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Review of modelling air pollution from traffic at street-level - The state of the science☆

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A R T I C L E I N F O

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A B S T R A C T

Traffic emissions are a complex and variable cocktail of toxic chemicals. They are the major source of atmospheric pollution in the parts of cities where people live, commute and work. Reducing exposure requires information about the distribution and nature of emissions. Spatially and temporally detailed data are required, because both the rate of production and the composition of emissions vary significantly with time of day and with local changes in wind, traffic composition and flow. Increasing computer processing power means that models can accept highly detailed inputs of fleet, fuels and road networks. The state of the science models can simulate the behaviour and emissions of all the individual vehicles on a road network, with resolution of a second and tens of metres. The chemistry of the simulated emissions is also highly resolved, due to consideration of multiple engine processes, fuel evaporation and tyre wear. Good results can be achieved with both commercially available and open source models. The extent of a simulation is usually limited by processing capacity; the accuracy by the quality of traffic data. Recent studies have generated real time, detailed emissions data by using inputs from novel traffic sensing technologies and data from intelligent traffic systems (ITS). Increasingly, detailed pollution data is being combined with spatially resolved demographic or epidemiological data for targeted risk analyses.

1. Introduction

This review was prompted by the need to better understand people's exposure to traffic pollution on city streets. Broad-scale, background levels of pollution are usually well monitored in major cities, but it remains difficult to determine air quality data at street level in most places. Concentrations can be highly variable over short distances and intervals of time, due to fleet composition, congestion, weather (mainly wind) and the shape of street canyons. For examples of what can be achieved with sufficient resources, readers are referred to the programmes: "Dispersion of Air Pollution and its Penetration into the Local Environment" in Westminster, United Kingdom (DAPPLE, 2009), the "New York City Community Air Survey" in New York, USA (NYCCAS, 2018) and vehicle-based measurements in Oakland, USA (Apte et al., 2017). Low cost wireless sensors show promise for the future, but currently there are only very few pollutants that can be measured well without expensive equipment. State of the science traffic emissions modelling provides estimates of a comprehensive suite of pollutants with fine spatial and temporal resolution, saving the considerable expense of monitoring equipment (Gois et al., 2007). The data is localised to tens of metres at street level, enabling more accurate estimates of air quality for pedestrians, commuters, children and the aged. Once problems are identified, they can be mitigated with barriers, spatial buffers, improved ventilation in buildings, or alterations to the fleet (Batterman et al., 2015).

The review starts by describing the effects of traffic emissions on air quality and why they are difficult to quantify. Then we examine the risks to health and costs incurred by the suite of gases and aerosols that are produced on urban streets. The majority of the review focusses on the state of the science of modelling traffic emissions. We briefly describe some approaches that can give reasonable estimates of roadside air quality given limited data and resources. There are detailed reviews of each of the 4 main steps of microscopic traffic emissions modelling: trip generation, traffic simulation, emissions modelling and dispersion modelling. We highlight the contributions of new technologies, intelligent transport systems (ITS) and emerging new directions that combine

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simulation with sensors for real-time emissions mapping. The section ends with a summary table of case studies and recommendations for users.

2. Understanding pedestrian exposure to traffic-related air pollutants

2.1. Traffic pollution in cities

Airborne pollution from traffic is a significant health hazard worldwide for the people who live in cities (UN-Habitat, 2013). The amount of freight moved by light commercial vehicles has increased by 300% in recent decades, due to increases in the size of the service sector (Houghton et al., 2003). Motor vehicles are responsible for a considerable fraction of many airborne pollutants (Table 1). As the numbers of vehicles using urban roads has increased, so has traffic congestion, exacerbating pollution, greenhouse gas emissions, delays and financial losses from wasted fuel and lost work time (Schrank et al., 2015). The financial consequences can be considerable, even neglecting lost productivity. Each emitted tonne of particulate matter smaller than 2.5 microns ($PM_{2.5}$) cost US$208,000 in Sydney, Australia and US$141,000 in Melbourne (Aust et al., 2013). Policy makers require good data to understand the problem and to plan for the future.

The toxic chemicals that comprise traffic emissions are released as gases and primary particles. The two most commonly used fuels generate different mixtures of pollutants in addition to CO_2: petrol vehicles are mainly responsible for emissions of carbon monoxide (CO), volatile organic compounds (VOCs), ammonia (NH_3) and heavy metals. Diesel vehicles produce most of the particles of 2.5 microns and smaller ($PM_{2.5}$) and oxides of nitrogen (NO_x) (Smit, 2014). Diesel particulate matter (DPM) is composed of a core of elemental carbon surrounded by organic compounds including polycyclic aromatic hydrocarbons (PAHs), nitro-PAHs, small amounts of sulphate, nitrate, metals and other trace elements. These particles have a large surface area, making them susceptible to adsorption to lung tissue (Wichmann, 2007).

The chemistry of emissions is highly variable in time and space (BTRE, 2005) and the composition affects toxicity (Rückerl et al., 2011). The composition of the mixture of gases and particles changes with time after release from the exhaust pipe. There are a number of possible chemical reactions, coagulation and condensation of gases, aerosols and particles. The transformations can be affected by local conditions such as the concentration of pollutants, temperature, turbulence (particularly wind), sunlight and humidity. For example, the concentrations of particular species, such as NO_x, can determine the production of secondary pollutants such as ozone (Ryu et al., 2013).

Although numbers of vehicles on roads continue to increase, emissions regulations have mandated increased efficiency of engine technologies to reduce outputs of harmful emissions. Older, carburetted cars released 10 times the HC, 4 times the CO and 3 times the NO_x of newer multi-point ignition engines (Qu et al., 2015). However, while newer cars release less pollution, the expected reduction in emissions from modern vehicles will only be realised if their emissions control equipment is properly maintained (Marquez and Salim, 2007).

2.2. Health effects of traffic pollution

Although traffic emissions (Table 1) are not the major fraction of airborne pollution in cities, they are a major source of airborne pollution for people, because traffic occupies space close to walkways, residences, workplaces and schools. The traffic intensity on the nearest road to a person's home address was linked to mortality in a long-term study (Beelen et al., 2008). Diesel exhaust poses the greatest risk of cancer of any air pollutant (Wichmann, 2007). An extensive sampling program for volatile organic compounds (VOCs)

Table 1
Total annual Australian National Pollutant Inventory (NPI) emissions (kg/yr) for industry and motor vehicles (National Motor Vehicle Emissions Inventory, NMVEI) in 2010 (Smit, 2014).

Pollutant	NPI industry	NMVEI	MV Contribution
Acetaldehyde	411,765	886,969	68.29%
Acetone	691,837	301,465	30.35%
Acrolein	11	314,000	100.00%
Ammonia	120,860,415	6,313,888	4.96%
Benzene	1,197,423	4,099,173	77.39%
1,3-Butadiene	14,635	971,856	98.52%
Cadmium	32,053	237	0.73%
Carbon monoxide	1,388,700,000	936,869,323	40.29%
Chromium	590,406	502	0.08%
Copper	677,884	794	0.12%
Cyclohexane	473,055	664,516	58.42%
Dioxins/Furans (i-TEQ)	0.194	0.005	2.75%
Ethylbenzene	138,330	3,116,430	95.75%
Formaldehyde	2,922,758	2,005,013	40.69%
Lead	687,463	17,171	2.44%
Methylethylketone (MEK)	700,618	77,818	10.00%
n-Hexane	1,709,621	1,322,489	43.62%
Nickel	772,525	267	0.03%
Oxides of Nitrogen	1,396,900,000	305,601,721	17.95%
PAHs (BaP-equivalents)	23,709	627	2.58%
Particulate Matter $\leq$ 10.0 μm	1,238,329,933	14,461,823	1.15%
Particulate Matter $\leq$ 2.5 μm	56,532,376	11,684,995	17.13%
Selenium	6348	4	0.06%
Styrene	393,246	470,431	54.47%
Sulfur dioxide	2,509,400,000	1,310,884	0.05%
Toluene	2,525,696	8,243,841	76.55%
Total Volatile Organic Compounds	157,006,103	107,329,985	40.60%
Xylenes	1,882,125	8085	0.43%
Zinc	1,597,971	47,352	2.88%