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A simple semi-empirical technique for apportioning the impact of roadways on air quality in an urban neighbourhood

M.A. Elangasinghe [a,*,1], K.N. Dirks [a], N. Singhal [a], S.B. Costello [a], I. Longley [b], J.A. Salmond [a]

[a] The University of Auckland, Private Bag 92019, Auckland, New Zealand
[b] The National Institute of Water and Atmospheric Research Ltd., Private Bag 99940, Auckland 1149, New Zealand

HIGHLIGHTS

- A semi-empirical model is proposed to apportion the air pollution from roadways.
- The estimated time variation of background concentrations matches observed values.
- Model needs data from one site to estimate site specific background concentration.
- Estimated time variation of box height explains dispersion features of the site.

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ABSTRACT

Air pollution from the transport sector has a marked effect on human health, so isolating the pollutant contribution from a roadway is important in understanding its impact on the local neighbourhood. This paper proposes a novel technique based on a semi-empirical air pollution model to quantify the impact from a roadway on the air quality of a local neighbourhood using ambient records of a single air pollution monitor. We demonstrate the proposed technique using a case study, in which we quantify the contribution from a major highway with respect to the local background concentration in Auckland, New Zealand. Comparing the diurnal variation of the model-separated background contribution with real measurements from a site upwind of the highway shows that the model estimates are reliable. Amongst all of the pollutants considered, the best estimations of the background were achieved for nitrogen oxides. Although the multi-pronged approach worked well for predominantly vehicle-related pollutants, it could not be used effectively to isolate emissions of PM_{10} due to the complex and less predictable influence of natural sources (such as marine aerosols).

The proposed approach is useful in situations where ambient records from an upwind background station are not available (as required by other techniques) and is potentially transferable to situations such as intersections and arterial roads. Applying this technique to longer time series could help to understand the changes in pollutant concentrations from the road and background sources for different emission scenarios, for different years or seasons. Modelling results also show the potential of such a hybrid semi-empirical models to contribute to our understanding of the physical parameters determining air quality and to validate emissions inventory data.

1. Introduction

Separating the relative contribution of different sources of air pollution, such as air pollution from a major highway, from the effect of background sources is vital for understanding its effect on the local community and for developing suitable control measures for these sources. For this purpose, various different approaches can be taken, depending on the particular application.

Many cities have continuous ambient air quality stations located near major roadways with measurements typically used to assess the ambient air quality against the national standards for air

* Corresponding author. Current address: Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland Mail Centre, Auckland 1142, New Zealand. Tel.: +64 9 3737599x81388; fax: +64 9 3737462.

E-mail addresses: mela005@aucklanduni.ac.nz, manushkae@yahoo.com (M. A. Elangasinghe), k.dirks@auckland.ac.nz (K.N. Dirks), n.singhal@auckland.ac.nz (N. Singhal), s.costello@auckland.ac.nz (S.B. Costello), i.longley@niwa.co.nz (I. Longley), j.salmond@auckland.ac.nz (J.A. Salmond).

1 Permanent address: Department of Chemical and Process Engineering, Faculty of Engineering, University of Peradeniya, Peradeniya 20400, Sri Lanka. Tel.: +94 81 2393692; fax: +94 81 238 8158.

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pollutants. The levels recorded represent the superimposed effects of many sources as the individual signals from different sources are modified by atmospheric dispersion processes and are mixed together (Malby et al., 2013). These source signals are further complicated by the time-variant effects of different sources, such as the diurnal variations in traffic emissions and the predominantly night-time sources such as wood burning for home heating.

Emissions from different sources decay to 'background levels' with increasing distance from the source as a result of dispersion (Karner et al., 2010; Wood et al., 2010). Simple multiple regression techniques can be applied over regional scales to isolate the urban increment of pollutants over rural background concentrations in situations where a set of urban and rural background records are available (Viana et al., 2008). At the local scale, the background subtraction technique can isolate the roadway contribution by subtracting the concentrations from an upwind monitor from concentrations measured downwind of the road (Henry et al., 2011; Karner et al., 2010). Another method is the gradient method in which pollutant concentrations recorded at a number of monitors located progressively downwind of the source are analysed to understand the rate of decrease in concentrations in order to isolate the roadway contribution from background level (Clements et al., 2009; Karner et al., 2010; Wood et al., 2010). The requirement of multiple measurement sites around the source limits the application of these techniques in practical situations where the monitoring stations are spread out in space. Some recent studies have used ambient data records from very few sites to separate 'target source' signals from other 'non-target' source signals (Carslaw and Beevers, 2013; Carslaw and Carslaw, 2007; Carslaw et al., 2006; Malby et al., 2013; Yu et al., 2004). For example Carslaw et al. (2006) analysed the relationship between NO_x concentrations, wind speed and wind direction data collected at several routine monitoring sites to isolate the contribution from aircraft emissions, and Malby et al. (2013) used a conditional selection of ambient records to track the source contribution from road traffic over several years. Such techniques are cost effective and make optimum use of expensively-collected ambient records. However, even some of these studies have highlighted the requirement of a proper background (or upwind) monitoring site which is not always available in practical situations (Carslaw and Carslaw, 2007; Malby et al., 2013). Even in major cities like Auckland, the ambient air quality monitoring stations are spread out and are restricted to sites on one side of a road only.

In this paper, we present and demonstrate a novel technique based on a semi-empirical modelling approach, the Site-Optimized Semi-Empirical (SOSE) model, coupled with the conditional selection of monitored data from a single monitor to separate the contribution of road sources (which are expected to have a strong wind dependence) from urban background concentrations that are not directly influenced by the local traffic sources. SOSE is empirically optimised (based on linear regression) and based on an underlying physically-based equation relating the meteorology and source emissions (Dirks et al., 2002, 2003). The model has been shown to produce reliable predictions of concentrations through the optimisation of site-specific data in a number of different topographical, meteorological and road emissions environments (Dirks et al., 2006; Gokhale and Pandian, 2007; He et al., 2009; Kassomenos et al., 2004). The nature of the governing equation of this model and the data stratification technique that treats upwind and downwind concentrations separately is expected to be effective in separating the road emission source contribution from other background sources. The current work explores this feature of the model using a case study for apportioning the background concentrations from contributions of a major highway using data from a single air quality station in the vicinity of a major traffic source of emissions. The estimated background concentrations are validated by comparing with background concentrations of NO_x, CO and PM_{10} measured upwind of the source. This work also explores the consistency of the model parameter 'box height' which is a measure of the height to which pollutants are assumed to be entrained and fully mixed (Dirks et al., 2002). Obtaining comparable 'box height' estimations for different pollutants can further validate the reliability of the source apportionment made by the model.

2. Model description

2.1. The SOSE model

The Site Optimized Semi Empirical (SOSE) model is based on the box model approach whereby the emission rate Q (μg m^{-1} s^{-1}) is assumed to be constant along a road segment and the pollutants mixed uniformly within a two-dimensional box of heightΔz (m). The horizontal wind speed,u (m s^{-1}), assumed to be uniform within the layer, removes the pollutants through advection. At the same time, pollutants are introduced into the box through advection of the background concentration. The concentration C (μg m^{-3}) under steady-state conditions and for conditions when the monitor is leeward (downwind) of the road is given by

$$C = \frac{Q_l}{\Delta z(u + u_o)} + C_l, \tag{1}$$

where the contribution from the background sources (concentrations that are not directly influenced by local emissions) for the leeward condition is given by C_l (μg m^{-3}). The emission term for the leeward condition (Q_l) incorporates the emissions from roads close to the monitor and other roads in leeward side that have wind speed dependencies.

For windward conditions (when the monitor is upwind of the road), the air pollution concentration is given by

$$C = \frac{Q_W}{\Delta z(u + u_o)} + C_W, \tag{2}$$

where the background concentration for the windward condition is given by C_W (μg m^{-3}). The emission term for windward condition (Q_W) is the emission strength of other roads in the windward side which have wind speed dependence.

The u_o term, in both equations is the 'wind speed offset' (in m s^{-1}) which is included to avoid severe over-predictions in very light wind speed conditions and is determined empirically through the minimization of the model root-mean-squared error (RMSE). The wind speed offset also accounts for any vehicular-generated turbulence which impacts on dispersion in the immediate vicinity of the road. A full description of the model is given in Dirks et al. (2002, 2003).

2.2. Quantification of road and background source contributions

The optimum model parameters for leeward conditions ($Q_l \cdot \Delta z^{-1}, C_l$) are found by performing linear regressions of air pollutant concentration (C) on the wind speed function $(u + u_0)^{-1}$ for leeward conditions for each time interval (10-min interval of each hour) throughout the day across all days in a dataset. The background estimates (C_l) are the intercept parameters of the SOSE model, calculated for each 10-min interval of each hour for weekdays and weekends. Therefore, if the model is applied to data from a roadside monitor, the modelled background concentration, denoted by these intercept parameters, is a daily time variation of the contribution of the sources that are not emitted directly by the