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A RENAISSANCE STUDY OF DISPERSION PROCESSES AROUND A MAJOR ROADWAY

J. Duncan Whyatt[1], Andy R. Malby[1], Vlad Isakov[2], David Heist[2], Steve Perry[2], Roger J. Timmis[3] and David J. Carruthers[4]

[1]Lancaster Environment Centre, Lancaster University, UK
[2]US Environmental Protection Agency, North Carolina, USA
[3]Environment Agency for England and Wales, UK
[4]Cambridge Environmental Research Consultants (CERC), Cambridge, UK

Abstract: Conditional analysis techniques have been applied to observed and modelled concentrations from a 13-month field study where monitors were deployed at different distances from an interstate highway in Las Vegas, USA. The ADMS Urban dispersion model reproduces the general decline of concentrations with distance from the roadway but tends to over-predict the decline under very stable conditions. The model reproduces the general characteristics of observed wake effects at 10m, but does not reproduce an apparent continuation of observed wake effects to greater distances. Overall, the Las Vegas data set makes a significant contribution to information and understanding of near road dispersion and prediction, and it warrants further studies to test model predictions in more detail and to explore uncertainties. The study has also demonstrated the value of conditional analysis when summarising observational data for purposes of model evaluation.

Key words: conditional analysis, stability classes, roadway studies, wake effects.

INTRODUCTION
Over 36 million people in the US currently live within 100m of a major highway. There is an increasing body of evidence to suggest that this can lead to adverse health effects (respiratory and cardiovascular disease, cancer, and even mortality) for populations living, working and/or attending schools near such locations. The US Environmental Protection Agency (USEPA) have identified characterisation of dispersion near major roadways as a priority for further research and have recently conducted intensive monitoring campaigns of traffic-related pollutants in Raleigh, Las Vegas and Detroit (Baldauf, et al., 2008 ; Kimbrough et al. 2008).

Dispersion studies around major roadways are currently undergoing something of a renaissance due to: a) new epidemiological evidence that some traffic-related pollutants do not have "no-effects" thresholds, but affect the health of susceptible groups even at low concentrations, e.g., PM_{10}; b) the deployment of new measurement methods to assess near-road concentrations and associated meteorology (e.g., sonic anemometers); c) the development of a new generation of models better able to represent the complexities of source characteristics (e.g., noise barriers, road cuts, buildings, vegetation) and related processes (e.g., vehicle-induced turbulence); d) the development of new directional and signal-analysis techniques to infer source or process behaviour from ambient concentration data; and e) the need to check that planned improvements in traffic emissions are occurring in practice for purposes of compliance with air quality standards.

Conditional analysis is the term used here for techniques that collate air quality data into distinct groups, e.g., for different emission and dispersion situations, so that observations and model predictions can be conveniently compared for each group. This paper uses conditional analysis to gain a better understanding of near-road dispersion processes and model performance. It focuses on 13 months of field data collected during 2008-2010 during a Las Vegas Monitoring Study and specifically on hourly NO_x concentrations and concurrent data on wind speed, wind direction and traffic flow. The monitoring involved co-located pollutant monitors and meteorological stations at 4 nominal distances from a major highway, Interstate-15, at 100m upwind and at 10, 100 and 300m downwind. The positions of stations relative to the north-south aligned highway are shown in Figure 1 together with a wind rose for the study period. Note that for practical reasons the positions of the stations could not be optimally aligned with the dominant south-westerly wind so that the stations form an oblique transect relative to the prevailing wind.
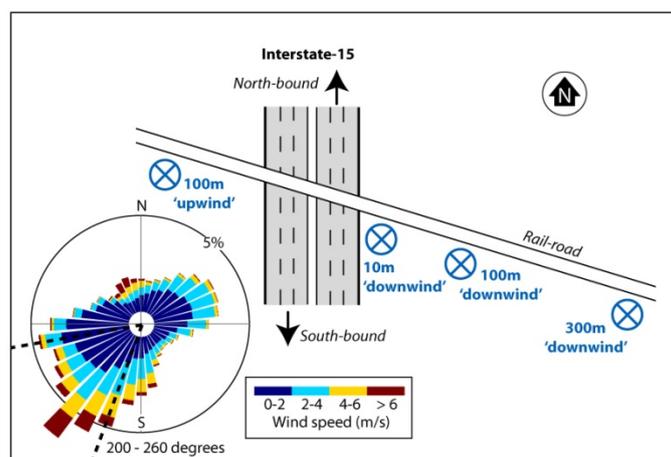

Figure 1. Monitoring positions and wind rose for the Las Vegas roadway study, showing wind sector 200-260 degrees (dashed) as used for conditional analysis.

The orientation and spacing of upwind and downwind monitors gives us opportunities to determine a) local background concentrations adjacent to the highway; b) the incremental impacts of road sources (excluding background concentrations); and c) the absolute and relative changes in concentrations with distance from the road. Such comprehensive and intensive data are rarely available. For example, Barrett (2008) had to use data from a single roadside monitor and background data from a site ~3.6km distant when analysing roadside PM_{10} concentrations in London.

In this paper we use innovative data mining techniques to gain a deeper understanding of dispersion processes downwind of the major highway. In particular we evaluate and analyse incremental concentrations (with background deducted) along the monitored transect in the wind sector 200-260 degrees which encompasses the prevailing south-westerly winds (Figure 1). We then assess the extent to which a new generation dispersion model is able to reproduce: (i) observed concentrations and their decline with distance from roadside and (ii) wake effects on dispersion as a result of wind-induced turbulence.

CONDITIONAL ANALYSIS
General approach
We use the term conditional analysis to describe the filtering process through which subsets of data may be selected and analysed in order to gain deeper insights into specific processes. Data may be selected on the basis of

- meteorology (wind speed, wind direction)
- atmospheric stability (e.g., convective, neutral, stable) and/or
- source activity (e.g., traffic volumes at different times of day or on different days of the week).

Here we use our conditional techniques to generate horizontal concentration profiles for ambient concentrations with distance from source under convective, neutral and stable dispersion classes. We then compare these with modelled concentrations produced using equivalent meteorological and traffic flow data together with appropriate emissions estimates. We also take our conditional analysis of the stable case further in order to quantify the influence of vehicle-induced turbulence on roadside concentrations, and to assess the model's ability to reproduce the impact of wake effects on concentrations.

Atmospheric stability groups
Our application uses NO_x as the pollutant of interest because this is effectively a conserved pollutant in the short-range dispersion situation considered here, so that it is a convenient "tracer" for considering near-roadway dispersion. We start by selecting hourly NO_x concentrations for all instances when the wind was blowing from the 200-260 degree sector. The subset of data from the 100m 'upwind' monitor is broadly representative of air that has not been influenced by traffic on the interstate highway. The equivalent subsets of data from the downwind monitors are representative of emissions from local background sources and the interstate highway. We therefore subtract background NO_x concentrations (recorded at the 'upwind' monitor) from the concentrations recorded concurrently at the 'downwind' monitoring stations in order to derive 'incremental' NO_x. This subtraction-of-background procedure is designed to distinguish the impact of the interstate highway on the downwind monitors.

Having derived a subset of hourly incremental NO_x concentrations for the 3 downwind monitors, we subdivide these hours into 5 atmospheric stability bins. These bins are termed 'very convective', 'convective', 'neutral', 'stable' and 'very stable' and are based on ranges defined by the ratio of boundary-layer height to Monin-Obukhov length (H/L_{MO}): the H/L_{MO} ranges for the 5 bins are < -6.0, -6.0/-0.3, -0.3/1.0, 1.0/2.0, and > 2.0, respectively. Figure 2 focuses on the very convective, neutral and very stable bins which contain 139, 527 and 651 hours of data, respectively. As expected, most convective cases occur during daylight hours when the surface heat flux is high and wind speeds are relatively low (< 6 ms^{-1}). Neutral conditions tend to occur at night or in the early/late morning/evening, and have a wider range of wind speeds, e.g., 2-10 ms^{-1}. Very stable conditions also tend to occur at night or in the early/late morning/evening, and have low wind speeds, e.g., 0-3 ms^{-1}. Figure 2 also shows the volume and mean speed of traffic along the interstate highway for the selected hours/conditions.
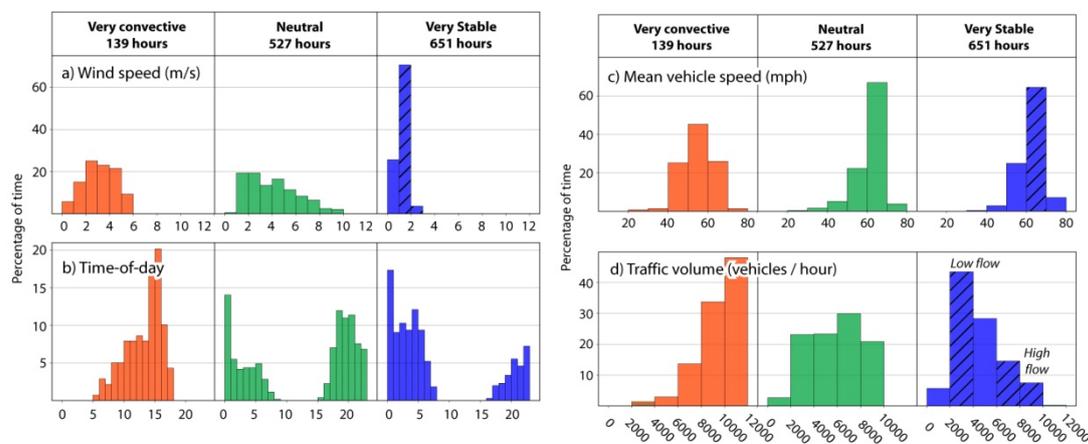

Figure 2. Characteristics of selected data as used in conditional analysis of roadway dispersion: data are summarised by stability groups for: a) wind speed (ms^{-1}) b) time-of day c) vehicle speed (mph) & d) traffic volume (vehicles/hour). All data were used for downwind decay analysis, and hatched data under 'very stable' group were used for wake effect analysis.

RESULTS OF CONDITIONAL ANALYSIS

We can now analyse the downwind decay of incremental NO_x concentrations under different, well-defined, dispersion conditions. Furthermore, we can also normalise for different traffic conditions (volume, speed) based on concurrent activity data and determine where and why impacts are worst. Our structured approach, based on conditional analysis, maximises our ability to resolve consistent signals within noisy data. One clear benefit of this approach in the context of HARMO is that we are able to separate specific dispersion conditions within the ambient record. These can be used to test specific aspects of model performance. This approach is fundamentally different to conventional approaches that compare model simulations against observed concentrations from a time-series or a population containing different dispersion conditions.

Observed distance decay

The downwind dispersion of observed incremental NO_x from Interstate 15 is illustrated by the solid box-and-whisker plots in Figure 3. The solid plots in Figure 3a show for each stability group how the concentrations change relative to the situation at 10m from the roadway – where the median concentration is given the value unity; it should be noted that these concentrations have been normalised for the number of vehicles on the highway in the relevant hour. The solid plots in Figure 3b show, for each stability group, the corresponding absolute concentrations observed at the 3 distances in units of ppt/vehicle.

Considering first Figure 3a, the decline of relative concentrations with increasing transverse distance from the roadway is greatest under 'very convective' conditions. The decline of relative concentrations is intermediate for 'neutral' conditions, and least for 'very stable' conditions. Considering next Figure 3b, the absolute reductions in concentrations between increasing transverse distances are smallest for 'very convective' conditions, e.g., ~2 ppt/vehicle between 10 and 300m. The decline of the corresponding absolute concentrations for 'neutral' and 'very stable' conditions are greater, e.g., ~3 and ~5 ppt/vehicle, respectively.
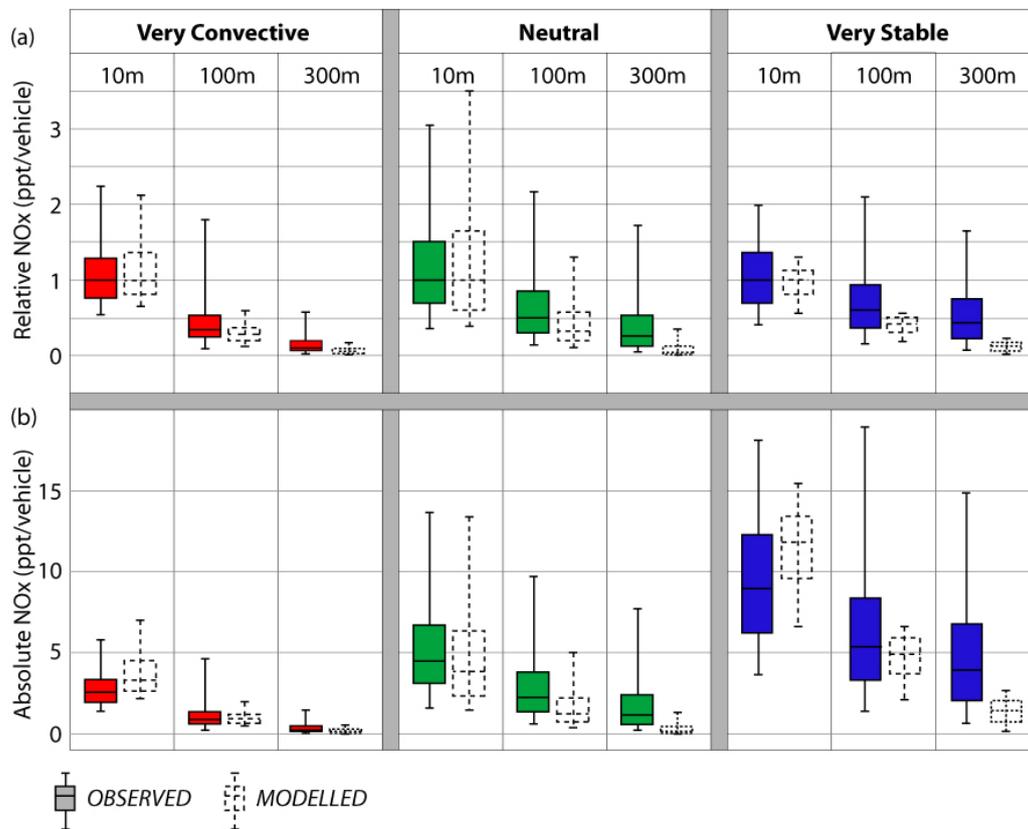

Figure 3. Declines of observed and modelled concentrations with distance from roadway for selected stability groups: (a) shows concentrations relative to 10m median value, which is set to unity; (b) shows absolute concentrations.

Overall, this conditional analysis of the monitoring data reveals significant differences in dispersion of pollution downwind of Interstate-15 under different conditions of atmospheric stability.

Modelled distance decay

We now test the ability of a new generation dispersion model, ADMS Urban, to reproduce these concentration gradients under the same meteorological (stability) conditions and similar conditions of traffic activity. This is a particularly stringent test of model performance because it focuses on well-defined cases containing multiple observations for relatively consistent and 'homogenous' conditions, as opposed to more conventional tests where models are compared with data spanning a wide range of more 'heterogeneous' stability and traffic conditions. Our approach enables us to focus on specific aspects of model performance while still having relatively large samples, so that disparities between observations and predictions can be

identified with more confidence. In this section and section 3.3 we consider the basic decline of concentrations with transverse distance.

ADMS Urban (CERC, 1997) was used to reproduce the source-receptor relationships of the Last Vegas Monitoring Study illustrated in Figure 1. The north and south bound lanes were modelled separately with the same traffic composition (10% HGV, 90% LGV) but different assumptions about traffic volume and speed. An initial mixing height for pollutants emitted from vehicles of 3.5m was used because the USA vehicle fleet includes large trucks with vertical exhaust pipes which will help to mix pollutants initially up to this height. Model receptors were set at the locations of the 3 downwind monitors at the nominal distances of 10m, 100m and 300m. ADMS Urban was then run using hourly meteorological data associated with the different stability groups described earlier, so that model output could be compared directly to the conditionally summarised ambient concentrations. The modelled results are shown in Figure 3 using dashed box-and-whisker plots that are drawn alongside the solid plots denoting observed concentrations; Figure 3a shows relative concentrations with the 10m modelled results set to unity, and Figure 3b shows absolute concentrations in units of ppt/vehicle.

Comparison of modelled and observed decay
The extent to which ADMS Urban is able to reproduce dispersion under very convective, neutral and stable conditions can be seen by comparing the solid and dashed plots on Figure 3. The model shows good agreement with the observed record under the very convective case in both relative and absolute terms. The model also shows reasonable agreement under the neutral case, but significantly over-estimates both the relative and absolute declines in concentrations under the very stable case. This is a significant finding in that residents downwind of major roadways may be exposed to higher concentrations than predicted by models under this stable case which occurs relatively frequently, i.e., for about 25% of the hours with winds from 200-260 degrees.

Comparision of modelled and observed wake effects
We have used our conditional analysis approach to identify observed dilution effects due to vehicle wakes, and to compare these observations with model predictions for wake effects. For this purpose we have focussed on conditions where wake effects are likely to be most apparent. In particular, we have focussed on the 'very stable' group, and on differences arising between contrasting situations with low and high traffic volumes. The observational data used for this study of wake effects are marked in Figure 2 where the 'very stable' histograms are hatched for low and high traffic flow regimes, corresponding to ~3100 and ~7300 vehicles/hour, respectively. In order to distinguish the effect of wakes as far as possible, the observed data were constrained to situations with wind speeds between 1 and 3ms^{-1} and with vehicle speeds between 60 and 70mph (as shown by hatching in Figure 2).

Observed incremental NO_x concentrations at 10, 100 and 300m downwind of the highway are shown in Figure 4 for the selected wake-effect conditions. There is some evidence for vehicle-induced dispersion in the near field (10m monitor), where incremental NO_x concentrations decrease from ~11 to ~7 ppt/vehicle when traffic volumes increase from ~3100 to ~7300 vehicles/hour. The observations at 100 and 300m also show some similar evidence of wake effects.
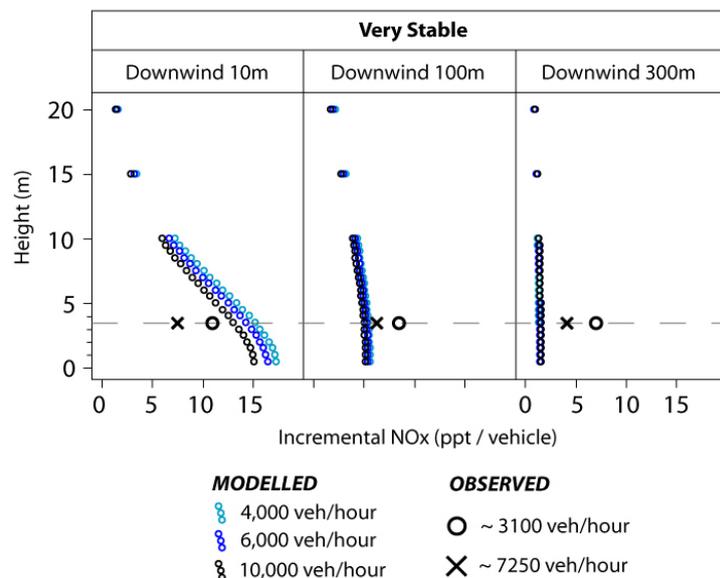

Figure 4. Observed and modelled wake effects at 3 downwind distances under very stable conditions. Concentrations are shown for different vehicle flows; observed values are at 3.5m height and modelled values at heights 0.5-20m.

For comparison with these observations ADMS Urban was used to model NO_x concentrations at the 3 distances and at a variety of heights above the surface under corresponding conditions of stability and under a range of traffic volumes (4000, 6000 and 10,000 vehicles per hour). The model includes a wake effect parameterisation, and Figure 4 shows model results

on the same ppt/vehicle basis as the observations. Considering first the absolute levels of observed and predicted concentrations, it can be seen that observed concentrations are over-predicted in the near field (i.e., ~40% over-prediction at 10m) but under-predicted in the far field (i.e., factor 2-3 under-prediction at 300m); this is consistent with the previous results in Figure 3b. Considering next the reductions in concentrations between the low and high vehicle flow cases, it can be seen that the predicted reduction at 10m is comparable to the observed reduction (~4 ppt/vehicle). However, at 100m the corresponding modelled reduction in concentration is smaller than that observed (i.e., ~1 versus ~3 ppt/vehicle); also, at 300m the model does not predict any wake effect, which contrasts with an observed reduction of ~4 ppt/vehicle.

The vertical profile of modelled reductions with height is consistent with a wake effect that is greater at low heights (< 5m) and declines at greater heights (> 5m). The main difference between models and observations is that the model does not predict substantive wake effects at a few hundred metres from the roadway, whereas the observations suggest there may be some wake effects still present at these distances.

DISCUSSION AND CONCLUSION
This has been a preliminary conditional analysis of a high resolution roadway transect study. We have focussed on grouping observations into homogeneous subsets of dispersion and traffic so that these observed subsets can be compared with model predictions for corresponding grouped situations. The model reproduces the general decline of concentrations with distance from the roadway but tends to over-predict the decline under very stable conditions. The model reproduces the general characteristics of observed wake effects at 10m, but does not reproduce an apparent continuation of observed wake effects to greater distances at 100 and 300m.

This study has used field observations that have required a number of simplifications and approximations in order to progress the analysis. In addition, although the field work site was carefully selected, it inevitably has some local features and complexities which add to the uncertainties. Particular limitations of the study include:
- The oblique alignment of prevailing winds relative to the roadway and monitored transect.
- The necessary assumption that background levels at one monitor (100m 'upwind') are representative.
- The neglect of a shallow cutting around Interstate 15 in the model, which assumed flat terrain.
- A simplified approach was taken to vehicle fleet composition.

Overall, we think the Las Vegas data set makes a significant contribution to the understanding of near road dispersion and prediction, and that it warrants further studies to test model predictions in more detail and to explore uncertainties. The study has also demonstrated the value of conditional analysis when summarising observational data for purposes of model evaluation.

ACKNOWLEDGMENTS

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