Meteorologische Zeitschrift, PrePub DOI 10.1127/metz/2016/0797

Environmental Meteorology

# Dispersion of traffic exhausts emitted from a stationary line source versus individual moving cars – a numerical comparison

Günter Gross*

Institut für Meteorologie und Klimatologie, Universität Hannover, Germany

(Manuscript received March 25, 2016; in revised form April 17, 2016; accepted April 18, 2016)

**Abstract**

A three-dimensional microscale model was used to study the effects of moving vehicles on air pollution in the close vicinity of a road. The numerical results are compared to general findings from wind tunnel experiments and field observations. It was found that the model is suitable to capture the main flow characteristics within an urban street canyon, in particular the modifications relating to running traffic. A comparison of the results for a stationary line source approach and for multiple single moving sources demonstrates significant differences. For a street in a flat terrain, the near-road concentrations are underestimated by up to a factor of two if the emissions are approximated by a stationary line source. This underestimation decreases with increasing distance, and becomes negligible 30–50 m away from the road. For an urban canyon situation, the line source assumption is a conservative approximation for the concentrations at the leeside of the street, while on the opposite pavement and wall, a systematic underestimation was found. Also, the effects of different traffic situations have been studied and discussed.

**Keywords:** Micro-scale simulation, running traffic, vehicle dispersion, urban canyon concentration

## 1 Introduction

Traffic emissions are a major source of air pollution in an urban environment. In order to maintain the range of the effects e.g. on human health and comfort within a reasonable scope, limit values and thresholds for certain pollutants in ambient air exist and are mandatory. For verification, monitoring and air quality planning, various approaches are available to estimate transport and diffusion of airborne material in a complex urban topology with an assembly of buildings, roads and open spaces. In this context, a road with traffic in a plain and a road within an urban street canyon with high buildings on both sides are two very contrasting situations.

In numerous field experiments, traffic pollutants as well as vehicle-induced modifications of the wind field are observed. In an early attempt, Eskridge and Hunt (1979) used observations to find an analytical description of velocity and turbulence change near a roadway. An extensive field experiment was carried out by Kalthoff et al. (2005), where meteorology and air compounds were measured at numerous positions and heights in the close vicinity of a four-lane motorway. An analysis of the data indicates strong differences of turbulence kinetic energy between the windward and leeward sides, which was attributed to additional turbulence production by running cars. They also found a significant upward velocity component on the leeside, which was explained by the location of the road on a 1 m-high dam.

Besides field experiments in flat surroundings, studies within urban street canyons are of special interest because of the direct impact on concerned citizens. In a full-scale experiment Vachon et al. (2002) measured mean wind, turbulence, and CO concentrations at different levels within a street canyon with an aspect ratio of $AR = 1.4$. They found a pronounced vortex in the canyon, a significant enhancement of turbulence kinetic energy in the near-surface car level, and a reduction of CO concentrations for increasing traffic density. In contrast to this and other studies, Murena et al. (2008) observed CO concentrations of the same order of magnitude on both sides of the bordering buildings within a deep street canyon with $AR > 5$. The authors attributed this finding to the more complex wind pattern instead of a single vortex-like flow for smaller aspect ratios, and to traffic-induced turbulence.

Wind tunnel experiments offer the possibility of studying the effects of individual parameters separately and systematically. Such studies of organised and turbulent motions in an urban street canyon, including running traffic, have been conducted e.g. by Kastner-Klein et al. (2001). The traffic was modelled in this study by plates mounted regularly on moving belts. Beside the characteristic modification of the wind field known from field experiments, a significant effect of traffic pattern, i.e. one-way or two-way traffic, on concentration was found. A more realistic experimental de-

*Corresponding author: Günter Gross, Institut für Meteorologie und Klimatologie, Universität Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany, e-mail: gross@muk.uni-hannover.de



Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

sign with a scale vehicle model was presented by Baker and Hargreaves (2001). They used a mounted gas delivery system that allows a moving point source to be studied. The results offer new insight into the complex interaction of moving vehicles, wind and concentration pattern.

A widely used approach to estimate the dispersion of traffic pollutants is the application of a numerical model. A simplified model, but suitable for routine application, is OSPM (= operational street pollution model, Berkowicz et al., 1997), where additional traffic-induced turbulence, depending on traffic speed and traffic density, is included. A similar parameterisation, but extended to include also local topographic effects, is used by Bäumer et al. (2005) within the framework of a mesoscale model. Numerous authors have used CFD models to study the effects of explicitly resolved moving cars on wind, turbulence and concentration (e.g. Venetsanos et al., 2002; Carpentieri et al., 2011; Barmpas et al., 2011; Kim et al., 2016).

Although such studies demonstrate clearly the high complexity of the dispersion process in the atmospheric surroundings of moving cars, the lack of detailed information and data restricts the applicability of such models to practical applications. Usually, the emissions of individual cars are summarised and are equally distributed along a street by a line source approach. The source strength is calculated for numerous driving situations and vehicle categories considering further parameters like road gradients or vehicle loading (INFRAS, 2014).

Here, a microscale numerical model is used to study systematic differences in traffic-induced concentrations, simulated by such a line source approach, and the emissions of a number of individual moving point sources. Two very different types of situations, i.e. a road in a flat environment and a street within an urban canyon, are considered.

## 2 The model

### 2.1 Main characteristics of the model

The microscale model ASMUS (= Ausbreitungs- und Strömungsmodell für urbane Strukturen, Gross 2012, 2014) is used to simulate wind and concentration distribution in a street environment with buildings. The obstacles are introduced into the model by a porosity concept, where buildings are represented by impermeable grid volumes with porosity $P = 0$, while for the atmosphere $P = 1$ is used. The model has been verified against wind-tunnel measurements according to German guideline VDI 3783 and has been applied for flow around solid bodies and individual wind turbines (Heimann et al., 2011). Cars are considered as solid blocks moving with a prescribed travel speed and interacting with the atmospheric wind and turbulence.

The basic framework of the model consists of the Navier-Stokes equations and the continuity equation. Temperature and humidity are also included, but are not considered here. A conservation equation for a chemical non-reactive compound is solved for calculating the distribution of a gas tracer in the atmosphere.

These equations are Reynolds-averaged, and the resulting correlations of fluctuating quantities are parameterised by flux-gradient relationships. The eddy diffusivity introduced by this approach is calculated via the turbulence kinetic energy, for which an additional prognostic equation has to be solved. The grid lengths in the three directions are used to determine the mixing length.

At the ground and the obstacle surfaces, a zero boundary condition is used for wind. Turbulence kinetic energy is proportional to the square of the local friction velocity, where friction velocity is calculated using a logarithmic wind profile between the surface and the nearest grid volume in the surrounding atmosphere. A roughness length of $z_o = 0.01$ m is used at the walls and $z_o = 0.001$ m is adopted on the smoother surfaces of the cars. At the upper boundary, the concentration and all disturbances generated by the obstacles vanish, and an undisturbed situation is assumed with the given values for the meteorological variables. Wind and turbulence kinetic energy are prescribed according to a logarithmic wind profile at the inflow (southern) boundary, while vanishing normal derivatives are used along the opposite border. For the representation of continuously moving traffic, cyclic boundary conditions are adopted on the western and the eastern border of the simulation region.

The set of model equations is solved on a numerically staggered grid, where all scalar quantities are arranged in the centre of the grid volume, while velocity components are defined at the corresponding side walls of the grid. The pressure disturbance is calculated by solving the three-dimensional discrete Poisson equation directly with Gaussian elimination in the vertical and fast Fourier transforms in the horizontal directions. A grid resolution of 0.5 m is used in the three directions, and the model equations are integrated forward in time with a time step satisfying the CFL criterion. Herein, wind as well as travelling speed of the moving cars is considered.

### 2.2 Input parameters and initial conditions

The road runs from west to east in a flat terrain, or within a 300 m-long street canyon (Fig. 1). The distance between the surrounding buildings with height $H = 16$ m varies and depends on the number of traffic lanes. For a superimposed wind from south, as adopted here, wall S is referred in the text as leeward side of the street canyon and wall N as the windward side.

The cars are represented in the model by solid obstacles with dimensions of $5 \times 5 \times 10$ grid boxes, which correspond to the size of a large van. The cars move for different scenarios with a travelling speed $U$ of 10, 30 and 50 km/h and a safety distance in the order of $U$ between them. Car emissions are released into the first single grid volume in the atmosphere that is located at

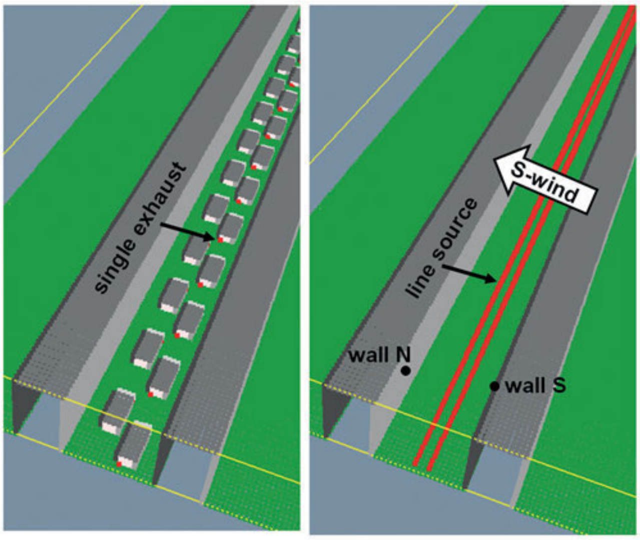


**Figure 1:** Schematic view of the initial situation with line sources and cars with individual emissions.

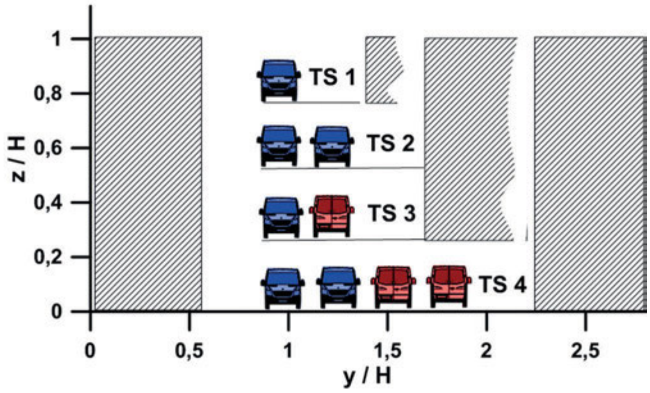


**Figure 2:** Schematic location of cars and buildings for the different traffic scenarios within the street canyon. Colours indicate different moving directions of the cars.

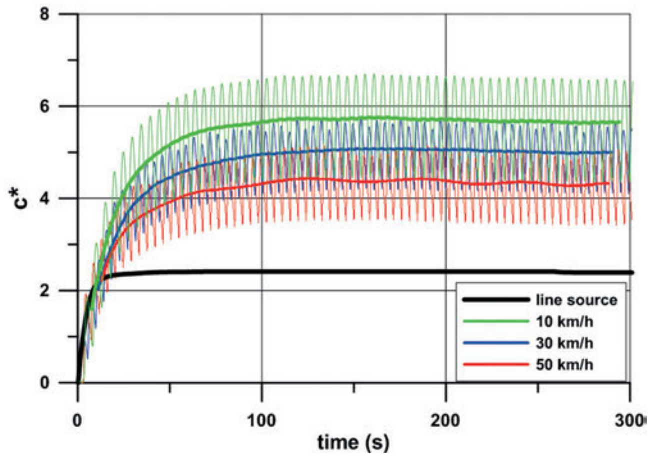


**Figure 3:** Time series of normalised concentrations 2 m away from the road for different traffic speeds, for scenario TS 2 and for the line source case. The thick lines are running means.

the lower left rear end of each moving model car. This is the typical position of the exhaust of European cars. In contrast, for the line source case, the emissions are uniformly distributed into the first grid in the atmosphere along the street. The exact volume of the emissions of each car is of no relevance here. However, it must be ensured that the total emissions of all individual cars along the road are equivalent to the integral emission of the line sources. According to the European emission standards for passenger cars Euro 6, the value for particulate matter (PM) of 0.0045 g/km is adopted to estimate a reasonable value for the simulations presented here. An estimate with a travelling speed of 50 km/h and 17 cars per km results in an emission rate of around $Q_L = 1$ µg/s m.

The numerical study is performed for different traffic scenarios (TS) in a building environment as well as in a flat terrain. TS 1 is characterised by a single lane within a narrow urban canyon (Fig. 2). All traffic lanes are 4 m wide followed by a 4 m wide pedestrian pavement along the buildings. The traffic moves from west to east. For TS 2 and TS 3, two lanes are adopted within a broader street canyon with uni-directional and bi-directional traffic. Finally, a main road with two lanes in each direction is defined as scenario TS 4. Heavy traffic with traffic density of 20000 vehicles per day on each lane, equivalent to 830 cars per hour, is adopted in this study.

In order to compare the results of the individual car emission case to the line source case correctly, the line sources are located along the grid points of the car exhaust locations. All concentrations presented in this study are normalised (Kastner-Klein et al., 2001) according to

$$c^* = c\frac{VH}{Q_L} \tag{2.1}$$

with simulated concentration $c$, superimposed wind speed $V$ and height of the buildings $H = 16$ m.

Wind and turbulence kinetic energy for a neutral atmosphere are prescribed according to a logarithmic wind profile at the inflow boundary for a superimposed southerly wind of 3 m/s at the upper boundary at a height of 100 m. Neutral conditions are adopted here for this exemplary study in order to make the results comparable to the findings of wind tunnel studies.

# 3 Results

## 3.1 Results for the flat terrain

The dispersion of traffic pollutants for TS 2 was first studied in a flat environment. The simulated time record of normalised concentration 2 m beside the northern lane is given in Fig. 3. After approximately 100 s adjustment time, the concentration patterns show a nearly periodic steady-state solution and the results at the end of the simulation between 200–300 s seem to be representative for

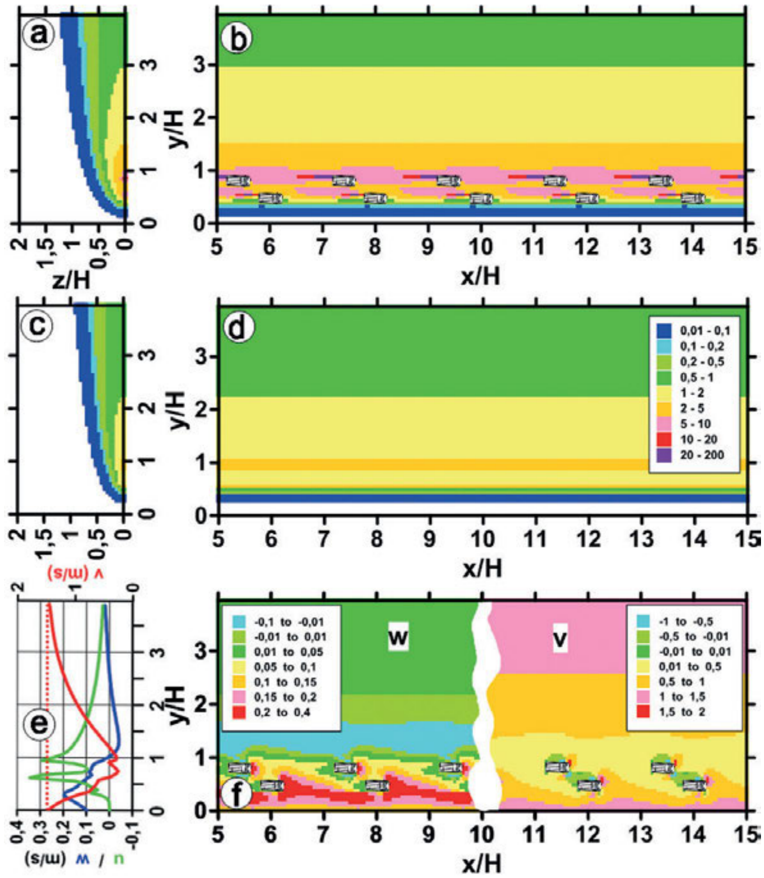


**Figure 4:** Horizontal distribution at 1 m height of normalised concentration (4b) and wind components in m/s (4f) for TS 2 and normalised concentration for the line source case (4d), all at $t = 250$ s. Car positions for $U = 30$ km/h are indicated. Vertical cross sections are shown of along-road mean normalised concentration for TS 2 (4a) and line source (4c). Along-road mean horizontal profiles of wind components at 1 m height (4e), where the dotted line indicates the situation without running cars are also shown.

the scenario adopted. When passing the measuring site, each individual car emits instantaneously air compounds resulting in short-term high concentrations. Until the arrival of the following car, the concentration decreases, caused by the advection and traffic enhanced turbulent mixing of cleaner air from the surrounding environment.

For increasing travelling speed, the concentration at the roadside decreases obviously. Reasons for this behaviour are the car-induced along-road advection and turbulent diffusion, as well as the larger distance between the cars, where the superimposed wind can intervene more directly and strongly. This direct wind exposure is also the reason for the relatively low concentrations for the line source case.

The differences in concentrations between the line source case and TS 2 are caused by the strong traffic-induced modifications of the wind field. While without obstacles, the wind is homogeneous in the horizontal plane, the moving obstacles (here $U = 30$ km/h) destroy this simple picture. In Fig. 4f, vertical wind w and S-N-component v are given for a small horizontal section of the simulation area. In this snapshot for $t = 250$ s at a height of 1 m, it becomes obvious that the moving vehicles modify the wind significantly. Along the traffic lanes, the v-component in general is reduced by the multitude of obstacles, while locally the air flow is pushed aside in front and behind the cars, resulting in larger values of v. The running traffic acts as an obstacle that the oncoming wind is forced to avoid. This flow pattern is recognisable by an updraft on the leeward side of the road and a downdraft behind. A significant, persistent vertical wind was also observed on the leeward side of a road with heavy traffic (Kalthoff et al., 2005); however, this was attributed to the topographic effects of a dam of 1 m height.

Even for the along-road mean values, these typical wind modifications are clearly visible (Fig. 4e). On average, a persistent wind component u along the road is simulated in accordance with wind tunnel studies (Kastner-Klein et al., 2000), while the aforementioned vertical velocities are also evident. The perpendicular wind component $v$ is reduced significantly in the vicinity of the running traffic down to a distance of $3H$, which corresponds to 50 m. This value is in good agreement with the findings of field observations (Kalthoff et al., 2005).

Such significant wind modifications result in a very different dispersion picture in the surroundings of the

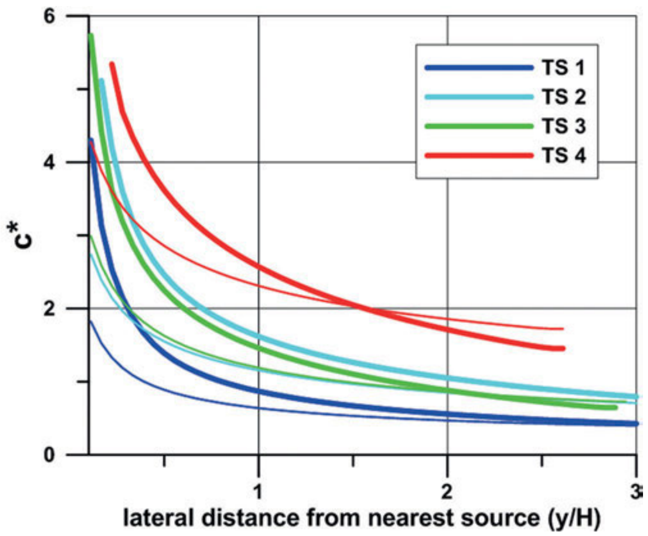


**Figure 5:** Along-road mean normalised concentration at 1 m height for different traffic scenarios. Thin curves are the corresponding results of the line source simulations.

road. While for the line source case, concentrations decrease on the windward side homogeneously along $y/H$ (Fig. 4d), the running traffic changes this feature. Each car leaves behind a trail of polluted exhaust gases with high concentrations near the source (Fig. 4b). Transport with the, on average, reduced cross wind is not as effective as for the situation without running obstacles, resulting in a significantly higher concentration level along the traffic lanes. In addition, with the periodic lateral boundary conditions adopted here, the polluted air is part of a continuous cycle and is effective time and time again. Such permanent locally high concentrations are mixed by the traffic-induced stronger turbulence with the air above; the effects of road emissions are visible even at higher levels (Fig. 4a) compared to the line source simulation (Fig. 4c).

The modification of the concentration pattern and the differences to the line source case depend on traffic characteristics like the number of lanes and cars, and travelling speed. However, for all scenarios considered here, a line source assumption is a very reasonable approximation for the complex release of car emissions for distances from the road of more than $y/H = 2$ to 3, which corresponds to 30–50 m (Fig. 5). Closer to the road, especially along immediately bordering pavements and bike trails, the line source approach underestimates the concentration distinctly and may need to be corrected (Bäumer et al., 2005).

## 3.2 Results for the street canyon

Beside the rural case with the road in a plain, also the situation of moving traffic in a built-up environment was studied. This urban scenery is simplified to a multi-lane road running within an urban street canyon. The street width depends on the number of traffic lanes, and the bordering buildings are $H = 16$ m high. The length is fixed at 300 m. However, adopting periodic boundary conditions, the exact length is of minor importance.

For a superimposed wind perpendicular to the orientation of the street, as adopted in this study, the air flow in the canyon is dominated by a pronounced vortex. There have been numerous studies on the vortex characteristics depending on the aspect ratio in the field (Sugawara et al., 2008), in wind tunnels (Kovar-Pansku et al., 2002), in water tunnels (Baik et al., 2000) and by numerical simulations (Li et al., 2012). Depending on the aspect ratio, a pronounced vortex is formed, or an even more complex flow structure. The simulated wind pattern in vertical cross section, averaged along the street, is given in Fig. 6a for scenario TS 4. The entire space of the canyon is occupied by a vortex, except for the lower part. In this region with moving vehicles, which act as additional obstacles for the near-surface recirculating wind, in general the mean wind speed is low. For the line source case without cars (Fig. 6b), the vortex is not disturbed towards the floor, resulting in significantly higher wind speeds near the ground.

In the moving car region, a wind component parallel to the street is induced, depending on travelling direction. For $U = 30$ km/h, mean values along the street of $u = 0.5$ m/s are simulated (Fig. 6e); however, they are limited to the lowest part of the canyon. Based on the findings of different field experiments, Kastner-Klein et al., (2000) provided an estimate of 3 m height for this region, which is the same order of magnitude as the simulation results.

The moving vehicles also modify the distribution of turbulence kinetic energy (TKE) within the street canyon. In the situation without running traffic, turbulence production is large at the roof level in the presence of strong wind shear (Fig. 6 h). However, turbulence kinetic energy decreases as the ambient wind enters the urban cavity; near the bottom, turbulence is low. Due to the advection by the vortex, TKE is expected to be weaker at the leeward side than at the windward side of the street. In the presence of traffic, additional turbulence is generated by moving cars especially in the lower part of the canyon (Fig. 6g). Maximum TKE is simulated above the car layer as well as between the lanes where strong horizontal wind shear is generated. This two-maxima structure of TKE was observed during field experiments by Vachon et al. (2002).

As a consequence of the significantly modified averaged air flow in the canyon, also differences in the dispersion from a line source and from a number of individual vehicle point sources must be expected. In the absence of vehicles, emissions are advected by the pronounced near-surface part of the canyon vortex to the leeward side of the street, resulting in high concentrations near the pavement (Fig. 6d). At the opposite side, concentrations are significantly lower, caused by the mixing with fresh air from above. This mean pattern of $c^*$ has been modified by the effects of moving vehicles on wind and turbulence. Reduced near-surface mean air flow transports the pollutants emitted by cars

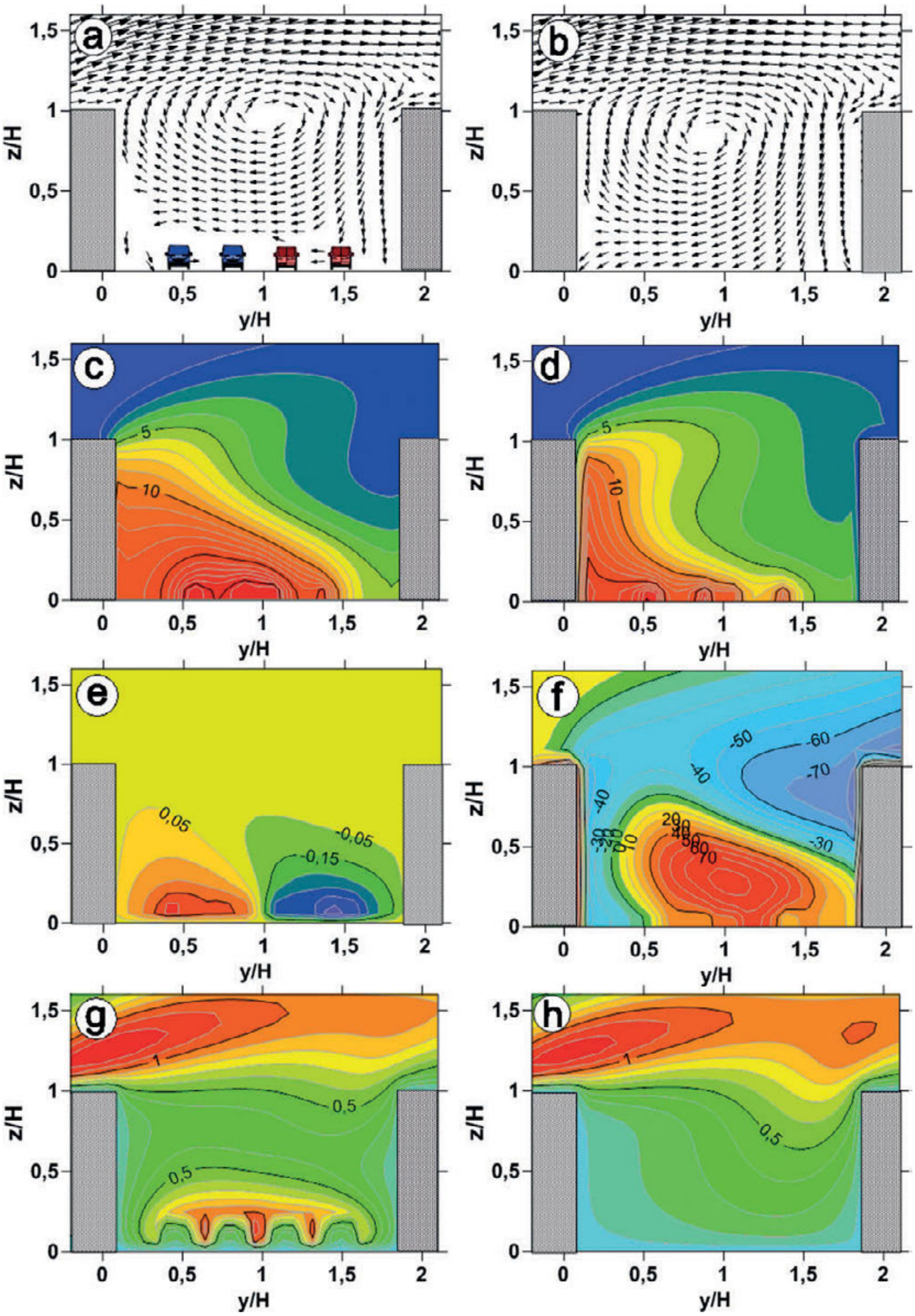


**Figure 6:** Vertical cross sections of along-street averaged air flow *v-w* (6a: car source, 6b: line source), normalised concentration $c^*$ (6c: car source, 6d: line source), along street wind component *u* (6e: car source, units m/s), relative differences of $c^*$ (6f: units %), and turbulence kinetic energy in $m^2/s^2$ (6g: car source, 6h: line source).

to a lesser extent to the leeward pavement. Pollutants remain longer near the street, and the car-induced enhanced turbulence disperses these substances very effectively inside the canyon (Fig. 6c). Compared to the line source scenario immissions near the leeward pavement are reduced, but are increased near the pavement on the opposite side of the street, as well as in the centre of the canyon above the car layer. The order of mag-

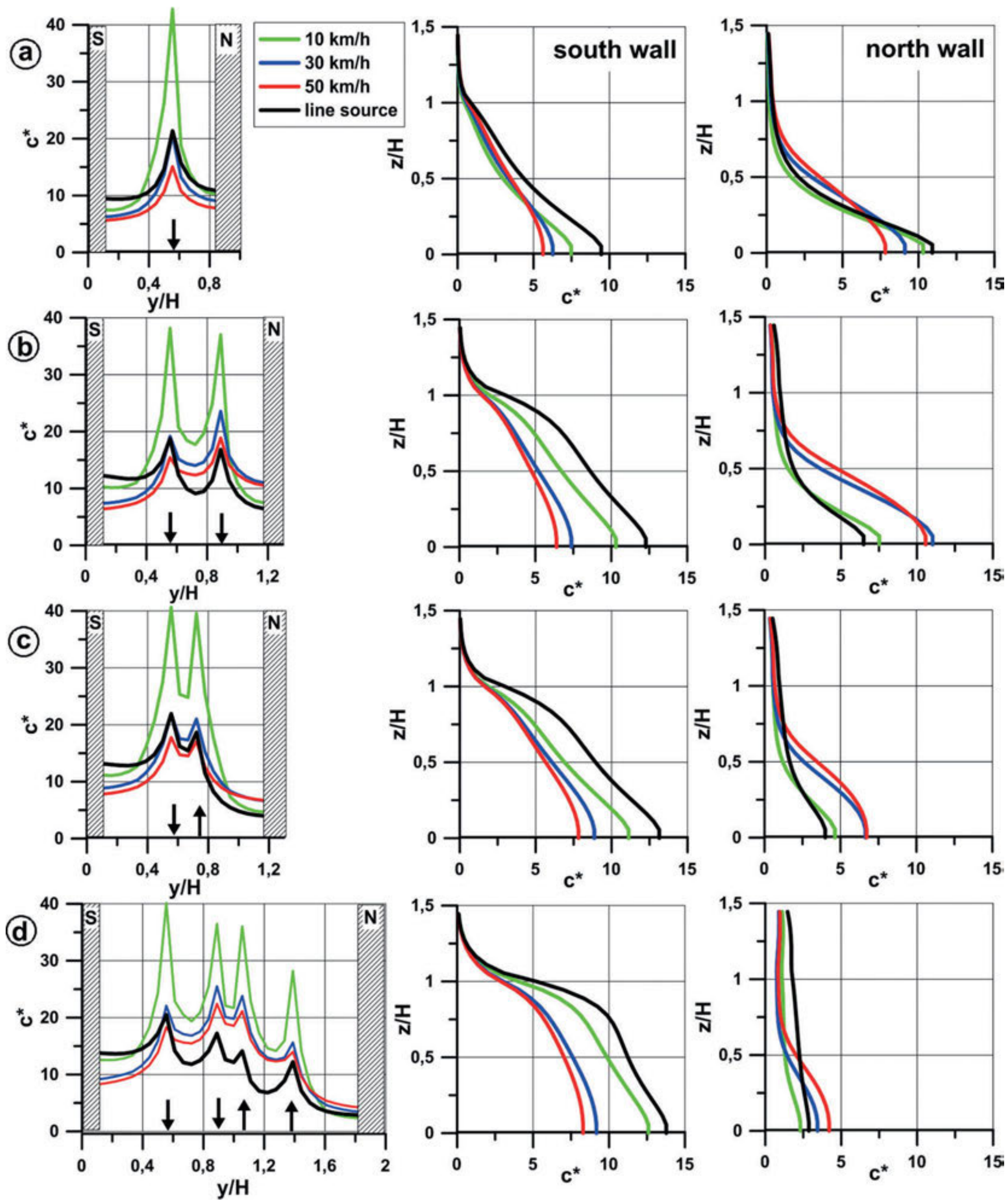


**Figure 7:** Horizontal and vertical profiles of normalised concentration averaged along the street for different canyon geometries and traffic scenarios. Arrows indicate traffic direction and source position.

nitude of these differences near the bordering buildings is 30–40 % and therefore not negligible or insignificant (Fig. 6f).

The simulated results can be compared to the general findings and main characteristics of wind tunnel outcomes, where the effects of running traffic on mean flow, turbulence and concentration pattern in street canyons have been studied (e.g. Kastner-Klein et al., 2000, Kastner-Klein et al., 2001). However, due to differences in experimental design and numerical setup, one cannot expect a completely matching picture of the results of these two different approaches. The main differences, which make such a comparison difficult, relate e.g. to the finite length of the street canyon in the wind-tunnel and the representation of traffic by small plates moving on belts along the street. Nevertheless, the numerical results should follow the main experimental findings.

In particular, traffic scenario TS 3 is close to the experimental assumptions, and these results can be used for a rough comparison. Primarily, the concentration pattern near the walls of the bordering building have been analysed and observed; vertical profiles in the centre of the model canyon are of particular interest.

For the two-way traffic situation TS 3, car emissions are released approximately in the middle of the canyon (Fig. 7c).The near-source concentrations, averaged along the street, are distributed inside the canyon by mean wind and turbulence modified by car-induced disturbances. For slow traffic conditions, the concentration maximum is very high, since cross-canyon circulation is reduced near the surface by the individual car obstacles; along-street advection is less pronounced, and traffic-induced turbulence is small. As a consequence, car emissions accumulate and the concentration is high. For increasing travelling speed $U$ of the vehicles, the near-surface concentration decreases in general except at the windward side. Vertical profiles of along street averaged $c^*$ at the south wall and the north wall demonstrate the effect of moving cars. As in the wind-tunnel studies of Kastner-Klein et al. (2000), $c^*$ decreases for increasing $U$ at the leeward side, while an opposite dependency is found, in the simulation as well as in the full-scale experiment, on the opposite wall. However, concentrations near the leeside of the canyon are higher than on the windward side.

The line source approach accentuates the concentration differences between the two sides with larger values of $c^*$ near the south wall and an underestimation near the north wall. The main reason for this simulation result is the significantly different picture of the canyon vortex near the ground in the car layer.

This situation becomes even more complex in a deep and narrow canyon, where the vortex-like circulation does not cover the complete road space, and vehicle-induced turbulence plays a more important role. The emitted pollutants by moving cars along the street are mixed very effectively, resulting in quite uniform concentrations across the street. On both sides, $c^*$ is in the same order at pedestrian level (Fig. 7a). This result was also found in the field experiments of Murena et al. (2008). For increasing travelling speed U, traffic-induced turbulence is enhanced and the near-surface concentration decreases. However, these pollutants are mixed into the layer above where higher concentrations are found for larger values of $U$. The line source approach is a conservative estimation for immissions at pedestrian level on the leeward as well as on the windward side of the street.

For an increasing width of the canyon with a four-lane street, the concentration differences near the two bordering buildings becomes more pronounced (Fig. 7d). While $c^*$ at the leeward side remains of the same order of magnitude for all street widths, the windward side near-surface concentration decreases noticeably. Again, this simulation result has also been found in wind-tunnel studies (Kastner-Klein et al., 2000). For all traffic and building scenarios considered in this study, an increasing travelling speed of the cars results in lower values of $c^*$ at the leeward side and in higher values along the opposite pavement.

This general picture is modified for traffic scenario TS 2, where one-way traffic on both lanes is adopted (Fig. 7b). In this scenario, the emissions from cars running on the northern lane are closer to the northern wall, resulting in significantly higher concentrations compared to TS 3. For increasing $U$, the along-street averaged concentrations are significantly higher on the windward side than on the leeward side of the street.

For all numerical investigations in this study with specified traffic and building situations, the line source approach overestimates the immissions at the leeward side of the street. However, an underestimation was typically found on the windward side.

# 4 Conclusions

A three-dimensional microscale model was used to study the effects of moving vehicles on air pollution in the close vicinity of a road. With the location of the street in flat terrain and within an urban canyon, two very contrasting situations have been considered.

The numerical results are compared to findings from wind tunnel experiments and field observations. Although a perfect match between specific experimental conditions and numerous numerical parameters is not guaranteed, a wide range of general and characteristic features of wind and concentration patterns can be found in the simulations. Besides the well-known canyon vortex, a significant generation of traffic-induced turbulence with a pronounced secondary maximum close to the near-surface car layer is calculated. As found in wind tunnel experiments for a superimposed wind perpendicular to the canyon, our model results demonstrate that running traffic causes a significant organised flow along the street canyon, altered by traffic density and direction.

For the rural case with a motorway in a plain, a systematic updraft was calculated on the leeside of the road caused by the airflow over the running car obstacles. A similar wind pattern was found in field experiments; however, this was completely attributed to a dam of 1 m height. One could assume that, beside such topographic effects, the multitude of running vehicles itself is part of the explanation for this experimental finding.

A qualitative assessment of the simulated concentration pattern results in very reasonable similarities with the observations. Vertical profiles of normalised concentration along the walls of the bordering buildings of the canyon are in good agreement with the findings of wind tunnel experiments, as well as with modifications for changing traffic scenarios. In addition, the characteristic concentration differences between the leeside and windward sides of a street are well reproduced by the model, especially for the situation of a deep canyon, where the differences are very small.

A comparison of the results for a line source and for multiple single moving sources shows some remarkable aspects. For the flat terrain case, the near-road concentrations are significantly underestimated by up to a factor of two if the emissions are approximated by a line source. This underestimation decreases with increasing distance and, depending on traffic speed, becomes negligible 30–50 m away from the road.

Also for the urban canyon situation, characteristic differences between the results of the two approaches are found. For all scenarios considered here, the line source assumption is a conservative approximation for the concentrations at the leeside of the street. However, on the opposite pavement and wall, a systematic underestimation was found of an order of magnitude, which cannot be ignored or disregarded. Also, a dependency on traffic situation was found, where the largest differences were simulated for one-way compared to two-way traffic. The significantly higher pavement concentrations for one-way traffic on two lanes can be attributed to the shorter distance to the exhaust system as the emission source.

The findings of the numerical simulations presented here are relevant for exposure studies, the arrangement of representative air quality monitoring systems, and the interpretation of observed concentrations near streets with running traffic.

## Acknowledgements

We acknowledge support by Deutsche Forschungsgemeinschaft and Open-Access Publishing Fund of Leibniz Universität Hannover.

## References

Baik, J.-J., R.-S. Park, H.-Y. Chun, J.-J. Kim, 2000: A laboratory model of urban street-canyon flow. – J. Appl. Meteor. **39**, 1592–1600.

Baker, C.J., D.M. Hargreaves, 2001: Wind tunnel evaluation of a vehicle pollution dispersion model. – J.Wind Eng. Ind. Aerodyn. **89**, 187–200.

Barmpas, F., I. Ossanlis, N. Moussiopoulos, 2011 : Numerical study for the flow around moving cars and its effect on the dispersion of the traffic emitted pollution within a road tunnel. – Int. J. Env. Poll. **44**, 307–315.

Bäumer, D., B. Vogel, F. Fiedler, 2005: A new parameterisation of motorway-induced turbulence and its application in a numerical model. – Atmos. Env. **39**, 5750–5759.

Berkowicz, R., O. Hertel, S.E. Larsen, N.N. Sorensen, M. Nielsen, 1997: Modelling traffic pollution in streets. – Danish Ministry of Environment and Energy, National Environmental Research Institute, Roskilde, Denmark, ISBN: 87-7772-307-4.

Carpentieri, M., P. Kumar, A. Robins, 2011: An overview of experimental results and dispersion modelling of nanoparticles in the wake of moving vehicles. – Env. Poll. **159**, 685–693.

Eskridge, R.E., J.C.R. Hunt, 1979: Highway modelling. Part I: Prediction of velocity and turbulence fields in the wake of vehicles. – J. Appl. Meteor. **18**, 387–400.

Gross, G., 2012: Effects of different vegetation on temperature in an urban building environment. Micro-scale numerical experiments. – Meteorol. Z. **21**, 399–412.

Gross, G., 2014: On the estimation of wind comfort in a building environment by micro-scale simulation. – Meteorol. Z. **23**, 51–62. DOI:10.1127/0941-2948/2014/0577.

Heimann, D., Y. Käsler, G. Gross, 2011: The wake of a wind turbine and its influence on sound propagation. – Meteorol. Z. **20**, 449–460.

INFRAS, 2014: Handbuch Emissionsfaktoren des Straßenverkehrs. – HBEFA 3.2. Auftraggeber: UBA Berlin, BAFU Bern, UBA Wien, u. a.

Kalthoff, N., D. Bäumer, U. Corsmeier, M. Kohler, B. Vogel, 2005: Vehicle-induced turbulence near a motorway. – Atmos. Env. **39**, 5737–5749.

Kastner-Klein, P., B. Ruck, E.J. Plate, 2000: Strömungsmechanische Aspekte in der Stadtplanung im Hinblick auf eine Reduktion von Kfz-Emissionen. – Forschungsbericht FZKA-BWPLUS, Inst. Hydrologie und Wasserwirtschaft, Univ. Karlsruhe.

Kastner-Klein, P., E. Fedorovich, M.W. Rotach, 2001: A wind tunnel study of organised and turbulent air motions in urban street canyons. – J. Wind. Eng. Ind. Aerodyn. **89**, 849–861.

Kim, Y., L. Huang, S. Gong, C. Jia, 2016: A new approach to quantifying vehicle induced turbulence from complex traffic scenarios. – Chin. J. Chem. Eng. **24**, 71–78.

Kovar-Panskus, A., P. Louka, J.-F. Sini, E. Savory, M. Czech, A. Abdelqari, P.G. Mestayer, N. Toy, 2002: Influence of geometry on the mean flow within urban street canyons – A comparison of wind tunnel experiments and numerical simulations. – Water, Air, Soil Poll. Focus **2**, 365–380.

Li, X.-X., R.E. Britter, L.K. Norford, T.-Y. Koh, D. Entekhabi, 2012: Flow and pollutant transport in urban street canyons of different aspect ratios with ground heating: Large-eddy simulation. – Bound.-Layer Meteor. **42**, 289–304. DOI:10.1007/s10546-011-9670-9.

Murena, F., N. Garofalo, G. Favale, 2008: Monitoring CO concentration at leeward and windward side in a deep street canyon. – Atmos. Env. **42**, 8204–8210.

Sugawara, H., A. Hagishima, K.-I. Narita, H. Ogawa, M. Yamano, 2008: Temperature and wind distribution in an E-W-oriented urban street canyon. – SOLA 4, 053–056, DOI:10.2151/sola.2008-014.

Vachon, G., P. Louka, J.-M. Rosant, P.G. Mestayer, J.-F. Sini, 2002: Measurements of traffic-induced turbulence within a street canyon during the Nantes'99 experiment. – Water Air Soil Poll. Focus **2**, 127–140.

VDI 3783, 2005: Environmental meteorology. Prognostic microscale windfield models – Evaluation for flow around buildings and obstacles. – VDI guideline 3783, Part 9. Beuth Verlag Berlin.

Venetsanos, A.G., D. Vlachogiannis, A. Papadopoulos, J.B. Bartzis, S. Andronopoulos, 2002: Studies on pollutant dispersion from moving vehicles. – Water Air Soil Poll. **2**, 325–337.