Atmospheric Environment 62 (2012) 9–25

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Wind tunnel measurements for dispersion modelling of vehicle wakes

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HIGHLIGHTS

► A car wake was characterised through wind tunnel measurements.
► Large gradients of velocities and tracer concentrations were found in the near-wake.
► Current wake models adequately describe the velocities in the far-wake.
► A better characterisation of turbulence and pollutant dispersion is needed.
► Near-wake models do not exist, yet they are necessary for some applications.

ARTICLE INFO

Article history:
Received 24 March 2012
Received in revised form
4 August 2012
Accepted 6 August 2012

Keywords:
Dispersion modelling
Near and far wake
Vehicle wake dispersion
Wind tunnel measurements
Mixing processes

ABSTRACT

Wind tunnel measurements downwind of reduced scale car models have been made to study the wake regions in detail, test the usefulness of existing vehicle wake models, and draw key information needed for dispersion modelling in vehicle wakes. The experiments simulated a car moving in still air. This is achieved by (i) the experimental characterisation of the flow, turbulence and concentration fields in both the near and far wake regions, (ii) the preliminary assessment of existing wake models using the experimental database, and (iii) the comparison of previous field measurements in the wake of a real diesel car with the wind tunnel measurements. The experiments highlighted very large gradients of velocities and concentrations existing, in particular, in the near-wake. Of course, the measured fields are strongly dependent on the geometry of the modelled vehicle and a generalisation for other vehicles may prove to be difficult. The methodology applied in the present study, although improvable, could constitute a first step towards the development of mathematical parameterisations. Experimental results were also compared with the estimates from two wake models. It was found that they can adequately describe the far-wake of a vehicle in terms of velocities, but a better characterisation in terms of turbulence and pollutant dispersion is needed. Parameterised models able to predict velocity and concentrations with fine enough details at the near-wake scale do not exist.

1. Introduction

Exposure to both short-term transient and long term mean concentrations of gas and particles emitted by ground vehicles in cities can cause severe damage to human health (Brugge et al., 2007; Atkinson et al., 2010; Kumar et al., 2011a). Transport of relatively inert gases and coarse particles has been well studied in the past (see, e.g., Vardoulakis et al., 2003), however physical and chemical processes involved in nanoparticles dispersion modelling are still poorly understood (Kumar et al., 2010, 2011b), especially at fine spatial and temporal scales, where the impact of a single vehicle wake on the dispersion process can become important (Baker, 2001). Vehicle wakes, for example, can strongly affect the turbulence field in street canyons (Di Sabatino et al., 2003), and their influence on pollutant dilution cause complex interactions with other transformation processes affecting nanoparticles (Carpentieri et al., 2011). Operational dispersion models rarely acknowledge these effects.

The vehicle wake is usually divided in two separate regions (Hucho, 1987): the *near-wake* and the *main* or *far-wake*. The near-wake consists of two components: a large scale recirculation region immediately behind the vehicle and a system of longitudinal trailing vortices with unsteady fluctuations caused by a variety of

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1352-2310/$ – see front matter
http://dx.doi.org/10.1016/j.atmosenv.2012.08.019

effects such as the instability of the separated shear layer and wake pumping (Ahmed, 1981; Hucho, 1987; Baker, 2001). Studies related to the characterisation of dispersion behaviour in the near wake are much rarer than those related to the far-wake regions. Baker (1996) describes a model based on the assumption that the pollutant emitted by the vehicle is spread uniformly in the near-wake, using a Gaussian puff approach to calculate the concentrations further downwind. This approach might be acceptable for passive gaseous pollutants, but not for nanoparticles that experience transformations on very short time scales (Pohjola et al., 2003; Ketzel and Berkowicz, 2004; Carpentieri and Kumar, 2011) and a more detailed characterisation of the near wake may therefore be necessary (Kumar et al., 2011b). Computational fluid dynamics (CFD) has recently been applied to the near-wake dispersion of pollutants (Richards, 2002; Dong and Chan, 2006; Albriet et al., 2010). The usefulness of the output from these simulations is however limited due to the lack of experimental studies specifically aimed at deriving suitable boundary conditions for the numerical calculations.

As far as the far-wake is concerned, the most well known and documented vehicle wake theory is that of Eskridge and Hunt (1979), hereafter referred to as E&H model. Based on the perturbation analysis of the equations of motion the theory describes the velocity field far downstream of a single vehicle moving through still air. Expressions were developed for the velocity deficit far downwind of a vehicle, assuming constant vehicle velocity, flat terrain and no wind. A more recent study by Hider et al. (1997) reported the derivation of the same expression using a different method. They also derived expressions for the lateral and vertical velocity components. Dispersion in the far-wake is usually represented by a standard Gaussian plume (Baker, 1996, 2001; Richards, 2002).

Very few models take into account the effect of the vehicle wake in the dispersion process. Clearly, further research is needed for the adequate characterisation of vehicle wakes in dispersion models. In particular, almost no information can be found on the mixing process in the near-wake, though this is the key region where the main nanoparticle evolution processes occur (Carpentieri and Kumar, 2011; Kumar et al., 2009).

Wind tunnel experiments have been used extensively for determining the flow characteristics of the wake behind vehicles, as in Eskridge and Thompson (1982), Hackett et al. (1987), and Shaw et al. (2000), but studies for pollutant dispersion are relatively rare. For the development of the ROADWAY model, Eskridge and Rao (1986) determined the optimal turbulence scales in the far-wake region of a moving vehicle. This was obtained by measuring concentrations of inert gaseous tracer in the far-wake (30–60 car heights downstream) of a full scale model of a passenger car in a wind tunnel. The near-wake was not the focus of their study, though. More relevant to the near-wake was the study conducted by Clifford et al. (1997). They used three passenger car models in a row in a wind tunnel, separated by half a car length from each other, and measured the distribution of the concentration of emitted tracer on the car surface, including the air inlet positions. Results of their study highlighted the strong influence on the mixing processes of the car immediately behind the emitting vehicle. The focus of their study, however, was on internal air quality rather than dispersion processes in the near-wake.

Richards (2002) and Baker (2001) analysed flow and dispersion characteristics in the near-wake of a vehicle model with no cross-wind. Results from these wind tunnel studies highlighted the close relationship between the inert tracer concentration field and the velocity and turbulence fields. Concentration fluctuations, measured by a flame ionisation detector (FID), were consistent with the fluctuations in the velocity field (obtained through a combination of particle image velocimetry, PIV, hot-wire anemometry, HWA, and flow visualisation methods). The time histories of concentration had a "peaky", intermittent nature. Kanda et al. (2006a) measured the flow characteristics in the near-wake of small-scale models of a car and a lorry emitting a thermally buoyant plume. They used PIV and laser Doppler anemometry (LDA) to measure velocity and turbulence fields in the wind tunnel, and an FID to measure tracer gas concentrations. They found that the buoyancy of the exhaust had generally a minor effect on the dispersion behaviour. The results from this study were then used as a basis for studying multi-vehicle configurations (Kanda et al., 2006b), with an approach similar to the one adopted by Clifford et al. (1997) in the wind tunnel. Chang et al. (2009a, 2009b) also investigated the dilution properties of gas released in the wake of several vehicles in the wind tunnel. While the measurement grid had a lower resolution, compared to the present study, they highlighted the influence of the vehicle shape on flow and dispersion in the near and far wakes.

Traffic produced turbulence and its effects on the flow and mixing processes have been the main focus of a number of wind tunnel studies. For instance, Kastner-Klein et al. (2000a,b, 2001a,b) studied different traffic configurations (one-way and two-way) simulated by small metal plates moving on two belts along the street in a wind tunnel model. Their main interest was in the interactions between traffic- and wind-induced flows in a street canyon. The presence of traffic and its arrangement were also shown to affect the concentration distribution along the leeward canyon wall (Kastner-Klein et al., 2001b). The results were then used to derive parameterisations for traffic induced turbulence in street canyon models (Kastner-Klein et al., 2003; Di Sabatino et al., 2003). Khare et al. (2002) and Ahmad et al. (2002) used a similar approach, consisting of moving belts carrying model vehicles, in their wind tunnel experiments. The system was placed in a number of different simulated atmospheric boundary layers, and the effect of the traffic condition and the wind direction on the vertical spread of the exhaust gas was examined. Since the main concern was the effect of traffic as a whole on the general flow and mixing processes in the urban environment, the above mentioned studies did not analyse in detail the characteristics of the wake behind a single moving element. None of them studied the near-wake region of the vehicles in any great detail.

The present study involves a series of experiments performed in the wind tunnel laboratory at the University of Surrey, UK. Flow and dispersion characteristics were investigated both in the near- and far-wake regions downwind of reduced scale car models, simulating a vehicle moving in still air. The aims included the experimental characterisation of the flow, turbulence and concentration fields in both wake regions, and the preliminary assessment of existing wake models using the experimental database. The analysis of previous literature clearly showed that dilution is the main driver for many transformation processes affecting nanoparticles once emitted from the tailpipe (Carpentieri et al., 2011; Chang et al., 2009a). While the present study is mainly focussed with understanding and characterising dilution and mixing processes in a vehicle wake using a passive tracer, the results are relevant to nanoparticle dispersion because of the primary role of dilution and mixing. This approach is similar to the one proposed by Chang et al. (2009a). Compared to previous studies, the research presented here benefits from the integrated approach used, which includes previous field measurements. The comparison between field measurements of nanoparticle concentrations and wind tunnel results on passive tracers, in particular, can help in better assessing and quantifying the role of dilution in nanoparticle transformations.

The work presented in this paper is part of a wider effort aimed at characterising the dispersion of nanoparticles in the wake of