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Large-eddy simulation study on the effect of vehicle-induced turbulence and exhaust fumes on wind flow and pollutant dispersion in urban street canyons

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In Short

- Vehicle-induced turbulence
- Air quality
- Street canyon
- PALM model system

The transport and dilution of pollutants at street level are the result of the interaction between the atmospheric (turbulent) wind flow, buildings, other obstacles, and vehicular traffic. A good understanding of these processes is crucial in terms of local air quality management as it improves the ability for predicting the spatial distribution of pollutants. Extensive research studies have been conducted on the wind flow and transportation of pollutants within urban street canyons. However, the impact of vehicle-induced effects (VIE) on the flow and pollutant dispersion have been considered only in few studies. The research in this project ties precisely with the point of representing, understanding, and quantifying the effects of vehicle-induced turbulence (VIT) on the wind flow and pollutant dispersion in street canyons.

We already developed, implemented, and validated a method for taking into account VIT in Large-Eddy Simulations (LESs) of urban boundary layers in the first project phase. Validation of the new method was based on two different wind tunnel data sets. In the first setup, a model of a Vauxhall AstraVan was placed in a wind tunnel with zero traveling speed and exposed to a uniform approach flow as described by [1]. This setup allowed for a comparison of the wind tunnel data with LES using Cartesian topography for representation of the car as an obstacle as well as the representation of cars with the new Induced Velocity Method (IVM). In the second wind tunnel setup, moving obstacles representing driving vehicles were placed in an idealized street canyon [2]. In this setup, the shape of a vehicle and the traffic flow were reduced to a series of plates that are moving through an idealized street canyon. A consistent picture emerged throughout the study from which it can be concluded that the IVM is very well suited for representing vehicles in both traffic cases.

In the subsequent project phase, we varied different wind-to-vehicle speed ratios and investigated thermal effects caused by solar heating of walls and streets in addition to traffic. For the vehicle speed, we modeled typical scenarios in city traffic, i.e. speeds of 5 m s^{-1}, 10 m s^{-1} and 15 m s^{-1}. The wind speed, however, was varied between 0 m s^{-1} and 7.5 m s^{-1} (in 2.5 m s^{-1} steps). Details of the normalized mean velocity distributions as well as the concentrations inside and above the street canyon can be seen in Figure 1. The latter is shown as deviations of the simulated concentrations with traffic from their counterparts without traffic. In the pattern of the normalized mean velocity in the no traffic case (a top) one may clearly see the main circulating vortex within the canyon and a mainly undisturbed mean free stream flow above the canyon. A very small and weak secondary vortex forms in the bottom right-hand corner due to the abrupt change in direction of the vertical airflow. Comparing the case with a vehicle speed of 15 m s^{-1} (Figure 1 b) with the no traffic case, it is noticeable that the flow pattern mainly changes near the ground, while the undisturbed flow above the canyon remains unaffected. Two small anti-clockwise and clockwise rotating vortices are visible to the left and right of the rows of car. These vortices are caused by the movement of the vehicles and the associated induced turbulence. In general, the near-surface transport towards the leeward side associated with the main circulating vortex mentioned above, effectively transports the emissions towards the leeward wall. Due to the anti-clockwise rotating vortices opposing this advection flux of the main vortex, the near-surface transport is blocked,

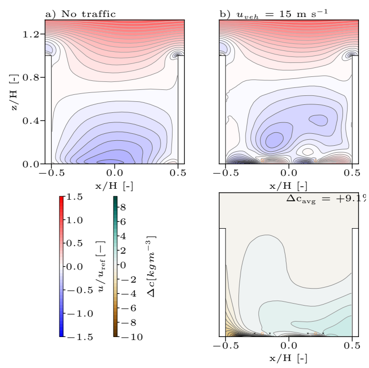

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Figure 1: $xz-$sections of the normalized mean velocity $u/u_{\rm ref}$ (top) and the concentration c (bottom) within the street canyon for a wind speed of 2.5 m s^{-1} and no traffic (a), a vehicle speed of 15 m s^{-1} (b)

causing the emissions to accumulate. This is particularly pronounced on the windward wall, as the size and strength of the vortices is accordingly more pronounced here (Figure 1 b bottom). The clockwise rotating vortices, however, are strengthening the advective transport of the main vortex, leading to a noticeable reduction in concentration particularly at the leeward wall at street-level of up to 60 %, which confirms findings of previous studies (see [3]). In order to find out if the mean ventilation rate inside the street canyon changes with additional vehicle movement or whether the emissions are merely distributed differently in the canyon, the mean values of the concentrations were calculated over the cross-sectional area of the street canyon. The respective difference to the no traffic case is additionally given in Figure 1 b bottom. In all investigated traffic cases there has been an increase in the mean concentrations. Only at a wind speed of 0 m s^{-1} does traffic lead to a reduction in the mean concentration, regardless of the vehicle speed (not shown). That is, the combination of the vehicle-induced motion and the wind-resulting main vortex appears to cause the unfavorable effect on the averaged concentrations.

Simulations including thermal effects were conducted with varying thermal conditions, representing solar heating of the ground, leeward wall, and windward wall, both with and without vehicle traffic. Results showed that traffic opposes buoyancy-driven flow, generally increasing mean concentrations by up to +22%, except when the windward wall is heated, where concentrations decrease by -15%. Despite these localized effects, the interaction between vehicle-induced emissions (VIE) and thermodynamics reduces overall mean concentrations in the street canyon by up to -28%. The findings highlighted the dynamic interplay of traffic and thermal effects on urban air quality.

In our follow-up study, we want to exploit the newly developed modeling framework and study the pollutant dispersion in street canyons with more realistic building configurations as well as boundary conditions from urban areas in order to complement and enhance our knowledge about the effect of VIT. The first part will focus on the effect of the position of the emission source. In our previous studies, the emission source was represented using the stationary line source approach. A more realistic representation would be to use the point source approach, in which the emission source is defined at the vehicles rear and moves with them. Past studies have shown that the line source approach can underestimate the concentration at the windward wall of a street canyon by an order of magnitude compared to the point source approach (see [4]). In the second part, the influence of traffic with different boundary conditions and in different building configurations will be investigated. For this purpose, we will vary parameters such as aspect ratio, roof shape, wind direction, traffic volume and vehicle fleet.

The planned simulations require enormous computational resources. This is partly due to the fact that a realistic representation of a vehicle with all its flow-influencing contours requires a correspondingly high resolution, i.e. small grid spacing. On the other hand, the time step is limited by both the fine grid spacing (due to the CFL-Criterion) and by the movement of the vehicles themselves that also have to comply the CFL criterion. The time step is thus also limited by the vehicles' speed. Moreover, environmental LES has to cover all relevant scales of atmospheric turbulence so that larger model domains have to be used than in traditional engineering LES setups. For this purpose a significant number of processor cores, memory and computing time is required, which in turn can only be satisfied by massively parallel computer architectures such as the NHR system.

WWW

https://www.meteo.uni-hannover.de/de/institut/

More Information

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Project Partners

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