what degree the transient flow at the intersection of Marylebone Road and Gloucester Place influence pedestrian exposure, exposure of a pedestrian supposedly crossing west Marylebone Road at the same time relative to traffic light during each traffic cycle is calculated (see Figs. 9 and 10). In contrast to Figs. 7 and 8, it can be seen that these exposure samples are quite scattered. Only the exposure samples measured during Cycle 4 & 5 show clearly the two peaks associated with passing the two sources on Marylebone Road. All the other exposure samples display only one peak, some more clearly than others. The average exposure samples shown in Fig. 10 do not present any trend. The ratio of sample standard deviation to sample average is about 28%, indicating much larger exposure variability than that of the exposure samples within one traffic cycle.

CONCLUSIONS

The novel large eddy simulation method produces airflows in the vicinity of the intersection of interest and provides time-varying velocity and concentration fields for the investigation of causes of exposure microepisodes for a pedestrian crossing Marylebone Road at the intersection. Exposure of a receptor is essentially dominated by the source(s) in closest proximity, due to the fact that traffic sources are almost ubiquitous and distributed more or less similarly in the vicinity of an intersection. A peak exposure at a receptor (microepisode), is shown to be primarily linked to the event that pollutant from a dominant source is blown directly to the receptor, i.e., the wind aligns the source with the receptor. Variability of exposure samples within a traffic cycle is as small as 5% whilst that of exposure samples between different cycles are as large as 28%.



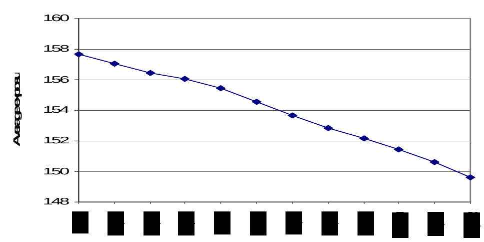
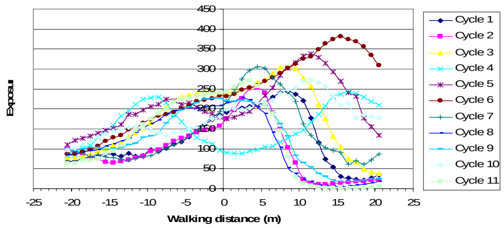


Fig. 7 (left) Exposure of a pedestrian supposedly crossing west Marylebone Road at different times with 0.8 s apart within traffic cycle 4. Sample 1 – leave kerbside at t=317.5 s immediately when the favoured light take effect. Sample 2 – 318.3 s; and Sample 12 – 326.3 s, 0.7 s before the next traffic light begins.

Fig. 8 (right) Average exposure of a pedestrian supposedly crossing west Marylebone Road at different times with 0.8 s apart within traffic cycle 4.



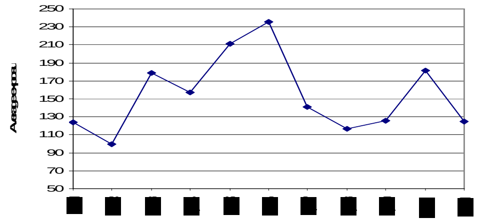


Fig. 9 (left) Exposure of a pedestrian supposedly crossing west Marylebone Road during different traffic cycles immediately after the favoured light takes effect.

Fig. 10 (right) Average exposure of a pedestrian supposedly crossing west Marylebone Road during different traffic cycles immediately after the favoured light takes effect.

REFERENCES

Aristodemou, E., et. al., "A comparison of adaptive mesh LES and wind tunnel data for flow past buildings: Mean Flows and velocity fluctuations." Submitted to Atmospheric Environment.

Bentham, T. (2003). "Microscale modelling of air flow and pollutant dispersion in the urban environment." PhD Thesis, Imperial College.

Colvile, R., H. Wang, et al. (2003). "Modelling the relationship between urban form and variability in exposure to vehicle emissions." 13th Annual conference, International Society of Exposure Analysis Abstract Book: 280