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The evaluation of air quality impacts of traffic on urban road networks

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Abstract

Air quality impacts of urban transportation policies and strategies are often assessed using modelling techniques based on traffic flow simulation and travel demand analysis tools. Such analytical methods have traditionally been aimed at estimating the overall mass of individual pollutants with an emphasis on gaseous emissions. Significantly less attention is usually given to the quantification of particle emissions.

Extensive data relating to fine and ultra-fine airborne particle concentration levels and the corresponding contributing vehicles have been collected at two significantly different Brisbane sites. Analysis of the relationships between the data so far point to a strong correlation between traffic flow and meteorological variables and particle concentrations.

1. Introduction

In addition to pollutant gasses such as oxides of carbon and nitrogen, attention is now increasingly focusing on the fine and ultra-fine particle emissions resulting from the combustion processes of the transport fleet. Fine particles are less than 2.5 micron diameter ($PM_{2.5}$) and ultra-fine particles are less than 0.1 micron diameter.

According to the USEPA, (1997) a number of scientific studies have linked particle matter, especially fine and ultra-fine particles with a series of significant health problems. In Australia alone, this could account for some 900 premature deaths per year.

The concentration of particle emissions at any site is dependent on a number of independent variables such as the number of vehicles, the type of vehicles, the fuel used and the driving cycles. However, the concentration of particles found at a specific site (as distinct from the concentration of emissions) is not only dependant on tailpipe emissions, but also the rate of dispersion of particles into the environment after emission. Meteorological conditions such as wind speed, temperature and humidity have a bearing on determining the final concentration.

This paper forms part of a continuing series of publications related to the research project currently being conducted at the Queensland University of technology. (Morawska et al. (2001); Johnson et al. (2000); Johnson and Ferreira (2001a; 2001b). The paper is organised as follow: Section 2 describes the data collection process; section 3 presents the formulation of predictive models of particle concentrations. This is followed in section 4 by a summary of some preliminary results obtained to date using a statistical analysis approach. Finally, some conclusions are offered in section 5.

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2. Data Collection

Particle Emissions

Since 1999, extensive data relating to fine and ultra-fine particle concentration levels and the corresponding contributing vehicles have been collected at two significantly different Brisbane sites. One site is a straight section of the four lane Pacific Motorway at Tora Street, with average free flowing peak hour flows of 1650 vehicles per hour per lane. The other site is a signalised intersection on a major urban freight arterial route outside a public hospital where the traffic has significantly larger proportion of diesel fuelled Commercial Vehicles (CVs) undergoing stop/start conditions at the signals. Thus, these sites have significantly different fleet compositions and driving cycles resulting in differing particle concentration levels and speciation.

Particle concentration data at each site was collected over several months as five-minute period averages, and matched to the corresponding vehicle counts. Fleet composition was determined from analysis of video data. Meteorological data (eg wind speed and direction, temperature, precipitation, humidity) and terrain data at the sites was also recorded. From an analysis of this data, the effect of various meteorological factors on the measured concentration levels can be determined.

By combining classified traffic count data with the video tape data at the investigated sites, functional dependencies between time of a day (for week and weekend days) and classified vehicle flow were developed. Flow rates for specific time of day /day of week were statistically analysed in order to predict average flow for those periods of interest within a 95% confidence level. Vehicle flow rates were further categorised by type and the flow rates for different vehicle classification for the period of interest were predicted.

The experimental data collected is actual counts of fine and ultra-fine particles in the $PM_{2.5}$ and less than 0.1 micron diameter range at various sites. Coarse particles are normally measured by their mass per cubic metre whereas instruments that are used to record fine and ultra-fine particles do this by counting the numbers of particles of specific sizes.

Although the numbers and sizes of these particles is assumed to be directly related to the numbers and types of vehicles present, the actual observed numbers and sizes of particles found at any particular time is dependant on a range of other variables. For instance, according: QLD EPA, (1994) the wind speed alone can mix and disperse particles, moving them significant distances from their production site, while rain can wash them out of the air. Thus, investigating the complex inter-reactions that occurs between the independent variables is crucial to the development of any mathematical model.

Other data

Coincident with the collection of particle emission concentrations, details of the contributing vehicles are also recorded with video cameras for later determination of fleet characteristics, such as speed, congestion levels, numbers, and vehicle types and age. This data is also collated and categorised into five-minute periods, in preparation for further analysis.

Site conditions that relate to the various topological conditions that impact on traffic flow, such as the street canyons, traffic lights, and road geometry are also recorded, as it is expected that they will have an impact on the observed concentrations. Ambient conditions such as wind speed, humidity and temperatures are also recorded.

In addition, the relationship between the particle count in any given five-minute period may not be directly related to the observed conditions during the same time interval, but may relate to conditions that occurred previously because of dispersive mechanisms acting on the particles.

3. Model Development

This project is developing micro models which are used to predict behaviours on specific links or nodes of a network, such as the growth or congestion of traffic on a road or the turning behaviour of traffic at an intersection.

The concentration found at a specific place depends on the amount of tailpipe emissions, as well as the dispersive mechanisms present. In order to predict the concentration at a point, additional parameters involving environmental conditions such as wind speed, temperature, humidity, topography, and landscape are utilised in the model to obtain a final concentration level.

Such models are extremely data intensive, and require considerable data for calibration and verification. Emission factors for the vehicle fleet are generally not considered to be very accurate, as they are often based on idealised driving cycles, and emission tests done on a few models under laboratory conditions or dynamometer tests.

It is expected that a model will be built up that can predict within a satisfactory level of accuracy the particle concentration expected to be found at a site. In addition, consideration will be given to the known particle emissions that are produced by vehicles during dynamometer testing.

Furthermore, the model should be sufficiently robust to give confident results, and be flexible enough to accommodate changes in vehicle fleet composition, changes in the types of fuels used, and be able to cater for a wide range of topographical and ambient weather conditions. This robustness can be tested at the calibration and verification stages by sensitivity testing.

Expected Model Formulation

The concentration of particles is the sum of the background particles plus the net contribution from vehicle activity and can be expressed as;

$$C_p = B_p + V_{net} \qquad \text{(Equation 1)}$$

Where:
C_p - Measured Particle Concentration (particles per unit volume), B_p - Background Particle Concentration (particles per unit volume), V_{net} -Net Vehicle Contribution of Particles

V_{net} is expected to be the gross amount of particles produced by the vehicles into a given unit volume less those removed by dispersion mechanisms, and can be expressed as;

$$V_{net} = V_e * D_f \qquad \text{(Equation 2)}$$

Where:
V_e - Particles emitted by vehicles
D_f - Dispersion Factors

Particles emitted by vehicles, V_e, are a result of a range of variables, such as vehicle flow rates, congestion factors, and other emission factors. As low vehicle flow rates can be found in either free flowing traffic or highly congested traffic, congestion levels are expected to be a major factor in determining V_e. V_e can be represented as;

$$V_e = V_n * C_f * C_b \qquad \text{(Equation 3)}$$

Where:
V_n - Vehicle flow rates, C_f - Congestion factors, C_b - Combination Factors

Combination Factors, C_b, in equation 3 primarily relate to vehicle and fleet characteristics and can be represented as a function of a range of independent variables by;

$$C_b = f\{F_c, F, D, E, R, H\} \qquad \text{(Equation 4)}$$

Where:
F_c, - Fleet Characteristics factor, F - Fuel Type factor, D - Driving Cycle factor, E - Vehicle Emission Rates, R - Road factors, H – Humidity (affects particle production during combustion)

Dispersion factors, D_f , in equation 2, primarily relate to meteorological factors and terrain factors and can be represented as a function of a range of independent variables by;

$$D_f = f\{W_s, W_d, T, H, T_f\} \qquad \text{(Equation 5)}$$

Where:
W_s, - Wind Speed, W_d, - Wind Direction, T – Temperature, H – Humidity, T_f - Terrain factors relating to the geography of the site

These dependencies together with the following mass/number balance equation have been used to estimate vehicle emission factors for different type of vehicles.

Using the number/mass balance approach, the relationship that has been developed linking emission factors of individual vehicle types with the measured concentrations for specific meteorological conditions is:

$$\sum_{i}^{n} E^{i}_{motion\,mode} \left(T, RH\right) N^{i}\left(t\right) = \left(C_B\left(t\right).p\left(RH\right) - C_o\left(t\right).p\left(RH\right)\right)\left(v_x H + v_2 W\right)L$$

Where:
$C_B(t)$ and $C_0(t)$ - particle concentration over the road and background, respectively [particle m^{-3}, or mg m^{-3}], W – width of the road canyon [m], H – semi-empirical

factor related to vertical concentration of pollutants [m], v_z and v_x - normal component of vertical and horizontal wind velocity, respectively [m s^{-1}], $N(t)$ - traffic volume [car s^{-1}], $E^{i}_{\text{motion mode}}$ - emission factor of i different type of vehicles out of n types identified (for example i = 1 is diesel bus, i = 2, petrol car, etc) [particles km^{-1}car^{-1}; or mg km^{-1}.car^{-1}], T – temperature, RH – relative humidity, p(RH) - function relating concentration to the RH, and L - topographical factor

4. Data Analysis: The Freeway Site (Tora Street)

Particle concentration data (numbers.cm^{-3}) collected at Tora Street from July 1998 to March 1999 in five minute intervals was matched with corresponding vehicle flows expressed as vehicles per hour for the same period. The vehicle flow data was obtained from Main Roads (MR) permanent traffic counters installed at the site. Each record also contains information about the ambient meteorological conditions such as wind speed, wind direction in relation to the road direction, temperature, humidity and rainfall. After editing, this resulted in a data base of 8,628 records. Several hours of video data over several days were also recorded and analysed in order to obtain fleet composition details, such as vehicle classification (car, light commercial vehicle, trucks, buses, etc) congestion conditions, and vehicle flow rates over five minute intervals. This video captured data set produced a database of 132 records corresponding to five minute particle count periods.

Figure 1 compares the average hourly traffic flow for the entire period to the traffic flow recorded on video.

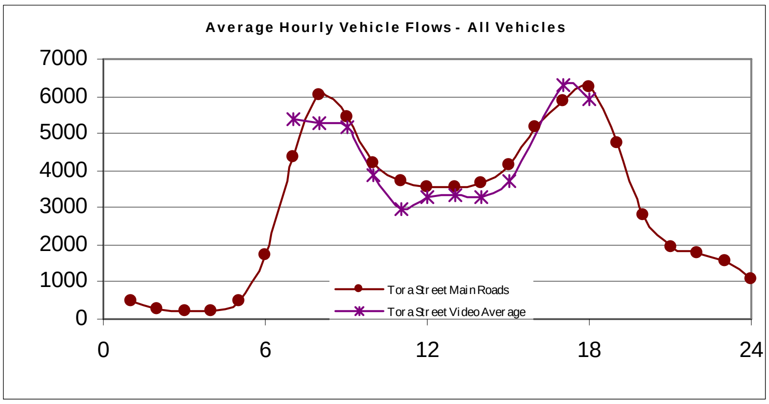

Figure 1: Comparison of Average Hourly Vehicle Flow for all data and Video data

The average hourly vehicle flow described above was combined with additional data relating to classified vehicle counts from other sites. This analysis produced a profile of average classified vehicle flows for each hour of the day. This was combined with figures from the Australian Bureau of Statistics (ABS) relating to vehicle fuel types, to produce an average hourly profile of vehicle flow sub-divided into vehicle classifications by fuel types.

Particle concentration is considered to be a dependent variable with independent variables consisting of vehicle flow, congestion rates, and dispersion factors such as wind speed, temperature and humidity.

Initial analysis of the video data was undertaken. This used traffic flow and wind speed as the two independent variables, and particle counts as the dependent variable. The results, which are shown graphically in Figure 2, yielded an R^2 value of 0.65. The wind speed values are not corrected for direction relative to the highway, and all vehicle flows are non-congested free flowing conditions. Inspection of Figure 2 indicates that particle count increases with increased vehicle flow, but decreases with increased wind speed.

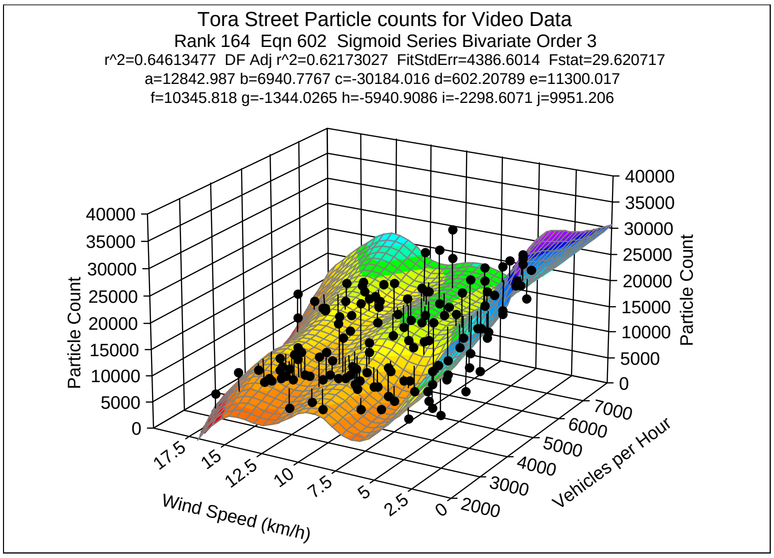

Figure 2: Analysis of Freeway Data with traffic Flow and Wind Speed as the two independent variables

Additional regression analysis was then undertaken with the meteorological variables of humidity and temperature. The results indicated that there was only a maximum of 2% improvement in predictive ability by including these two variables.

Further regression analysis of the database involved an analysis of the particle counts corrected by the estimated background particle counts. The latter were obtained from an extensive data collection program at a site away from traffic effects. This produced an estimation of the particle concentrations that would have been contributed by vehicles. Independent variables were also analysed to determine which of the vehicle/fuel types contributed most significantly. It was found that the diesel fuelled commercial vehicles and total vehicle flow produced the most consistent and significant regression results.

A multiple linear regression yielded the results shown in Table 1. The equation coefficients shown in Table 1 produced an R^2 of 0.23. It is clear from the regression coefficients that the particle concentration is inversely related to both wind speed and temperature, but directly related to the traffic flow.

Table 1: Linear Regression Results - Dependent variable: Particle Counts

(Sample size = 5572, $R^2 = 0.232$)

Variable	Coefficient	t Statistic
Constant	25067.0	14.59
Wind Speed (km/h)	-1201.5	-22.77
Temp (deg C)	-764.5	-15.48
Relative Humidity (%)	99.1	6.84
Total traffic flow (vehicles/hour)	1.9	9.64
CV Diesel vehicles (vehicles/hour.)	97.9	15.5

Inspection of the results indicates that there is considerable variation in the original data. It is considered that this may be caused by the mixing and retention of the particles in the environment so that there is not an exact correlation between the concentration and the vehicle flow for any specific five minute period. Accordingly, there may be a ‘lag’ period involved.

5. Conclusions

Although fine and ultra-fine particles are a major contributing portion of the air pollution which impacts on the economy, human health and amenity, they are poorly understood from a modelling perspective.

There is a paucity of microscopic modelling being done using real time traffic data and concentrations as the input data, according to CONCAWE (1997). Most emission models depend on other traffic simulation models and idealised emission factors for their input to calculate the tailpipe emissions, along with standard dispersion models to calculate final environmental concentrations. Idealised emission factors are developed from dynamometer tests of several ‘typical’ cars, driven under various controlled conditions. These emission factors are then used across the entire vehicle fleet.

Analysis to date shows that there is a strong link between particle concentrations, vehicle flows, fuel types and ambient meteorological conditions, with the final observed particle concentrations being highly dependant on the wind speed. Further analysis is necessary to improve the predictive capacity of the models.

The models developed should be sufficiently robust to give usable results, and be flexible enough to accommodate changes in vehicle fleet composition, changes in the types of fuels used, and able to cater for a wide range of topographical and ambient weather conditions.

There is a demonstrated need to predict the contributions that motor vehicle emissions from various fuel types, fleet compositions and traffic conditions make to the quantities of airborne fine and ultra-fine particles at a microscopic level. Development of an improved predictive capability will enhance existing tools for the environmental evaluation of specific transport strategies.

If such models, specifically calibrated for an area under study, could predict the concentrations of particles, they would provide a significant environmental evaluation and assessment tool. Only then will various control measures be able to be evaluated, implemented and monitored for effectiveness. This in turn will enhance the health and welfare of the population and improve their urban amenity through improved air quality.

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