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Review

A review of fundamental drivers governing the emissions, dispersion and exposure to vehicle-emitted nanoparticles at signalised traffic intersections

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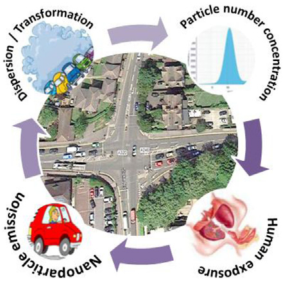
HIGHLIGHTS

- Parameters governing the emissions, dispersion and exposure at TIs are reviewed.
- Extent of PNCs and their exposure at TIs relative to other environments is analysed.
- Critical knowledge gaps in dispersion modelling parameters of PNCs are discussed.
- Peak PNCs at TIs were found 17-fold higher compared with average roadside PNCs.
- Nucleation is a foremost process, followed by dilution, deposition and coagulation.

GRAPHICAL ABSTRACT



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ABSTRACT

Signalised traffic intersections (TIs) are considered as pollution hot-spots in urban areas, but the knowledge of fundamental drivers governing emission, dispersion and exposure to vehicle-emitted nanoparticles (represented by particle number concentration, PNC) at TIs is yet to be established. A number of following key factors, which are important for developing an emission and exposure framework for nanoparticles at TIs, are critically evaluated as a part of this review article. In particular, (i) how do traffic- and wind-flow features affect emission and dispersion of nanoparticles? (ii) What levels of PNCs can be typically expected under diverse signal- and traffic-conditions? (iii) How does the traffic driving condition affect the particle number (PN) emissions and the particle number emission factors (PNEF)? (iv) What is the relative importance of particle transformation processes in affecting the PNCs? (v) What are important considerations for the dispersion modelling of nanoparticles? (vi) What is extent of exposure at TIs with respect to other locations in urban settings? (vii) What are the gaps in current knowledge on this topic where the future research should focus? We found that the accurate consideration of dynamic traffic flow features at TIs is essential for reliable estimates of PN emissions. Wind flow features at TIs are generally complex to generalise. Only a few field studies have monitored PNCs at TIs until now, reporting over an order of magnitude larger peak PNCs ($0.7–5.4 \times 10^5$ cm^{-3}) compared with average PNCs at typical roadsides (~0.3×10^5 cm^{-3}). The PN emission and thus the PNEFs can be up

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to an order of magnitude higher during acceleration compared with steady speed conditions. The time scale analysis suggests nucleation as the fastest transformation process, followed by dilution, deposition, coagulation and condensation. Consideration of appropriate flow features, PNEFs and transformation processes emerged as important parameters for reliable modelling of PNCs at TIs. Computation of respiratory deposition doses (RDD) based on the available PNC data suggest that the peak RDD at TIs can be up to 12-times higher compared with average RDD at urban roadsides. Systematic field and modelling studies are needed to develop a sound understanding of the emissions, dispersion and exposure of nanoparticles at the TIs.

1. Introduction

Airborne nanoparticles (referred here to those below 300 nm to represent majority of particle number concentrations, PNCs) come from a variety of exhaust and non-exhaust sources in the urban environments (Kumar et al., 2013a). Road vehicles are a major source of nanoparticle emissions (Johansson et al., 2007; Keogh et al., 2009; Kumar et al., 2011a; Shi et al., 2001), and these can contribute up to 90% of total PNC in polluted urban environments (Kumar et al., 2010a; Pérez et al., 2010; Pey et al., 2009). Small size of nanoparticles enables them to enter deeper into lungs, causing both acute and chronic adverse health effects such as asthma, cardiovascular and ischemic heart diseases (HEI, 2013). However, the number of excess deaths that occur in cities worldwide due to the exposure to nanoparticles are yet largely unknown (Kumar et al., 2014). A very few preliminary estimates are available on this topic, showing high numbers. For instance, Kumar et al. (2011b) showed that the exposure to particle number (PN) emissions from road vehicles in Delhi caused 11,252 excess deaths in 2010 that were predicted to reach to 58,268 by 2030 under the business as usual scenario.

Majority of cities worldwide are facing challenges associated with the air pollution (Kumar et al., 2013b). For example, a recent report of World Health Organisation on ambient air pollution suggests that annual mean concentration of PM_{10} (particulate matter less than 10 μm) has increased by more than 5% between 2008 and 2013 in 720 cities across the world (WHO, 2014). The issue of air pollution becomes more prominent at certain locations, such as signalised traffic intersections (TIs) with high pollutant concentrations, which are generally termed as “hot-spots”. Whilst some studies (Mohan et al., 2007; Wu et al., 2010; Zhu et al., 2008) define hot-spots as a localised place where maxima of air pollutant concentration can occur, the United Stated Environmental Protection Agency (USEPA) defines these as small geographical locations such as the TIs and the busy roadsides where pollutant concentration is higher than the National Ambient Air Quality Standards (NAAQS). In case of airborne nanoparticles, neither such a definition nor NAAQS are yet available for comparison and distinguishing the hot-spots in a particular area. Nonetheless, the same terminology can be adopted for nanoparticles by using the typical average values of PNCs in urban environments as a reference value to identify the nanoparticle hot-spots. Recently, Kumar et al. (2014) compiled the data on roadside PNCs in 42 different cities worldwide. They found the average values of PNCs as $3.2 \pm 1.6 \times 10^4$ cm^{-3} and $1.2 \pm 1.0 \times 10^5$ cm^{-3} in European and Asian cities, respectively. These or other localised PNCs measured elsewhere can be taken as a preliminary threshold value for determining the nanoparticle hot-spots in urban areas.

Evidences of hot-spots for gaseous pollutants are available in abundance. For instance, Coelho et al. (2005) and Li et al. (2009) found that a frequent stop-and-go situation at TIs often results in excessive delays, speed variations, alleviated fuel consumption and gaseous emissions. Likewise, hot-spots of nanoparticles can frequently occur at TIs due to the creation of pollution pockets by changing traffic conditions (e.g. acceleration-deceleration, stop-go). However, a very few studies have measured PNCs at the TIs to present an exhaustive picture of nanoparticle hot-spots in urban areas (see Table 1). These studies have found up to ~17- and 5-folds larger values of peak PNCs at the TIs (e.g. $5.4 \pm 1.7 \times 10^5$ cm^{-3}; Tsang et al., 2008) compared with the average typical values of roadside PNCs in European and Asian cities, respectively (Kumar et al., 2014). A number of practical and technical constraints such as portable instruments having high sampling response and broad size range, their low-cost and robustness for continuous unattended monitoring, and lack of standardised measurement methods make the study of nanoparticles at TIs even rarer (Kumar et al., 2011a). This is reflected by the fact that there are not many field studies available for TIs (Table 1), clearly indicating a need for more measurement studies to understand PNC levels in diverse traffic and driving conditions. These studies would be instrumental for developing particle number emission factors (PNEF) that are one of the key inputs for dispersion modelling which is, in turn, important for understanding the exposure to vehicle-emitted nanoparticles at TIs.

As seen in Table 2, a number of review articles are currently available in the published literature. Although these articles either deal with the flow and dispersion of gaseous pollutants at TIs (e.g. Ahmad et al., 2005; Tiwary et al., 2011) or particle transformation processes (dilution, nucleation, coagulation, condensation, evaporation and deposition) at various spatial scales (e.g. Kumar et al., 2011c; Carpentieri et al., 2011). For instance, Ahmad et al. (2005) summarised the results of wind tunnel simulations for TIs. They also discussed the effects of building configurations, canyon geometries and variability in approaching wind directions on flow fields and exhaust dispersion at TIs. Tiwary et al. (2011) reviewed the state-of-the-art knowledge on modelling the airflow and concentration fields of inert pollutants at TIs. Kumar et al. (2011c) discussed dispersion modelling techniques of nanoparticles at five local scales (vehicle wake, street, neighbourhood, city and road tunnels). However, the complexities associated with the emissions, dispersion and exposure related to vehicle-emitted PN emissions at TIs have not been discussed in detail until now (see Table 2).

The aim of this review is therefore to assess the fundamental drivers that govern the emissions, dispersion, concentration and exposure to PNCs at TIs. In order to set the background context for our review article, the key traffic and wind flow features at TIs are first briefly presented (Section 2). This is followed by an up to date summary of field studies that have monitored PNCs at TIs over the past one decade (Section 3) and the effect of traffic driving conditions and meteorology on PNEFs (Section 4). Further section presents a discussion on relative importance of particle transformation processes in altering the ambient PNCs at TIs (Section 5). A