1.6 **Implementation of a traffic-produced turbulence scheme into the fast-response model QUIC**

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1. INTRODUCTION:

The fast response model QUIC (Pardyjak and Brown, 2002, Williams et al., 2002, Brown, 2004) was designed to generate high resolution, 3-dimensional wind and dispersion fields for urban areas. It is comprised of a diagnostic wind field model, QUIC-URB, and a Lagrangian dispersion model, QUIC-PLUME. QUIC-URB uses empirical flow parameterizations to generate an initial flow field near buildings. The final velocity field is then obtained by forcing the initial velocity field to be mass consistent, and resembles a time-averaged experimental result.

Kastner-Klein and Clark (2004) recently evaluated the QUIC model against wind-tunnel data sets for idealized street canyons. As part of their evaluation studies they also improved parts of the empirical street-canyon parameterizations. Overall, the QUIC results agreed fairly well with the wind-tunnel flow data and as a next step a comparison with street-canyon concentration fields was planned. However, Kastner-Klein et al. (2003) have shown that the dispersion of pollutants inside street canyons is governed by both wind and traffic induced motions. As outlined in Kastner-Klein and Clark (2004), QUIC-PLUME was thus recently extended by a traffic-produced-turbulence (TPT) scheme. This paper presents an overview of the theoretical background of the TPT scheme and its implementation into QUIC. The TPT scheme is then evaluated against extensive wind-tunnel data sets of concentrations fields inside street canyons for cases with and without traffic effects. Finally, the practical applicability of the TPT scheme for dispersion modeling in urban areas, where traffic conditions vary significantly, will be discussed

2. WIND-TUNNEL DATA SETS

Kastner-Klein et al. (2004) presented wind-tunnel data from flow field measurements for idealized street canyons, which were used to evaluate and improve QUIC-URB (Kastner-Klein and Clark, 2004). For the same street-canyon configurations, concentration measurements were also carried out, and the influence of TPT on street-canyon dispersion was studied in the wind tunnel (Kastner-Klein et al. 2003). All experiments were performed in the atmospheric boundary layer wind tunnel of the University of Karlsruhe (UKA), Germany. Details about this facility and the characteristics of the neutrally stratified boundary-layer simulated in the wind tunnel are given in Kastner-Klein (1999). Further information about the UKA street-canyon studies can also be found in Kastner-Klein and Plate (1999) and Kastner-Klein et al. (2001).

Basically, the dispersion in an isolated street canyon consisting of two bar-type buildings was investigated. Fig. 1 illustrates the set-up during the wind-tunnel studies, but only cases without buildings III and IV have been considered for the current model evaluation studies. The height of the buildings was 0.12m, their length 1.20m, and the distance between the buildings 0.12m. This provides the canyon-aspect ratio $S/H = 1$ and a length-to-height ratio of $L/H = 10$. The upwind flow was perpendicular to the axis of the street, and a

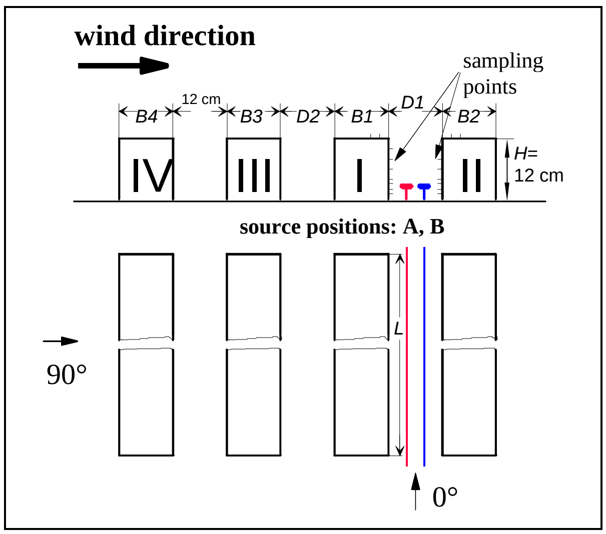


Figure 1: Sketch of the experimental set-up for the wind tunnel studies with idealised street canyons in the atmospheric boundary-layer wind tunnel at the University of Karlsruhe.

tracer gas was released from the two ground-level line sources A and B (Fig. 1).

Vertical concentration profiles along the walls of building I and II were measured. Usually three profiles were taken at each building at the positions: $y = 0$ m (central profile at the symmetry plane of the buildings) and $y = \pm(L/2 - 0.15\text{ m})$ (profiles near the lateral building edges with a distance of 0.15 m from the edges). The sampling points had a distance of 7 mm from the building walls. Emissions from the two line sources A and B were studied independently and their length was $L_q = 1.42$ m The distance between the wall of building I (in future called leeward building wall) and source A was 35 mm, the distance of source B was 85 mm. Test measurements proofed the lateral homogeneity of the line sources and the Reynolds - number independence of the concentration results (Kastner-Klein, 1999).

The wind-tunnel concentrations were normalized according to

$$c^* = \frac{c \cdot u_{4H} \cdot H}{Q / L_q}, \qquad (1).$$

where c corresponds to the measured tracer gas concentration, Q describes the source strength and u_{4h} is the wind speed measured at a height equal to four times the building height.

The effect of traffic motions on the street-canyons concentration patterns was simulated using small metal plates mounted on two belts moving along the street. In order to ensure Reynolds number similarity the wind velocity was set to be rather high and was varied in the range from 5m/s up to 14.2 m/s. The realized traffic speeds were in the range from 30 km/h to 61 km/h. Additionally, also the traffic densities were varied. More details on the technical design and results from the TPT studies can be found in a series of subsequent publications by Kastner-Klein et al. (2000a,b and 2001) and a summary of the results is also included in Di Sabatino et al. (2003).

For two-way traffic situations, one of the main findings has been, that the traffic motions enhance the mixing inside and ventilation of the canyon, which causes an attenuation of the concentrations measured at the leeward canyon walls. As illustrated in Fig. 2, the wind-tunnel tests have shown that the dimensionless concentrations calculated according to Eq. (1) vary with a similarity parameter $P = n^{1/3} v / u$, which allows to account for the combined effects of wind speed u, traffic speed v, and traffic density n. These results have been of particular interest for developing expanded street-canyon scaling concepts and testing of different TPT parameterizations (Kastner-Klein et al. 2000b and 2003), which are further discussed in the next section.

3. QUIC TPT SCHEME

The results presented in the previous section, have demonstrated the strong influence of traffic

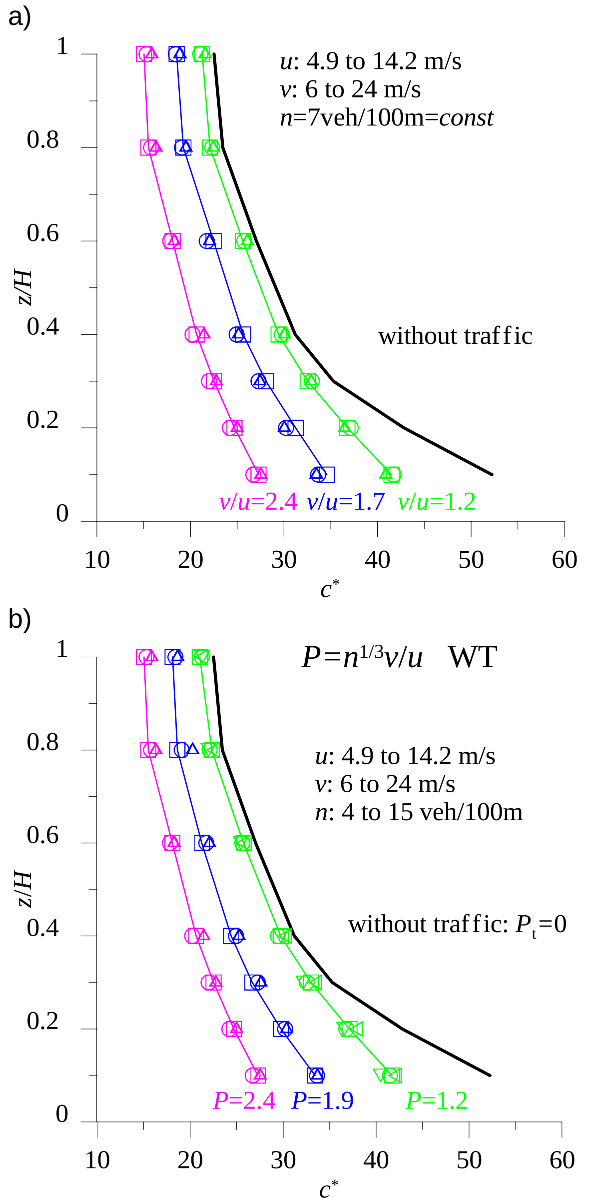


Figure 2: Influence of TPT on wind-tunnel concentration profiles along a leeward street-canyon wall (Kastner-Klein et al. 2000b): (a) influence of traffic to wind speed ratio v/u for cases with constant traffic densities and (b) variation with the similarity parameter P.

motions on street-canyon dispersion as observed in wind-tunnel experiments. To assure that similar effects can also be observed in the nature, Kastner-Klein et al. (2003) analyzed full-scale concentration measurements conducted in a number of European Cities. They have shown that traffic-produced turbulence (TPT) can have a strong influence on dispersion in street canyons and that the prediction of street-canyon pollution levels can be significantly improved if simple TPT parameterization schemes are applied. These results were the main motivation to implement a TPT parameterization scheme into the Lagrangian dispersion model QUIC-PLUME. As outlined in Kastner-Klein and Clark (2004), in a first approach, the parameterization of Di Sabatino et al. (2003) for intermediate traffic densities

$$\sigma_t^2 = c_t \left(\frac{nC_D h^3}{S_c} \right)^{2/3} v^2 \qquad (2)$$

is applied. In Eq. (2), c_t is a dimensionless proportionality constant, n describes the number of vehicles per unit length (traffic density), C_D the drag coefficient, and v the vehicle speed. The average vehicle length scale, h, is typically calculated by $h = \sqrt{A}$, with A equal to the frontal vehicle area, and S_c corresponds to the street canyon region, in which TPT is of importance. Appropriate values for the different variables appearing in Eq. (2) will be further discussed below.

Since the flow model QUIC-URB provides only information about the mean flow field but not about the turbulent flow components, the Lagrangian dispersion model QUIC-PLUME, uses either a local (basically surface-layer similarity theory) or non-local (accounts for enhanced mixing in the wake of buildings) mixing approach to determine the turbulence characteristics (Williams et al. 2002). New particle positions are then calculated solving the random walk equations, whereby at first a coordinate rotation is applied such that wind is parallel to the x-axis and the mean v and w components are zero. The same approach is used in the QUIC-PLUME TPT version. However, the total turbulent kinetic energy is determined as sum of the wind and TPT contributions:

$$\begin{aligned} TKE_{tot} &= TKE_{wind} + TKE_{TPT} \Leftrightarrow \\ \sigma_{tot}^2 &= \sigma_{wind}^2 + \sigma_{TPT}^2 \end{aligned} . \qquad (3)$$

The turbulent kinetic energy due to TPT is calculated using Eq. (2) and the variances of the velocity components are estimated assuming that TPT is isotropic:

$$\sigma_{ut}^2 = \sigma_{vt}^2 = \sigma_{wt}^2 = \frac{1}{3} c_t \left(\frac{nC_D h^3}{S_c} \right)^{2/3} v^2 . \qquad (4)$$

The above equations form the theoretical background for the QUIC-PLUME TPT scheme. However, for practical applications of the TPT scheme a number of additional questions must be addressed. Critical issues are e.g. the domain over which the TPT parameterizations should be applied in an urban landscape, and the settings for the different parameters used in Eq. (4).

In its current version, the TPT scheme offers three different options for choosing the horizontal domain over which TPT is applied. In option 1, TPT is automatically applied in street canyons, i.e. in regions over which the QUIC-URB street canyon parameterizations are applied. In other words, the information which region is considered as street canyon is passed from the flow model QUIC-URB into the TPT scheme. This option was motivated by the facts that the above parameterizations were developed and evaluated based on street-canyon data sets, and that traffic effects can be expected to be strongest inside street canyons. In real cities, it is however likely, that not all street canyons experience heavy traffic while heavy traffic zones may exist in other parts of the domain. Due to that, option 2 allows the user to specify the regions where TPT should be applied. Finally, option 3, is a combination of 1 and 2, where TPT is first automatically applied in all street canyons but the user has the possibility to add or remove TPT effects in certain areas.

Variations of the vertical extent of the TPT zone and testing of different settings for the parameters in Eq. (4) were part of a sensitivity study described in the following.

4. QUIC TPT SIMULATIONS

To evaluate the QUIC TPT scheme, a model sensitivity study has been conducted using a set-up similar to the one used in the wind-tunnel studies by Kastner-Klein et al (2000a, b). The dispersion of pollutants emitted from a ground-level line source in an idealized street canyon with $S/H = 1$ and $L/H = 10$ (Fig. 3) was studied. While in the wind-tunnel, the two line sources A and B (Fig. 1) were simultaneously operated during the TPT studies, only one line source in the centre of

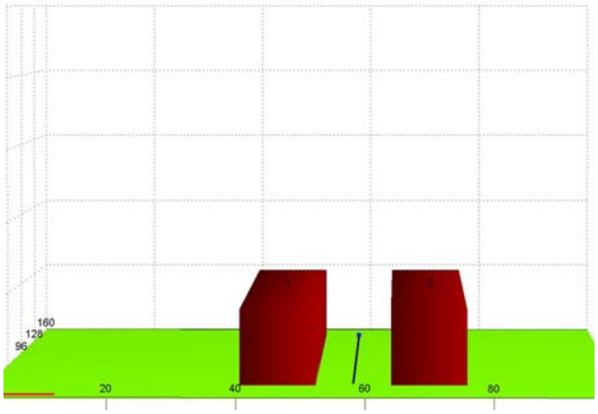


Figure 3: QUIC domain for the simulations of the wind-tunnel street canyon studies with *S/H* = 1 and *L/H* = 10

the street canyon was used in the QUIC simulations. This was done because QUIC currently has no option to use more than one line source in the domain. However, due to the enhanced, traffic-related horizontal mixing, this difference in the set-up should not have a significant impact on the results. The building dimensions and positions are given in Tab. 1.

For the QUIC-URB flow simulations, a power-law wind profile with an exponent 0.23 was used. As reference height 48 meters (4H) was chosen, and for most of the studies the reference wind speed at 4H was equal to 7 m/s. As empirical street canyon scheme, the Exp-Par scheme discussed in Clark and Kastner-Klein (2004) was applied.

For the QUIC-Plume simulations, the particle release number was 500,000 with a total of 10 grams released continuously over 3600 seconds and averaged over 1800 seconds. Using these half-hour averages, vertical concentration profiles along the buildings walls were analyzed and compared to the wind-tunnel data. Since initial tests have shown that the QUIC-PLUME non-local mixing scheme resulted in much better model performance than the local mixing scheme all simulations were done with the option non-local mixing.

To match the simulated traffic conditions in the wind tunnel, the drag coefficient, C_D, was set to 0.4 and the frontal vehicle area, A, was estimated as 3 m^2 which leads to an average vehicle length scale of $h = \sqrt{A} = 1.73m$. These values can be considered to resemble conditions with mostly passenger cars and a 10% rate of heavy traffic. The value of the dimensionless proportionality constant, c_t, has been shown to vary from values of 0.007 to 1.00 depending on whether it is evaluated using wind-tunnel flow data or full-scale concentration measurements (Di Sabatino et. al., 2003 and Kastner-Klein et. al., 2003). For our implementation, the value of c_t will also depend on how the street canyon region, S_c, in which TPT is of importance, is specified. Di Sabatino et. al., 2003 discuss different options for choosing S_c but do not provide particular recommendations for its value. In a first series of tests, appropriate values for the dimensionless proportionality constant c_t and the street canyon region, S_c, have thus been identified.

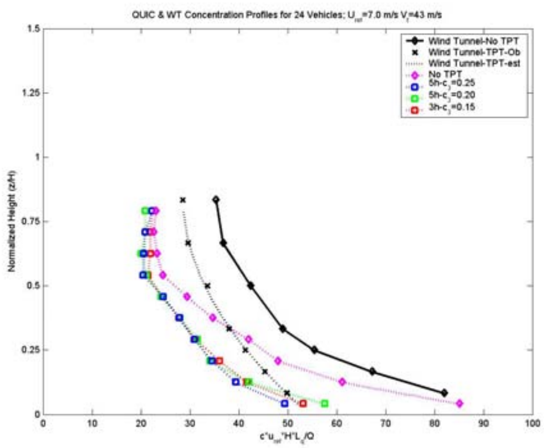
For this portion of the studies, the reference wind speed was set to 7.0 m/s and the vehicle speeds and traffic densities were varied. For each parameter setting, six simulations were conducted. Three of these simulations were for 12 cars (n=0.1 m^{-1}) and the other three were for 24 cars (n=0.2 m^{-1}). For the vehicle velocities the three values 30, 43 and 61 km/h were studied. It was decided to apply the TPT parameterizations over the whole widths *S* of the street, but the vertical extent of the traffic layer was varied along with the value of the TPT coefficient $c_{t.}$ In a number of extensive tests, the range of values was narrowed down to the following settings: Two values, 3*h* and 5*h* were considered for the depth of the traffic layer and three values, 0.15, 0.20, and 0.25, for the coefficient c_t resulted in realistic concentration predictions. These values for c_t correspond to the values applied in the lowest grid cell. The coefficient then decreases linearly with height and is zero at the top of the TPT region (i.e. at 3*h* or 5*h*).

Fig. 5 shows a comparison of the QUIC and wind-tunnel concentration profiles along the leeward canyon wall, for two exemplarily chosen cases. In can be clearly seen, that independent of the particular settings, in the lower part of the canyon the TPT simulations agree well with the corresponding wind-tunnel data. Differences can be noted in the upper part of the canyon with lower values predicted by QUIC than the ones observed in the wind-tunnel. In this canyon region,

Table 1: Building dimensions and locations for the QUIC TPT simulations

Building Number	Building Type	Building Length	Building Width	Building Height	x_{fo}	y_{fo}	z_{fo}
1	Rectangle	12 m	120 m	12 m	40 m	80 m	0 m
2	Rectangle	12 m	120 m	12 m	64 m	80 m	0 m

a)



b)

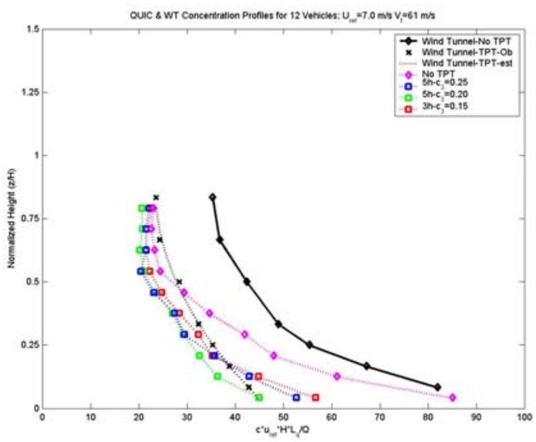


Figure 4: Comparison of QUIC and wind-tunnel concentration profiles along a leeward street-canyon wall for different TPT settings. Two cases with traffic density n=0.2 m^{-1} and vehicle speed v=43km/h (a), as well as traffic density n=0.1 m^{-1} and vehicle speed v=61km/h (b) were exemplarily chosen to illustrate the model sensitivity towards variations of c_t and depth of the TPT layer (simulated values indicated in legend).

differences can however already be noted in the no-TPT case and the model deficiencies are thus not related to the TPT parameterizations. As illustrated in Fig. 5, the concentration attenuation ratio due to TPT effects predicted by QUIC agrees very well with the results observed in the wind tunnel, particularly in the lower half of the canyon where TPT effects are most pronounced.

An overall comparison of the concentration attenuation ratios found in the initial test studies is shown in Fig. 6 in form of a scatter plot. The QUIC results are plotted against the wind-tunnel data. Since, the sampling heights in the wind tunnel did not fully agree with the grid cell heights of the QUIC runs, the wind-tunnel profiles were fitted with polynomials (lines shown in Fig. 5), and the wind-tunnel values at heights corresponding to the QUIC grid cells were then estimated using these fits. The results for the two cases (i) TPT coefficient $c_t=0.15$, depth of the traffic layer 3h and (ii) TPT coefficient $c_t=0.25$, depth of the traffic layer 5h are compared. The overall performance for these two cases is fairly similar, but option (ii) with the larger values for the coefficient c_t and depth of the traffic layer performs slightly better.

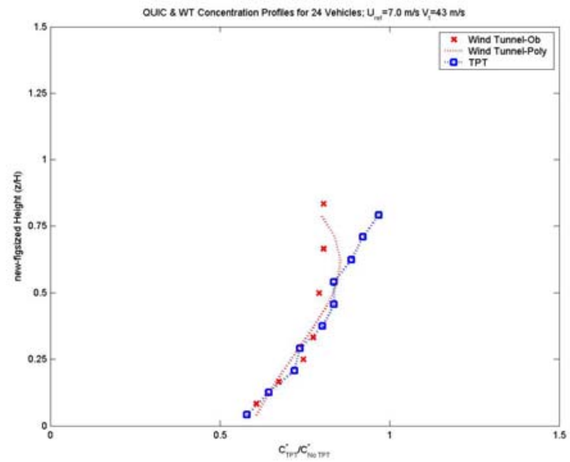


Figure 5: Comparison of concentration attenuation factor as predicted by QUIC (blue symbols) and observed in the wind tunnel (red symbols).

For option (ii), studies with different wind velocities were conducted as final tests. The values of the traffic and wind speeds were chosen such that the same ratios of *v/u* were realized by different combinations of *v* and *u*. As shown in Fig. 2 and discussed above, the wind tunnel studies had shown that the concentration attenuation is only a function of *v/u*, and not the individual values of *u* and *v*. The results obtained with QUIC (Fig. 7) show the same behavior and agree generally very well with the wind tunnel results.

The chosen approach to implement TPT into QUIC is thus rather promising in terms of improving the predictions of street-canyon pollution levels for situations with significant traffic motions. The studied parameter settings resulted in good agreement with the wind-tunnel data and it should be possible to apply these values in studies for similar building geometries and traffic conditions. A number of additional tests are currently performed to prove the practical applicability of the scheme for realistic, rather complex building and traffic arrangements.

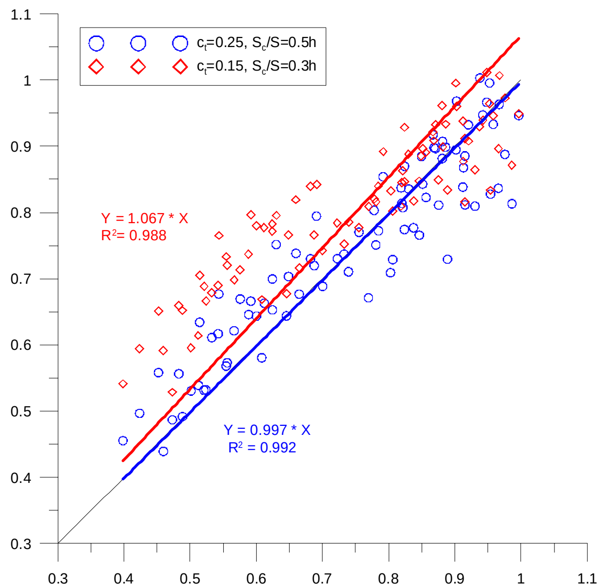


Figure 6: Scatter plot comparing the concentration attenuation c^*_{TPT}/c^*_{no-TPT} factors predicted by QUIC and measured in the wind-tunnel experiments.

5. CONCLUSIONS

The paper presents an evaluation of QUIC predictions against wind-tunnel concentration data sets for idealized street canyons with and without moving traffic. The implementation of a TPT scheme into QUIC is described and results from extensive quantitative evaluation studies against wind-tunnel data are discussed. These tests allowed identifying values for empirical parameters used in the TPT scheme. Overall, the QUIC predictions agree well with the wind-tunnel data. It must however be noted, that wind-tunnel flow and concentration data for the studied set-up have been used in previous and the current tests to improve QUIC parameterizations which certainly contributed to the good agreement. Further tests are thus necessary to independently evaluate the performance of QUIC and the TPT scheme against data for more complex urban settings.

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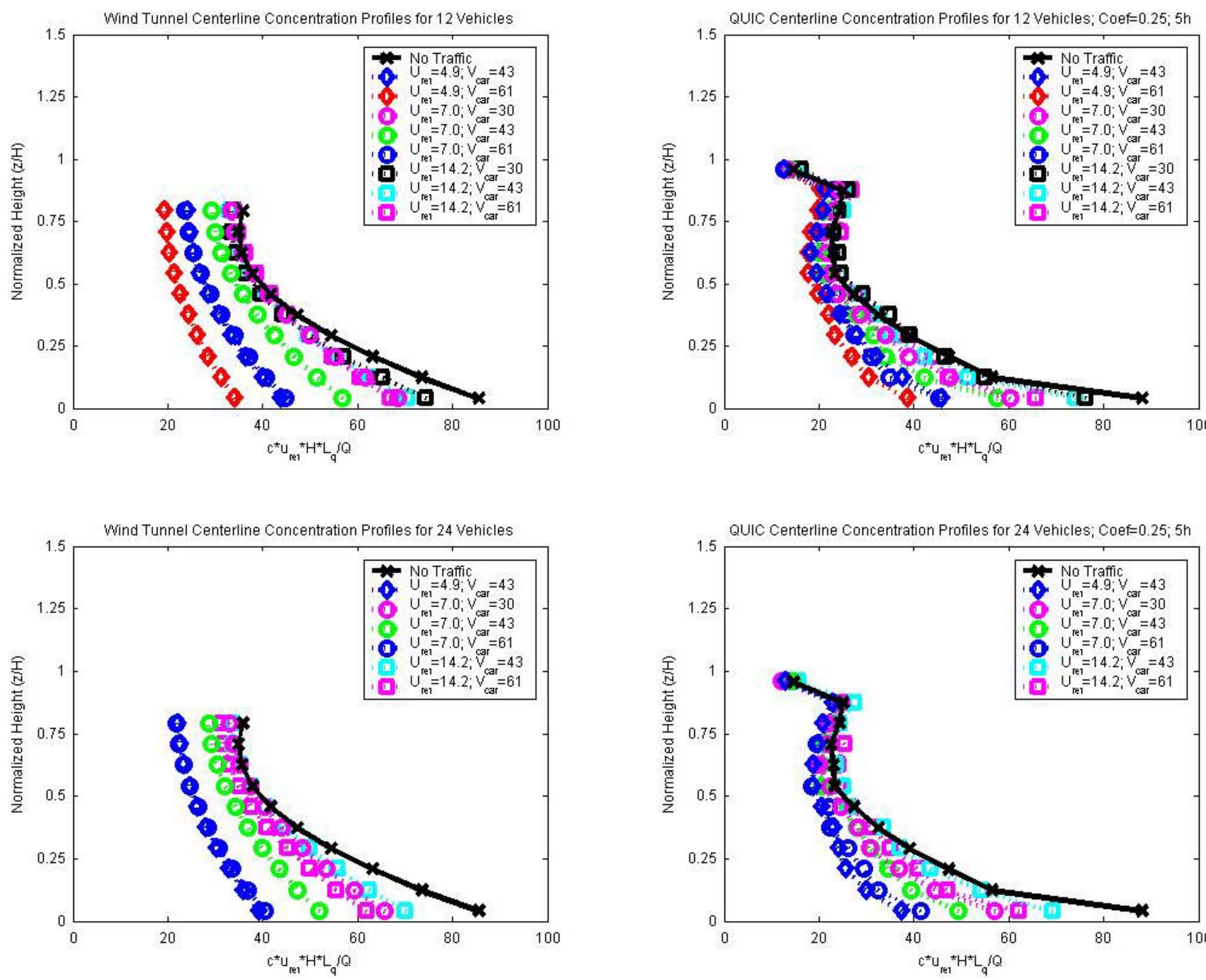

Figure 7: Comparison of QUIC (right) and wind-tunnel (left) concentration profiles along a leeward street-canyon wall for different wind to traffic speed ratios and traffic densities. The top plots correspond to cases with traffic density n=0.1 m^{-1} the bottom plots to cases with traffic density n=0.2 m^{-1}. The value of the coefficient c_t was 0.25 and the extent of the traffic zone 5h.