DAPPLE – Dispersion of Air Pollutants and their Penetration into the Local Environment

Background

The key aim of the DAPPLE project was to enhance understanding of pollutant dispersion processes, emissions and exposure in realistic urban environments and so make possible improvements in predictive ability that would enable better planning and management of urban air quality. The context was the combination of space and time scales that distinguished individual sources and the exposure of individuals within the population; i.e. short-range. The initial proposal was written in terms of exposure to vehicle exhaust emissions, though acknowledging an important additional application concerning acute exposure to toxic materials. Subsequent global political events dictated that the latter should take a more prominent position and DAPPLE activities were modified where feasible to accommodate this, whilst still keeping traffic pollution at their heart. The impact of this change was perhaps most noticeable in the programme of wind tunnel work and the direction of new research being undertaken by the DAPPLE Consortium.

Urban areas, such as found in central London, can best be characterised as intersections linked by relatively short street segments, clearly demonstrating that excessive emphasis on the simple street canyon is misplaced. This becomes even more obvious when the likely distribution of emissions is analysed, for these are predominantly found in regions where vehicles are accelerating. Thus DAPPLE selected an intersection as its focus, at a site that was typical of many to be found in UK and other European cities. The area surrounding the Marylebone Road – Gloucester Place intersection contains street segments of differing height to width ratios, as well as isolated tall buildings and open spaces. It thereby encompasses the key urban elements and proved an ideal experimental site – previous use as a research site and the presence of long term urban air quality monitoring stations further enhanced its value.

A notable outcome of the project as a whole was the establishment of the DAPPLE team as an important national asset, capable of conducting complex research in urban areas. Though integrated, the activities can be conveniently grouped and discussed under six related headings: exposure, vehicle movement and emissions, air quality, local-scale meteorology, tracer dispersion, computer modelling and simulation, and wind tunnel modelling. A central role of the computer and wind tunnel simulations was to support the field studies, firstly in their planning and then, more importantly, in their interpretation. The co-ordinated use of field, computational and wind tunnel studies was a major strength of DAPPLE, greatly enhancing the overall value of the individual activities and ensuring the project a high international standing. Modelling work (large eddy and wind tunnel simulation) was also used in its own right to investigate the nature and sources of variability in dose rates, to establish the capabilities of operational models and to develop detailed data-sets for examining the performance of CFD and other predictive methods. The modelling was therefore able to play a integrating role, bringing together the findings from a diverse range of field observations.

Experimental work at the field site took place between April 28th and May 23rd in 2003 and then again between April 19th and June 13th in 2004. Some additional tracer studies, funded as a DAPPLE extension by the Home Office, were conducted in November, 2004. The planned meteorological, vehicle movement, air quality, personal exposure and tracer dispersion measurements were all completed during the two main experimental periods. The achievements of these periods far exceeded expectations by virtue of there being more instruments deployed than initially planned and because of the extremely high degree of reliability of the instrumentation installed, the latter reflecting the dedication and quality of the staff responsible and the value of having a "project manager" as a defined and resourced role within the research team. The smooth operation and success of the field work would not have been possible without the willing support and co-operation of the local authorities, in particular Westminster City Council (WCC) and Transport for London. This, in turn, attracted others to want to work at the site and the overall added-value to the project proved substantial. These enhancement are described in the individual institution reports, but some are worthy of mention here. Additional experimental work was carried out during the Spring 2004 campaign that addressed the integration of an exposure visualisation system with conventional exposure measurements, the suspension and movement of dust from road surfaces and the velocity profile in the lower 200m of the atmosphere. The additional tracer studies in November 2004 included two novel experiments in which the tracer was released from a vehicle moving through the study area.

Advances

Exposure

The project exceeded expectations in providing new insight into individual exposure in a real city, where people are exposed to high concentrations of pollutants during the short times they spend close to traffic emissions. Unprecedented numbers of samples were collected: 394 during the first campaign and 603 during the second. These covered individual exposure to PM2.5, ultra-fine particles and CO along two different routes, using five modes of transport. The results showed a moderately strong correlation between personal exposure of ultra-fine particles and CO but a weaker correlation between PM2.5 and ultra-fine particles and a low correlation between PM2.5 and CO exposure. The exposure assessment also revealed that the local background and kerbside monitoring stations were not representative of the exposure of individuals to PM and CO at and around the street canyon intersection. The exposure visualisation technique was found to be a valuable environmental risk communication tool when used for presenting exposure data to both technical audiences and laypersons.

The relationship between individual exposure and its controlling factors was found to be extremely complex, made more so because people frequently move through a city faster than the pollution. Individuals were seen to pass through clouds of pollutants, that were themselves drifting through the street systems some minutes after being emitted, and thereby experienced surprisingly high short-term exposure. Simple strategies for limiting personal exposure were devised and evaluated. In spite of the overall complexity, some basic principles and assumptions were identified that could provide greatly improved understanding of the processes that control short-term exposure peaks.

Taken together with results from field experiments in York, the data highlighted the main causes of elevated concentrations of traffic related CO within urban streets that may influence high exposure. The most important factors were found to be: i) the level of traffic congestion, rather than the total vehicle flow, during daytime periods; ii) the overall height to width ratio of the streets; iii) the interaction of above roof winds and canyon geometries, leading to a build-up of pollutants in leeward locations under certain background winds and resulting CO concentrations up to 3 times higher than windward locations; iv) the proximity to heavily trafficked intersections.

There were several implications for measures to reduce exposure at the road-side in urban locations. Firstly, significant benefits in street canyon air quality may result from reductions in the level of congestion within streets of similar geometry to those considered here, since potentially this could reduce the local emissions from a large number of individual vehicles. This suggests the use of air quality management policies where a city is modified or designed so that non-polluting modes of transport (e.g. cyclists) are able to avoid pollution hot-spots. The use of side streets rather than main roads by pedestrians and cyclists travelling through Central London could lower overall exposure to traffic related pollutants by up to a factor of 3 under worst case conditions. The marked spatial and temporal concentration variability suggests that any attempt to model personal exposure would require accurate representations of traffic related emissions under varying traffic regimes as well as complex turbulent dispersion mechanisms dependant on above roof wind flows as well as the specific location within the streets. The analysis methods focussed on mean concentrations and air flow and traffic characteristics. Future work should investigate the intermittency that is, in reality, present in all these processes in order to determine the effect on micro-exposure events within urban streets.

Exposure Reduction (one of the main application areas of DAPPLE) has been adopted in the EU's draft revised Air Quality Directive. Surrounding this, DAPPLE has contributed to debate at the NSCA and DEFRA into the nature of exposure reduction that is appropriate, as DAPPLE has focused on micro-scale effects and peak short-term exposures that are tending to be ignored in other EU member states. DAPPLE has similarly also contributed to DEFRA's consultation on the Review of the Air Quality Strategy, where DAPPLE has been supported by local authorities concerned that action they can take to reduce exposure is being undervalued in national and EU-level discussions.

Vehicle movement and emissions

DAPPLE provided the opportunity for the traffic demand responsive controlled area of Marylebone Road in central London to be set-up as an urban laboratory. Validation of the SCOOT (Split Cycle Offset Optimisation Technique) traffic flows was carried out during the first field campaign using manual counts of traffic from the roadside. Traffic flow masking occurred because one detection loop crossed two lanes and this resulted in poor predictions during the high flow periods that occurred for a large proportion of the time in Marylebone Road. Although an empirical correction was developed and applied in the initial estimation of emissions, the second campaign was used to obtain a better understanding of the masking phenomenon. The analysis, using additional SCOOT outputs, resulted in a more rigorous empirical relationship that improved the predictions of traffic flow during periods of masking. The empirical relationships developed for the second campaign were then applied to the first campaign, demonstrating increased accuracy. The methodology for treating masking can be applied wherever this is an issue.

The WEBCOMIS information platform for congestion, air emissions and noise estimation was set up for the Marylebone Road area and then applied to the two survey periods. Emissions were predicted for each five minutes, based on SCOOT data and using the Leicester Enhanced Traffic Emission Module (ETEM). Results were obtained using the fleet characteristics as defined by the Leicester emissions factors and secondly using the vehicle composition and fleet characteristics for London.

Air quality

Between 10 and 15 Learian Streetbox CO monitors and 2 Streetbox Gold CO and NOx monitors were mounted in the vicinity of the intersection at heights of 4 and 7m. Output was recorded as 5 minute average concentrations. Further Learian CO instrumentation was mounted indoors. Data were also available from the Leeds ITS Instrumented Vehicle and the Marylebone Road AURN and WCC House air quality monitoring sites. The CO data enabled an exploration of the variability of long term average concentrations in the vicinity of the intersection, which identified locations where monitoring recorded up to twice the mean from the AURN site. These results complement those from the exposure studies in demonstrating the degree to which even a well sited monitoring station can misrepresent air quality within its near-environment.

Streetbox sites were selected to reveal concentration gradients across the streets and the intersection, and vertical variations within street canyons. This proved particularly valuable and data from selected monitors were used to identify the flow characteristics within street canyons when tracer experiments were undertaken. For example, during the first tracer experiment, the onset of a classical canyon circulation in Marylebone Road with increasing wind speed during the latter part of the day was clearly seen in the carbon monoxide data.

Internal CO levels were monitored at different locations within the Westminster City Council building for three periods of approximately one week each. Mean levels, mean I/O (indoor-outdoor) ratios and correlations with outdoor CO were generally found to decrease within the building away from the two busy roads (Marylebone Road and Gloucester Place). The data were analysed with respect to the prevailing meteorological conditions. Peak indoor and outdoor CO concentrations were found for south-easterly winds although peak I/O ratios were associated with north-westerly winds. A weak negative correlation was observed between wind speed and I/O ratio, while a positive correlation was found between ambient temperature and I/O ratio.

Local-scale meteorology

Between 7 and 11 sonic anemometers were mounted at heights of 4 and 8m, mainly on lampposts. Additional mobile instruments measuring at a height of 1.5m were deployed as required. Reference instruments were installed on the WCC House and Library roofs at 18m above street level and, during the Spring 2004 campaign, at 180m on the BT Tower. Comprehensive short range weather forecasts and meso-scale model output were provided by the Meteorological Office. Together, this provided a most detailed data-set, both in its own right and in support of the exposure, air quality and tracer studies; there was a close and constructive interaction between the meteorological and dispersion studies.

Characteristic flow regimes at the intersection and within the street canyons were identified and related to the external (above roof level) wind conditions. Inspection of the probability density distribution of the horizontal wind direction revealed examples of bimodal forms at the intersection that, following further time domain analysis, were interpreted as intermittent flow switching. This arose when the external wind was at significant incidence to the (more-or-less orthogonally aligned at the field site) street network. In such situations, the winds in the streets around the intersection could be modelled conceptually as the vector sum of a channelling and a recirculation vortex component. Furthermore, analysis over a relatively broad range of roof-top wind directions demonstrated that channelling depended linearly on the along-street component of the roof-top reference wind, whilst the strength of the cross-street recirculation vortex depended linearly on the component of the roof-top reference wind perpendicular to the street.

In general, the mass balance at the intersection involved an input from two streets feeding flow and an output from two removing flow, together with vertical exchange with the flow above roof level. Flow switching implied that a flow entering from an “input” street left by either of the two “output” streets. The full, three-dimensional complexity of this motion was further investigated through computational and wind tunnel modelling in order to obtain deeper insight.

Analysis of the turbulence within the streets showed the controlling variables to be not as clear as for the mean flow, though turbulence in the boundary layer above the buildings (as measured on the BT Tower) correlated best with the turbulence within the street. This suggests that some turbulent events above roof level may penetrate into the street canyons, or at least trigger related events within the street canyons. Results from high resolution numerical simulations of flow around an array of cubes support his picture, suggesting that the recirculation within the street is intermittent and driven by high wind speed events above the roofs.

Tracer dispersion

The DAPPLE experiments were the first major tracer studies carried out in European-style cities. The extreme sensitivity of tracer (PFC) detection implied that very low tracer emission rates could be used, typically of order 100mg in 15 minutes. This, in turn, greatly simplified the health and safety and other formal approvals needed before field work could be undertaken – particularly important, given the prevailing political climate. The first tracer dispersion experiment was run on 15/5/03 and was planned primarily as test of the methodology. Ten sampling units were deployed at distances up to about 450m from the source (9 being within 300m with 1 at approximately 430m), each collecting ten consecutive three-minute air samples. This proved completely successful, though at that stage sample analysis times were very prolonged and only one tracer experiment was carried out in the Spring of 2003. Two further tracer experiments were conducted in the Spring of 2004, in each of which two PFC tracers were released simultaneously from separate sources and 16 sampling units deployed, one located indoors. Preliminary trials with a fast response SF_6 detector were also run during this period, as were some studies of the suspension and dispersion of road dust. Finally, in November 2004, four experiments were completed, again each with two PFC tracers released from separate sources, including a moving vehicle. In all, 13 tracer dispersion data-sets were obtained; far exceeding initial expectations and adding significantly to the small but growing collection of such data world-wide. Experimental methods were continuously developed throughout the DAPPLE project, to reduce analysis times and increase the number of PFC tracers that could be used simultaneously.

Analysis of the tracer studies focussed equally on their use in developing and evaluating modelling, particularly at the operational level, and in building an understanding of short range dispersion processes in urban areas. These activities were not conducted in isolation and benefited greatly from related wind tunnel work, described below, and collaboration in the international effort (centred mainly in the USA) concerning the dispersion of hazardous materials in urban areas.

Computer modelling and simulation

Large eddy simulation studies were run using the Imperial FLUIDITY code, which is an adaptive grid method designed to optimise gridding in response to the changing features of a turbulent flow. The objective was not to reproduce the field site in any detail but to use a simplified geometry that captured the important processes affecting flow and dispersion around intersections. Related wind tunnel work addressed the importance of modelling detail on flow and dispersion behaviour. Initial LES effort focussed on developing suitable methodologies for code application - this was a protracted but necessary part of the work. FLUIDITY was then used to model the dispersion of pollutants from sources resolved spatially at resolutions from 50m to 1m and temporally from 1 hour to 1 second, in the unsteady flow through the study domain. The relative importance of sources of variability in the concentration field (i.e. due to both the emissions and the flow) and in individual exposure were investigated. These simulations contributed greatly to the analysis of the exposure measurements and the development of practical advice for reducing exposure.

Other computational activities, spanning the full range from RANS CFD to simple empiricism, were carried out to examine the use of such procedures in an operational framework. This had two strands, one relating to standard air quality concerns and the other to emergency response and management; indeed, the work formed a major contribution to the current international effort in the latter context. Air quality modelling concentrated on the application of “advanced” regulatory models, typified by ADMS. Prediction of exposure was attempted using ADMS-Urban at various resolutions, with and without modifications, and with a simpler box model of street canyon air quality. Results were also compared with findings from representing exposure by a moving receptor in the pollutant field simulated by the large eddy simulations. Important timescales and length-scales of variability were identified that are not normally resolved in operational modelling and consequences for the prediction of exposure reduction were assessed.

A simple empirical relationship was developed from the field and wind tunnel experiments to predict the maximum concentration as a function of straight-line distance from a point source. This proved to be remarkably robust when evaluated against other data from field studies in the USA. A range of operational dispersion models, including the UK-MoD UDM model and “base-line” models (such as BML and ASUDM), was also evaluated with the DAPPLE field data. Models predict ensemble average behaviour (the most advanced may also provide an indicator of variability) whereas tracer studies are always single realisations from the ensemble, frequently in circumstances where variability is large (as was so in the case in hand). Thus the reliability of conclusions describing model performance may be quite limited unless a large number of individual realisations is available. The 13 examples provided by DAPPLE constitute a most useful body of data, though a much larger data-set would provide for more definite conclusions. Obtaining this is one of the goals of continuing research at the DAPPLE field site, funded by the Home Office.

Wind tunnel modelling

Like the large eddy simulation studies, the wind tunnel work was not intended to be a faithful representation of all features of the field site. Initial studies were used to help design the first field tracer experiment and then to build understanding of dispersion at the DAPPLE site. This involved both steady and finite duration emissions and particular attention was given to variability, through measurement of the mean and mean-square concentration field and construction of probability density functions of concentration. Travel, rise and decay times were also determined and related to the building scale and the wind conditions just above roof level. Comprehensive and detailed flow and dispersion data-sets were collected that were suitable for model evaluation work at all levels from the empirical to CFD. This data has already been widely used outside of the DAPPLE project, for example within the NERC-UWERN urban boundary layer programme.

Considerable attention was given to experimental repeatability and the sensitivity of flow and dispersion behaviour to boundary conditions (i.e. source conditions, external flow conditions, model extent and model detail). Understanding these issues was important in interpreting field data, in judging model performance and, perhaps most importantly, in establishing guidance for adequate simulation, whether by wind tunnel or computational methods. Standard model evaluation measures were used to quantify repeatability and the sensitivity of results to changes in boundary conditions. Repeatability was well within the intended ±10% level and the response of near ground level concentrations to the variations in the boundary conditions examined was generally within ±20% of the baseline results. Areas were identified where sensitivity to small variations in receptor location exceeded this level due to there being large local gradients in mean concentration.

Comparisons with results from the field tracer studies were based on the single realisations from the field and the probability density distributions of concentration from the wind tunnel. Simulations of both the Spring 2003 and 2004 tracer experiments showed concentrations in the field that were at the extreme lower end of those derived from the wind tunnel ensemble. Light winds were a feature of all the tracer study days and it is quite feasible, though not readily proven, that additional dilution mechanisms were active, driven by vehicle movement and thermally induced mixing. However, the November 2004 field studies were found to give concentrations greater than those deduced from the wind tunnel. A definitive comparison probably awaits the availability of a much larger field data-set. Comparison of wind fields avoided many of these issues by concentrating on those times during the whole field study periods when winds were moderate or strong. This provided a much more satisfactory agreement between field and wind tunnel.

Flow processes at the intersection and in the street network were investigated in detail through a combination of flow visualisation studies and flow and dispersion measurements. A detailed mass flux balance was determined for the intersection and the surrounding streets. This revealed the balance between advection along the streets, exchanges between streets at intersections and exchanges with the external flow, providing important information for guiding the development of “integral” urban dispersion models, such as the French SIRANE model. Vertical exchanges in the vicinity of a tall building, Marathon House in Marylebone Road, was also investigated.

Extensive flow visualisation studies using spotlight and laser light sheet illumination were conducted and found to be a great aid in the interpretation of wind field measurements at the intersection. This showed the complex, unsteady, three-dimensional nature of the flow field and explained the “flow switching” phenomena deduced from field observations as a consequence of the unsteadiness. Transfer between streets proved not to be intermittent but a continuous process within the three-dimensional motion. The unsteadiness then resulted in measurements at a fixed point to appear to switch as, for example, the depths of interacting flow fields changed. Another very important use of the flow visualisation material was in the field of public communication of the research.

Project Review

The first comment to make is that the project benefited greatly from the genuine interest and involvement of stakeholder groups in London; the APRIL (Air Pollution Research in London) network played a prominent role in ensuring this. The consequences meant that many potentially difficult issues were overcome in a straightforward manner, frequently without cost; for example, in gaining required permissions from authorities to conduct field work, in the provision of a base within Westminster Council House, in the installation of instrumentation on lampposts etc. by Transport for London and in provision of meteorological data by the UK Met. Office. As noted above, having a project manager as a defined role within the consortium proved essential to its efficient operation. Initially, this was funded to cover the field work but some rearrangement of planned expenditure and use of additional MoD funds at Reading meant that the role could exist almost to the end of the project. Surrey planned to support a research studentship but, having failed to find a suitable candidate, converted this (with EPSRC agreement) into a PDRA appointment. This had no financial implications, though it did result in the award completion date being extended by three months.

Aspects of the programme were revised in reaction to political events and the subsequent clear need for detailed information describing "puff" dispersion in London (and elsewhere in the UK). This particularly affected the direction of the wind tunnel programme but also led to some additional funding from the Home Office for further field trials in November, 2004, and to extensive follow-on activities. Other aspects of the wind tunnel programme responded to information coming from the field work. In particular, the field observations describing the unsteady, three-dimensional flow at the intersection needed detailed support from the wind tunnel so that the full picture could be revealed and understood. This comment is equally applicable to the large eddy simulations, which gathered much greater prominence and largely replaced the RANS work planned at Imperial. Another driver for this was the need to understand the relative importance of the causes of variability in the concentration field (i.e. due to emissions, dispersion and movement).

The developments very briefly summarised above led to some planned objectives not being met. No field measurements were made of pressure differences across the building envelope, though some indoor pollution measurements were obtained. The difficulty in making pressure measurements in the WCC building were found to be insurmountable, and it was deemed better use of resources to focus on more detailed computational modelling and wind tunnel simulation of the additional tracer releases instead. Nevertheless, some wind tunnel pressure field measurements were made during an associated project using an extensive array of cubical obstacles in the skimming flow regime. Wind tunnel experiments with a stable upstream flow were not completed, primarily due to the much more extensive study of puff dispersion that was conducted and, to a lesser extent, to failures in the wind tunnel flow heating controls. This matter will be returned to in continuing research, now funded by the Home Office.

Research Impact and Benefits to Society

The international research community will benefit from the dissemination of DAPPLE outputs, providing extensive new insight into the emission and dispersion of and exposure to pollutants in an urban environment, comprehensive high quality data-sets, and the delivery of practical benefits. Policy makers, regulatory authorities and other interested groups, such as environment epidemiologists, will gain improved understanding of the accuracy of air pollution estimates, and the nature of pollution hot-spots and their control. Local authorities and the consultants who serve them will have improved capability in carrying out air quality review and assessment work and those responsible for traffic management will be better able to assess the air quality implications of their decisions. Emergency planning authorities and MoD will gain improved understanding and predictive capability for assessing the implications of an accident or deliberate release of a hazardous substance in an urban area. The population will benefit from the guidance developed to reduce personal exposure and, in the longer term, from more pleasant and healthy urban conditions as the urban environment and its use are changed to reduce air pollution exposure.

Further Research and Dissemination Activities

Analysis of DAPPLE results and publication of research papers by consortium members will continue for some time to come. This observation is particularly germane to the wind tunnel and large eddy simulation studies, as these were heavily used during the project in their integrating role, producing substantial outputs that have so far only been more widely disseminated through conferences. As already noted, the quality and quantity of output in all aspects of DAPPLE exceeded expectations and, consequently, analysis of the data will continue into the foreseeable future. Increasingly, this will involve groups that were not directly involved in the project itself.

DAPPLE benefited by attracting additional funding that extended the range of activities followed and their analysis. This derived from a number of sources, including local authorities and national government; in total it exceeded £200,000, plus a considerable "in-kind" component. The consortium played a key role in establishing a concerted UK action in urban climatology and members represent the UK on COST 732. Throughout, the consortium provided regular feedback of research progress and outputs to the full range of stakeholders. More general dissemination was achieved through broadcasts on BBC Radio and articles on the BBC web-site and in New Scientist. Regular reports and presentations were given to local authorities, agencies and other interested groups in London. The APRIL network played a major role in these activities. All these activities are continuing and will continue for some years as the analysis of DAPPLE data progresses further and new research is carried out. The consortium has been awarded funds from the Home Office of approximately £850,000 to continue with tracer and meteorological studies for another three years, and £35,000 to collaborate with ECL (France) in evaluating the French SIRANE model applied to London. The meteorological work has led to collaboration in a BOC Foundation funded BT Tower experiment, which will investigate aspects of urban particle pollution. Other work in hand, funded by the Home Office, is the production of a DVD that can be used in training first responders. This makes extensive use of new flow visualisation material from the EnFlo tunnel. A similar product dealing with "routine" air quality issues is contemplated.