ORGANISED AND TURBULENT AIR MOTIONS IN A WIND TUNNEL MODEL OF A STREET CANYON WITH AND WITHOUT MOVING VEHICLES

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Submitted to Proceedings of 6th International Conference on Harmonisation within Atmospheric Dispersion Modelling

ABSTRACT
A cloud of exhaust gases produced by traffic in big cities can be trapped inside deep and poorly ventilated urban street canyons. High concentration of pollutant gases may be expected with low winds or in cases when the wind is oriented perpendicular to the canyon axis. It is still an open question whether moving cars themselves can generate ventilating air motions, both organised and turbulent. Flow parameters in a model of a street canyon with and without traffic were measured in a wind tunnel. Results show significant influence of the traffic arrangement (one-way vs. two-way) on the mean and turbulent components of flow in the canyon. For the case without traffic, comparisons are presented with results of full-scale measurements.

KEYWORDS
Traffic, turbulence, air pollution, dispersion, street canyon, wind tunnel, modelling, field measurements.

INTRODUCTION

Street canyons of big cities are usually rather poorly ventilated by natural air motions associated with external wind. Even when the wind is strong, the cloud of exhaust gases produced by traffic can be trapped in the lower portion of the canyon. Especially high concentrations of pollutant gases may be expected when the wind is oriented perpendicular to the canyon axis and the canyon aspect (depth to width) ratio is large, of the order of one or more.

It is still an open question to what extent the moving vehicles can themselves contribute to air motions close to the canyon bottom. There are practically no data available from direct full-scale measurements of local air motions produced by vehicles in urban street canyons. Most frequently used tools for estimating vehicle-induced effects on pollutant transport in urban environment are numerical models. In these models, rather arbitrary assumptions are usually drawn to parameterise the impact of vehicles on the in-canyon flow. Existing parameterisation schemes typically do not distinguish between traffic-generated air motions of different nature and scale. Some models, (among them, for instance, Hertel and Berkowicz 1989, Sini et al. 1996, and Stern and Jamartino 1998), merely consider the whole spectrum of these motions as traffic-induced turbulence. However, experimetal studies of Eskeridge and Hunt (1979), and Delaunay and Houseaux (1997) provide a certain evidence of semi-organised, advection-type air motions in the flow field affected by moving vehicles.

A series of wind-tunnel experiments has been performed in order to evaluate the contribution of city traffic to air motions in a street canyon formed by two parallel building rows. The canyon aspect ratio has been equal to one. The experimental programme included measurements of the mean-flow and turbulence parameters in the situations without traffic and with two-lane traffic. The traffic was simulated using an experimental approach described in Kastner-Klein et al. (1998). The cases of both one-way and two-way traffic have been studied. As the reference case, the flow field in the canyon without traffic has been employed. For this case, the wind-tunnel data have been compared with flow measurements in full-scale urban street canyons.

EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUE

The experiments have been performed in the atmospheric boundary layer wind tunnel of the University of Karlsruhe (UniKa), Germany. A description of this facility is given in Kastner-Klein (1999). A scaled analogue of the atmospheric neutrally stratified boundary-layer flow is reproduced in the wind tunnel. This is realised with the aid of vortex generators installed at the entrance of the test section and by means of the roughness elements mounted on the wind-tunnel floor. The typical boundary-layer depth in the vicinity of the street-canyon location is of the order of 50cm. The height and length of the buildings forming the canyon have been 12cm and 120cm, respectively. In the performed experiments, the distance between the buildings has been chosen to be 12cm. This provided the canyon aspect (depth-to-width) ratio equal to 1. In all cases to be presented in this paper, the external wind flow has been oriented perpendicular to the axis of the canyon. The *X*-axis has been oriented along the direction of external wind.

Rectangular plates attached to moving belts stretched along the canyon simulate the two-lane traffic in an urban street (Brilon et al. 1987, and Kastner-Klein et al. 1998). To enable the reproduction of situations with one-way or two-way traffic, the belts can be moved in alternative directions with regulated velocity.

Mean-flow and turbulence measurements in the tunnel were conducted with a laser Doppler velocimeter. In most of measurement locations inside the canyon and above it, the components of the velocity vector across and along the canyon were measured. In several locations, also the vertical velocity component was registered. From the obtained time series, mean-flow parameters and one-point, second-order turbulence statistics have been derived.

In parallel to the flow parameters, the mean concentration values of a passive gaseous tracer have been measured throughout the whole volume of the canyon. The tracer was emitted from two line sources co-located with the traffic lanes. The concentration patterns were analysed in conjunction with the mean-flow and turbulence fields.

MEASUREMENT RESULTS

Concentration fields in a canyon with and without traffic

First we consider concentration distributions over the leeward walls of the upwind building of the canyon with three different traffic arrangements: without traffic, with two-way traffic of 30km/h, and with one-way traffic of the same density and velocity. The corresponding concentration patterns are presented in Fig. 1.

One may use these concentration distributions as indicators of the transport properties of the flow in the canyon under different traffic conditions. In the case without traffic, the maximum of concentration is observed around the central plane of the canyon. Due to ventilation through the open lateral sides of the canyon, the concentration symmetrically decays towards the canyon edges. It is possible to see however that the noted symmetry is observed also in the concentration pattern corresponding to the simulation case with two-way traffic. Such symmetry indicates that the two-way traffic does not generate any significant mean-flow motion along the canyon. This conclusion will be supported later by results of the mean-flow measurements. The lower concentration values in the two-way traffic case compared to the zero-traffic situation give an evidence of the additional diffusion of tracer due to the vehicle-induced turbulent motions. This diffusion is apparently invariant with respect to the sign of *y*.

When the cars in both lanes move in the same direction, the situation is principally different. The concentration distribution in this case points to a strong piston effect leading to the skewed concentration field in the canyon. Hence, in the one-way traffic case, the car-induced mean air motion along the canyon plays the dominant role in the formation of resulting concentration pattern. Presumably, the turbulent component of motion also contributes in this case to the dispersion of tracer, but its effect is clearly subordinate to the transport of gaseous admixture in the canyon by organised motion.

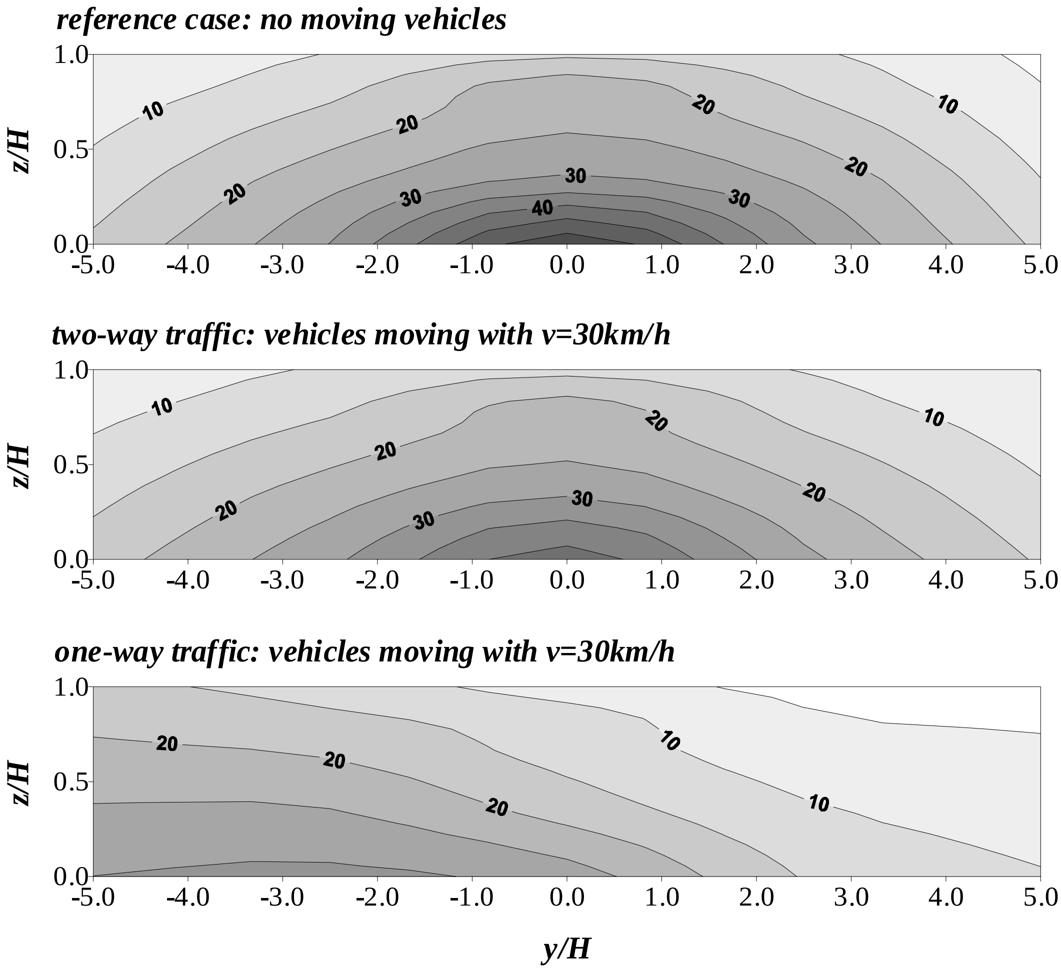

Fig 1. Distributions of normalised concentration $c_*=c \cdot U \cdot H \cdot L_s/E_s$ (*c* is the measured concentration, *U* is the reference wind velocity, *H* is the canyon depth, L_s is the length of the line source simulating the traffic emission, and E_s is the source strength) at the leeward wall of the canyon with different traffic arrangements.

Mean flow and turbulence profiles in a canyon without traffic

In order to evaluate validity of the wind tunnel mean-flow and turbulence measurements for the reference (zero-traffic) case, we will compare them with results of corresponding field measurements of Rotach (1995) and Louka (1998). The comparison of profiles of the modulus of the longitudinal mean-flow component, |*u*|, is given in Fig. 2a. The rms values of the longitudinal and lateral (along-the-canyon, *v*) velocity fluctuations are compared in Figs 2b and 2c, respectively.

The vertical coordinate is scaled with the building height *H*, and the measurement data are normalised by *u*(*H*), the value of *u* at *z*=*H*. Such choice for the normalisation parameter was primarily determined by the availability of *u*(*H*) for all compared datasets. Nevertheless, as will be shown below, this normalisation cannot be considered optimal for presenting velocity data from different wind-tunnel and field experiments.

In all plots, the wind-tunnel measurements are given by stars for the canyon length *L*=120cm, and by diamonds for the canyon length *L*=60cm; the urban data from Rotach (1995) are presented by filled circles; and the data from "smooth-rough" and "rough-rough" cases of Louka (1998) are shown by filled and open triangles, respectively. In the experiments of Louka (1998), the "smooth-rough" case corresponded to the building arrangement without any large-scale obstructions affecting the approach flow, and in the "rough-rough" case several additional buildings were located upwind the canyon. The wind-tunnel data refer to the central, (*x, 0, z*), plane of the canyon, and represent averaged values from seven vertical profiles inside the canyon (one of them in the centre of the canyon, and the rest at equal distance intervals from the centre to the walls).

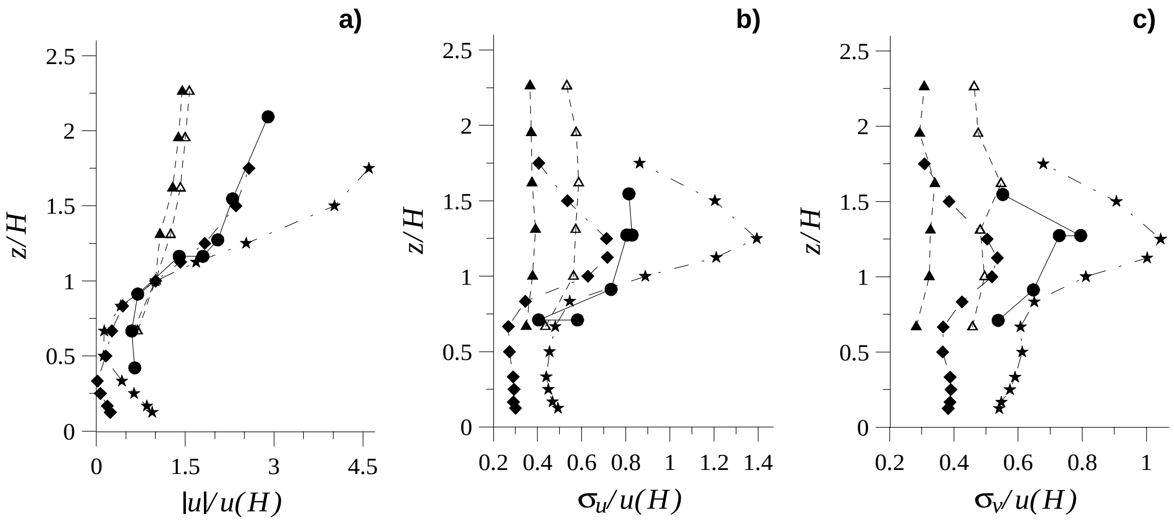

Fig 2. Normalised profiles of the modulus of the longitudinal mean-flow velocity component (a), and rms values of longitudinal (b) and lateral velocity (c) fluctuations inside and above an urban street canyon. See the text for details.

The mean-flow profiles from different datasets shown in Fig. 2a diverge considerably inside the canyon as well as above it. The closest conformity of the wind-tunnel data with field measurements is observed in profiles from the 60-cm long wind-tunnel canyon and from the full-scale study of Rotach (1995). The difference between the velocity data for the 120-cm and 60-cm long wind-tunnel canyons is mainly due to rather small velocity value *u*(*H*) in the case of longer canyon. Our wind-tunnel experiments have shown that the mean-velocity field in the central plane of sufficiently long canyon is not affected by the lateral (with respect to the external flow) exchange of momentum along the canyon, whilst for the short canyon this effect is rather strong. This leads to larger velocity values at the building-height level in the latter case.

One may suppose that the lateral exchange of momentum (also associated with influence of street crossings on the velocity field, see Kastner-Klein et al. 1997) can play a significant role in real urban street canyons. The momentum exchange is also a probable reason for comparative weakness of in-canyon circulation in the case of shorter canyon. This circulation is stronger in the full-scale urban canyon from the study of Rotach (1995) and in the longer wind-tunnel canyon. Note that in the wind-tunnel experiments the actual velocity values in the lower portion of the canyon were negative, while during the field measurements the sign of mean velocity inside the canyon was not defined.

The vertical distributions of velocity in the experiments of Louka (1998) appear to be rather uniform with height as compared with the data of Rotach (1995) and with the wind-tunnel results. Probable reasons for such behaviour of velocity profiles in Louka's experiments may be the smaller canyon aspect ratio (0.7), slightly slanted roofs of the buildings, and deviation of the external flow from the direction perpendicular to the canyon axis.

The rms values of *u* and *v* velocity components from the wind-tunnel and field experiments (Figs. 2b and 2c) are rather scattered as well. This scatter, like in the case of mean-flow velocity, is mainly caused by the divergence of the *u*(*H*) values used for the normalisation of statistics. In this connection, it will be desirable to normalise the measured mean-flow and rms velocity values by the velocity of the undisturbed flow at some sufficiently large height above the canyon. Unfortunately, this velocity value was not determined for the full-scale measurement data employed for comparison. Nevertheless, the features of rms vertical distributions of both components are quite similar for the data originating from one and the same source. The wind-tunnel *u* and *v* rms values are nearly constant with height in the lower portion of the canyon. They reach their maxima slightly above the roof level. The field data of

Rotach (1995) display a similar tendency in this region of the flow. Much less pronounced maxima are observed in the profiles measured by Louka (1998). They show rather small variation of turbulence intensity with height above the canyon. Nevertheless, the rms velocity values in the "rough-rough" case are persistently larger than in the "smooth-rough" case which looks sensible from a physical point of view.

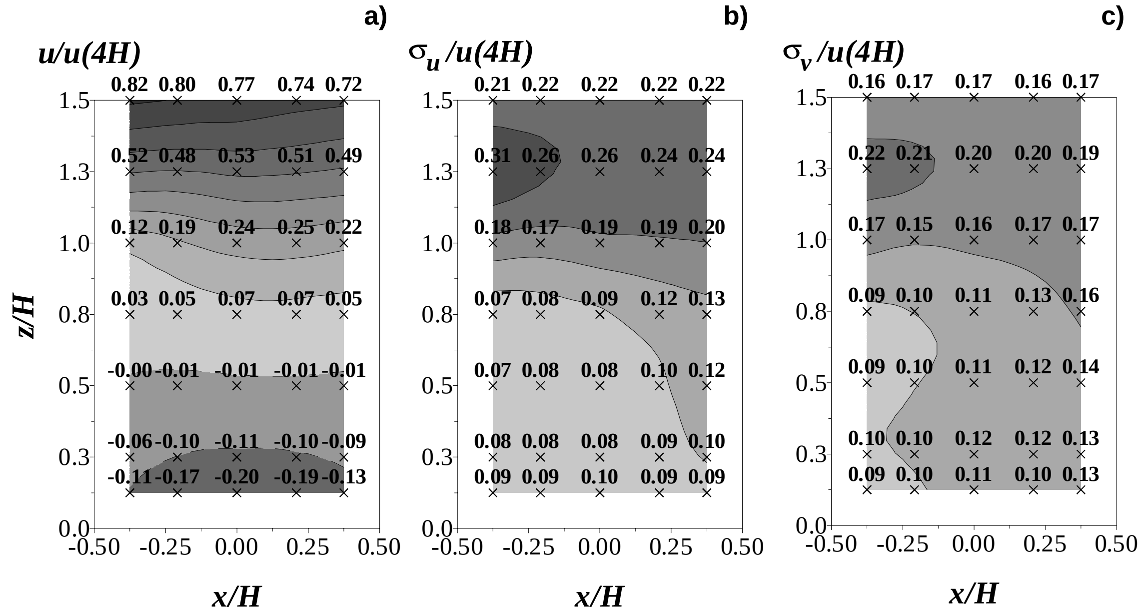

Fig 3. Normalised distributions of the longitudinal mean-flow velocity component (a), and rms values of longitudinal (b) and lateral velocity (c) fluctuations measured in the wind tunnel inside and above an urban street canyon without traffic. See the text for details.

Details of the mean and rms velocity distributions inside and above an urban street canyon can be seen in Fig. 3, where the results of measurements performed in the central plane of the wind-tunnel model of the canyon are presented. The data are shown being normalised by the wind velocity of outer flow measured at z=4H above the floor of the tunnel. In the pattern of mean-flow velocity (Fig. 3a), one may clearly see the re-circulation zone inside the canyon with almost zero velocity values in its centre. The near-surface negative mean air motion associated with such a flow re-circulation effectively transports the emitted tracer towards the leeward wall of the canyon thus enhancing concentration values near the wall at the roadside level, (see concentration distribution at the wall in Fig. 1). Immediately above the roof level (z/H=1), the region of strong mean-flow shear is located with sharp vertical gradients of the mean velocity.

The intensity of velocity fluctuations (Figs. 3a and 3b) is rather uniformly distributed in the canyon without traffic. The fluctuations of both velocity components have nearly the same magnitude, which suggests the approximate isotropy of horizontal velocity fluctuations in the centre of the canyon. The slight increase of rms velocity values takes place immediately above the canyon, where the turbulence production is intensified due to the flow shear that was identified in the mean-flow pattern. It is possible to assume that this shear at the same time produces a certain sheltering effect on the vertical turbulent transport of admixture across the canyon top and thus hampers the ventilation of the canyon. A similar turbulence-blocking effect was observed by Fedorovich and Kaiser (1998) in the case of shear sheltering of buoyancy-generated turbulence. The related physical analysis is presented in Hunt (1998).

Traffic-induced organised and turbulent motion

Now we proceed to the wind-tunnel measurements of the in-canyon flow for the cases of two-way and one-way traffic. The results of these measurements are presented in Fig. 4. The data are given as deviations of the measured flow characteristics in the canyon with traffic from their counterparts in the canyon without traffic. The employed scaling is the same as in Fig. 3.

Patterns of the longitudinal mean-flow component *u* (not shown) were not found to be significantly altered by traffic. Modification of the lateral velocity component *v* essentially depends on the traffic arrangement. In the case of two-way traffic, the changes of *v* are negligible (Fig. 4a, upper plot). This is consistent with our earlier observation of the symmetry of concentration distribution in the canyon with two-way traffic (Fig. 1). Only in the close vicinity of the leeward wall of the canyon a slight motion can be noted. This motion is associated with upwind transport of momentum from the row of cars closest to this wall. The sign of transport is determined by the direction of the flow in the lower region of in-canyon mean circulation zone (from right to the left, see Fig. 3a).

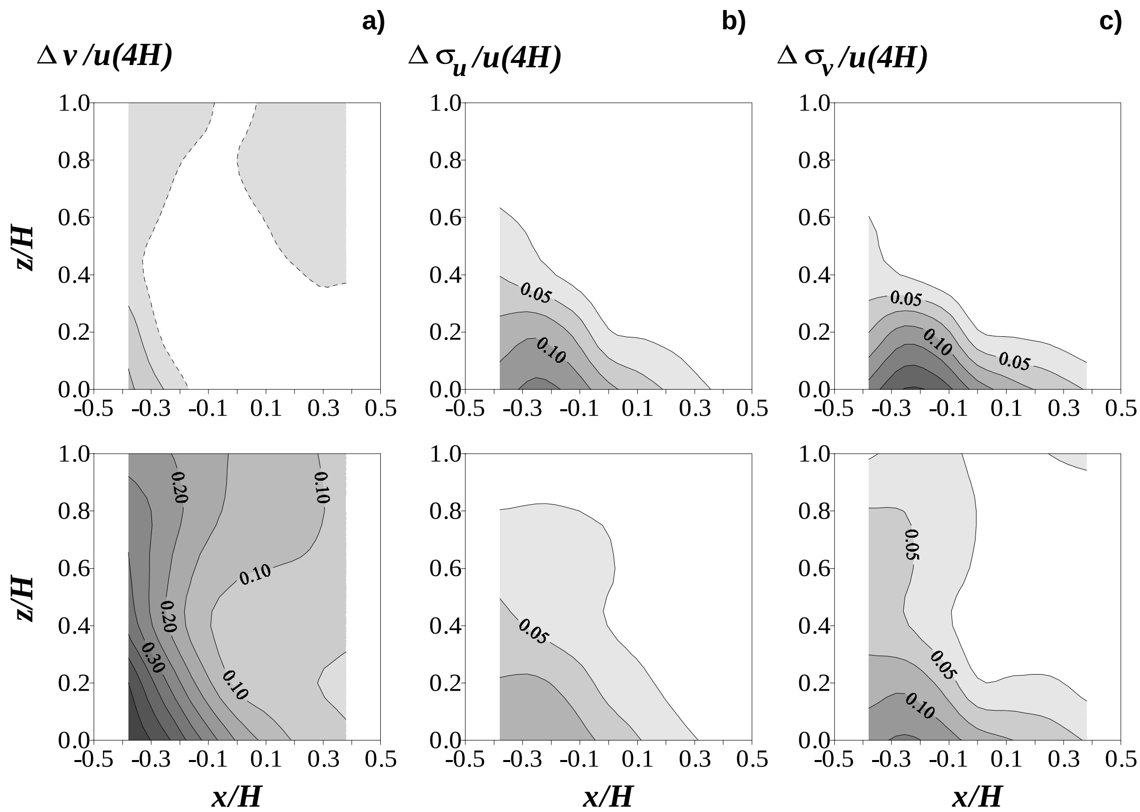

Fig 4. Traffic-induced contributions to the normalised fields of the lateral (along-the-canyon) mean-flow velocity component (a), and rms values of longitudinal (b) and lateral velocity (c) fluctuations inside an urban street canyon. The plots in the upper row refer to the case of two-way traffic and the lower row corresponds to the case of one-way traffic.

When cars in both lanes move in the same direction (Fig. 4a, lower plot), they produce noticeable organised motion that is rather non-uniformly distributed over the canyon cross-section. Due to the in-canyon vortex-like mean circulation, the maximum of momentum in the lower portion of the canyon is shifted upwind which results in a spiral-type organised motion inside the canyon. This motion produces the aforementioned piston effect leading to the skewness of the concentration distribution along the canyon in the case with one-way traffic (see Fig. 1).

The upwind near-floor advection associated with the in-canyon circulation also makes asymmetric the distributions of traffic-induced turbulent motions. The maxima of these distributions are persistently shifted towards the leeward wall of the canyon. It is easy to notice that the magnitude of velocity fluctuations induced by traffic is larger in the two-way traffic case than in the one-way traffic case (compare upper and lower plots in Figs 4a and 4b). This is apparently a result of enhanced turbulence production in the separation zone between lanes with cars moving in opposite directions. In this zone, turbulent eddies generated by vehicles moving from both sides are mutually destroyed thus enhancing the small-scale chaotic component of motion and not contributing significantly to the mean transport along the canyon. The situation in the one-way traffic case is different. With this traffic arrangement, one may expect mutual amplification of the momentum impulses of the same sign generated by vehicles moving in the parallel lanes. This results in the noticeable mean motion along the canyon, but does not produce as much energy of smaller-scale turbulent motions as in the case with two-way traffic.

SUMMARY AND CONCLUSIONS

Interaction between air motions generated by the external flow oriented perpendicular to the axis of an urban street canyon and vehicle-induced air motions inside the canyon has been investigated for a variety of traffic arrangements. The study was carried out in the atmospheric boundary-layer tunnel of the University of Karlsruhe.

For the zero-traffic case, the observed mean-flow and turbulence profiles in the canyon have been analysed in comparison with data from related field studies of flow structure in full-scale urban street canyons. Qualitative similarity has been found between the flow characteristics in the wind-tunnel model and their atmospheric counterparts. The relatively large discrepancies between the wind-tunnel and field measurement data were primarily caused by the inappropriate scaling velocity $u(H)$, which had to be used due to data availability restrictions in the full-scale experiments. The problem of lacking information about the undisturbed-flow velocity, which is probably better suited for normalisation purposes, is common for essentially all full-scale studies and thus deserves attention in further field experiments.

Data from all sources gave evidence of the flow acceleration (in some cases, rather sharp) above the roof level. The shear production of turbulence in this acceleration region was apparently responsible for relatively high rms values of horizontal velocity fluctuations above the canyon. Inside the canyon, the turbulence intensity was found to be approximately uniformly distributed over the canyon cross-section. It was suggested that this turbulence is to a certain extent blocked in the canyon due to shear sheltering in the flow-acceleration region above the roof level.

Values of the longitudinal mean-flow component u turned out to be practically unaffected by traffic, either one-way, or two-way. In contrast to this, the lateral (along-the-canyon) component of the mean flow displayed strong dependence on the traffic arrangement in the canyon. With the two-way traffic, the traffic-induced component of the mean air motion along the canyon was very small and restricted to the flow region in the vicinity of the leeward wall. At the same time, the turbulence intensity inside the canyon with two-way traffic was markedly larger than in the case of no traffic and one-way traffic. The latter case was characterised by the traffic-induced organised air motion along the canyon leading to the pronounced piston effect.

Relations between flow and concentration patterns in the canyon with different traffic arrangements were investigated. In the case of quasi-isotropic turbulent transport corresponding to the two-way traffic situation, the concentration distribution in the canyon was found to be approximately symmetric with respect to the central transversal plane of the canyon. Mean transport of tracer gas by vehicle-induced air motions was negligibly small in this case. With the organised motion induced by one-way traffic, the concentration distribution along the canyon was strongly skewed, with concentration values increasing in the direction of traffic-induced air current.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support provided for the presented study by the Training and Mobility of Researchers Programme of the European Commission within the TRAPOS Project, and by the Air Pollution Prevention Measures Programme (PEF) funded by the Land of Baden-Württemberg (Germany) and the European Commission.

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