18th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 October 2017, Bologna, Italy

ASSESSMENT OF NO_2 CONCENTRATION LEVELS WITHIN A STREET CANYON AND A TUNNEL PORTAL MICRO ENVIRONMENT

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Abstract: Substantial breaches in NO_2 have been recorded at an air quality station located in a busy road in a German city. The daily traffic volume is about 26 000 vehicles a day. Critical is that traffic from the 540 m long city tunnel joins the road and that there are tall buildings located near the portal at both sides of the road. 9 additional measurements with passive samplers indicate that the air quality limit value is exceeded from the tunnel portal towards the next major intersection.

The aim of this study is to capture the relevant processes, i.e. emissions from the tunnel and open roads respectively, the flow and dispersion within the complex urban micro-environment (depressed portal level, sunken roads, street canyons) using a coupled flow and Lagrangian dispersion model at 2 m x 2 m x 2 m resolution. Further, the impact of portal air management and traffic reduction scenarios was computed to assist authorities in mitigation and compliance with NO_2 annual mean (AM) air quality limits.

The dispersion of emissions from open roads and from tunnel portals was computed respectively. A Romberg type approach was used to compute NO_x to NO_2 conversion. The measurements were used for model evaluation and a good match was obtained for NO_2 AM. The NO_x/NO_2 concentration pattern revealed that the portal area is affected by the portal emissions about 60 m in driving direction. However, only a small kerbside area of about 30 m in driving direction is clearly affected by the portal emissions. At the air quality station at ~150 m distance from the portal, 75 % of the NOx concentrations can be already attributed to open roads and the rest is mainly attributable to urban background. A zero portal emissions scenario resulted in a strong localized NO_2 decrease (up to -25 µg/m³), whereas 65 % traffic reductions are required to fulfil the AM NO_2 air quality limit.

Key words: urban street canyon and tunnel portal micro environment dispersion modelling& limits?

INTRODUCTION & BACKGROUND

Kerbside NO_2 measurements were carried out along a road transection with 26 100 vehicles (as annual daily traffic volume, ADTV) and up to 5 storeys tall buildings (Figure 1). The EU air quality limit for the annual mean (AM) NO_2 was exceeded at all 9 monitoring locations. The share of HDV is only 2 %. The traffic from the city tunnel which is directed north south and traffic from a comparatively short underpass (65 m) merge and resurface at a three lane tunnel portal in this road. In addition to the (open road) emissions released within the street canyon, the tunnel and underpass accumulated (portal) emissions resurface as well. At the reference air quality station the air quality limit was exceeded by a factor of 1.5 and in the vicinity of the portal by up to a factor of 2.

A tunnel ventilation system is installed. However, so far its intended use is to control fire and smoke in case of an emergency. In this case fire and smoke related emissions can be vented through a tall stack in order to avoid extremely high near surface air pollutant concentrations. As the traffic is mainly unidirectional directed in the tunnel system, the accumulated tunnel vehicle emissions are usually vented by the vehicles momentum particularly towards the (south) east portal.

The measured NO_2 concentrations clearly show a general decrease from west to east (Figure 1). Alternative active ventilation may improve the air quality situation in the vicinity of the exit portals, particularly in the area where the monitoring took place.

AIMS

The aim of this study was firstly to assess whether dispersion and simplified (parametrised) NO to NO_2 conversion within these complex urban micro environment can be represented adequately using the Lagrangian particle model GRAL (Öttl, 2015) and several monitoring results for validation. Another aim was to assess the relative contributions from tunnel portal emissions and open sources and different tunnel ventilation conditions by source attribution modelling and to study the impact of tunnel ventilation scenarios in order to lower the air pollution burden in the vicinity of the portal. Finally, measures were evaluated, so that breaches of the AM NO_2 can be prevented in the area analysed (Figure 2).

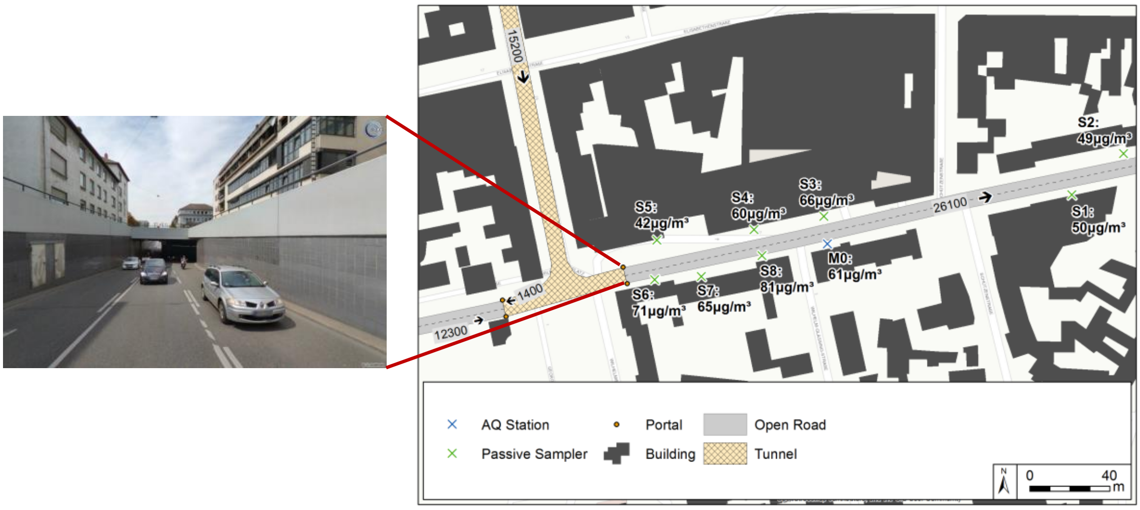

Figure 1. Tunnel exit portal and studied road transect with 26 100 ADTV and monitored AM NO_2 concentrations.

METHODOLOGY

In this study, a chain of deterministic computer models and appropriate input data was used to compute traffic related NO_x emissions and air pollutant dispersion.

Traffic model results containing traffic densities for light vehicles and heavy-duty vehicles (HDV), as well as average speeds were used as an input to compute traffic related air pollutant emissions. In addition, information about the frequencies and extent of traffic jams was used to assess the level of service (LOS). The vehicle emission model HBEFA 3.2 (2014), which contains German vehicle registration data, was used to compute traffic related air pollutant emissions for the open road line sources as well as tunnel and underpass related road sections. The share of diesel light vehicles is 34 %.

In order to compute dispersion of NO_x, the GRAMM (Graz Mesoscale Model) and GRAL (Graz Lagrangian Model) models were used (Uhrner et al., 2014). Meteorological data from a station located in a nearby urban park, see Figure 2, were analysed and classified into different prevailing flow conditions (wind speed classes, 10° wind sectors and 7 stability classes (Venkatram, 1996). The pre-calculated larger domain and comparatively coarse GRAMM flow fields (100 m x 100 m) were used as a first guess and refined by the GRAL inherent flow solver (Öttl, 2015) in the vicinity of buildings. Finally, dispersion computations were carried out for a selected area using a very fine resolution (2 m x 2 m x 2 m) to compute complex flow and dispersion in the vicinity of buildings and the tunnel depression. AM NO_x concentrations were modelled, NO_x to NO_2 conversion was computed using a Romberg type empirical conversion formula (see e.g. Retny et al, 2016). A constant NO_x background value was used to account for NO_x transported through the system boundaries of the modelling domain as well as neglected NO_x sources. Finally, air quality data from the station located in a nearby urban park (Figure 2) was used to adjust the background value. The traffic related data used to compute traffic emissions, 3-D building data, meteorological and air quality data were provided by local and federal state authorities.

The GRAL model can account for the dispersion processes in the vicinity of the tunnel portals. As outlined in Öttl et al. (2002), the dispersion of pollutants from tunnel portals is strongly influenced by the excess temperature of the tunnel air, the interaction of the tunnel exit jet carrying the tunnel integrated emission burden and ambient flow and dispersion conditions. The computation is based on the tunnel jets exit velocity U_0, excess temperature ΔT and an empirical stiffness parameter in order to describe the impact of ambient conditions on the persistence and evolution i.e. widening and bending of the tunnel exit jet. Details about the tunnel module and its validation are found in Öttl et al. (2003), Öttl et al. (2004), Uhrner and Reifeltshammer (2012). Over the years the tunnel module has been refined (Öttl, 2017).

Tunnel jet exit velocity measurements were not available, hence the exit velocity U_0 was computed according to the Piston effect, see equation (1).

$$\left(1+\zeta+\lambda\frac{L}{D}\right)U_0^2=\frac{A_m\, n}{A_t}\left(V_t-U_0\right)^2 \qquad (1)$$

ζ is the tunnel entrance/exit loss coefficient (2.0), λ is the tunnel wall friction loss coefficient (0.02), L is the tunnel length (500 m), D is the hydraulic diameter of the cross-section (6.6 m), A_t the tunnel cross sectional area, V_t the traffic speed within the tunnel, n the number of vehicles in the tunnel and A_m the equivalent resistance area of the vehicles (m^2). In total, 26 100 vehicles exit the (southern) east portal, 12 300 vehicles result from the underpass, and 15 200 pass the city tunnel. 1 400 vehicles exit the city tunnel at the southern west portal. The 3 lanes of the W-Portal were modelled as two separate portals, i.e. for the city tunnel (2 lanes) and the underpass (1 lane). The share of HDV is small (2 %) due to a transit ban for these vehicles.

Night time traffic volumes are low and daytime traffic volumes are high, see Figure 3. Hence according to equation (1), U_0 is low at night time ~1 m/s and on average at daytime ~3 m/s. In order to compute realistic ventilation scenarios and to assign different LOS parameters in the emission computations (at day/night time), line and portal source emissions were attributed to four different source groups (open roads and tunnel at 6:00 to 23:00 and 23:00 to 6:00 respectively).

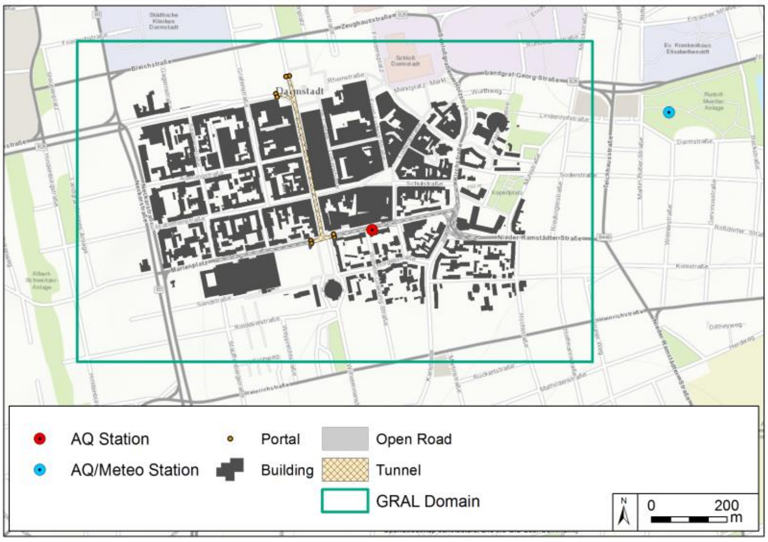

Figure 2. Modelling approach and domain, the location of the station used for the meteorological model forcing and NO_x/NO_2 background is indicated by the blue circle.

RESULTS

The computed NO_x emissions were allocated spatially along the respective road sections. Sections with different road gradients were split and gradient dependent emissions computed. Maximum emissions were found at the steep ramp at the southern west portal. Tunnel emissions were summed up over the tunnel sections with different road gradients and set as portal area sources (0.222 kg/h at day time, 0.021 kg/h at night time).

Figure 3 shows the processed wind monitoring data for a nearby station located in a park. These measurements were used for the model forcing as they describe the prevailing urban wind conditions in close vicinity to the area of interest. Winds are predominantly west and east. Generally, the monitored winds are weak, with the annual mean wind speed at 1.1 m/s. For each of the simulated flow situations a dispersion computation was carried out and, finally, the results were weighted with the frequency of occurrence (each hour in 2012) to obtain an *AM* NO_x concentration for each counting grid point. The total *AM NOx* concentrations were converted to *AM* N_2 by using the following conversion formula:

$$AM\ NO_2=\frac{29\times(AM\ NO_x+bg\ NO_x)}{\left(35\frac{\mu g}{m^3}+AM\ NO_x+bg\ AM\ NO_x\right)}+0.217\times(AM\ NO_x+bg\ NO_x) \qquad (2)$$

With *AM NO$_x$* as the computed grid NO_x value in µg/m³, the background *bg AM NO$_x$* was specified to 39.5 µg/m³. The factors 29, 35 (µg/m³) and 0.217 are fitting parameters. Figure 4 shows the result for the *AM NO$_2$* for the investigation area. The locations and monitored values are indicated as well. The official air quality monitoring station *M0* was used to calibrate the passive sampler measurements (S1 to S8). The results of the comparison monitoring results versus simulations are shown as well in Figure 4. Overall, a good agreement was obtained (R^2 = 0.87) and a slope of 1. Highest values are simulated directly at the portal and near the two monitors *S4* and *S8*. The kerbside concentration levels remain very high from the portal until the next (small) road crossing (Figure 4).

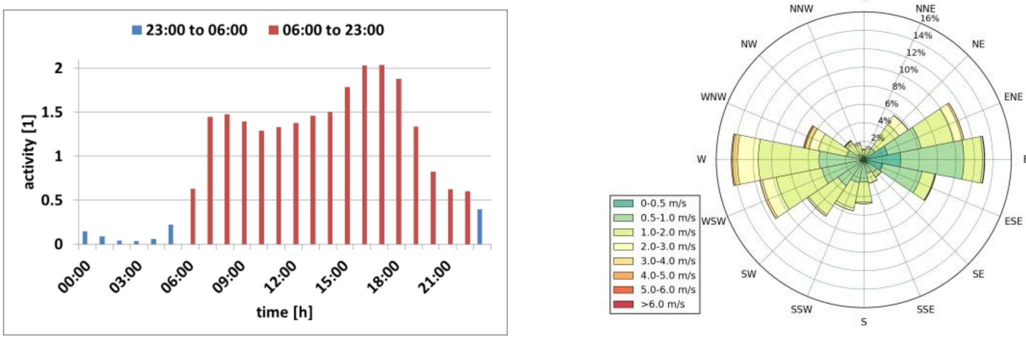

Figure 3. Model input data. Diurnal traffic activity cycle (left) and classified meteorological data (right).

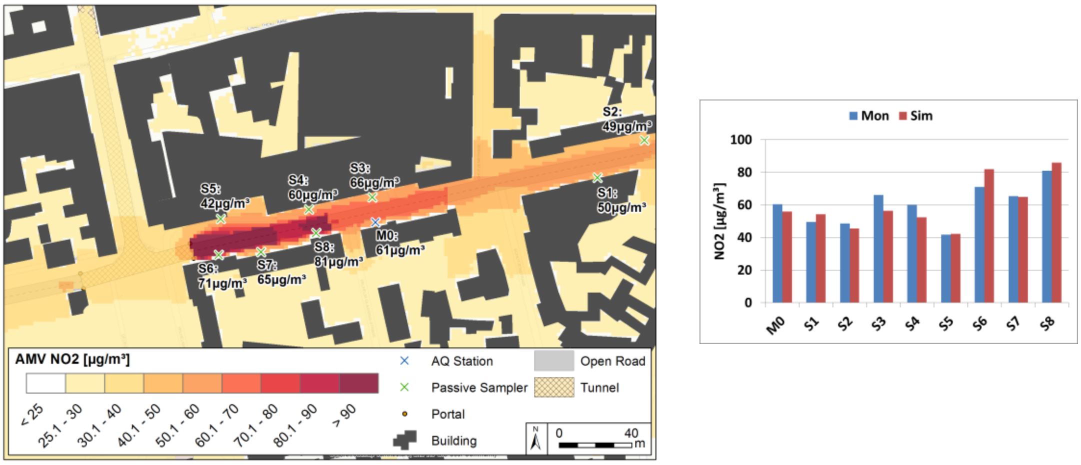

Figure 4. Simulated AM NO2 concentration and location and results of air quality monitoring (left) and comparison of monitored versus simulated AM NO_2 (right).

Next, we analysed the impact of a portal zero emission scenario which can be achieved by ventilating either against the traffic flow and release through the northern portals or by venting the traffic emissions using the available stack. As there is low traffic activity between 23:00 to 6:00 and tunnel ventilation will result in high power costs and may cause enlarged noise levels the scenario was considered as useful only at daytime (6:00 to 23:00). Figure 5 shows that close to the portal at kerbside locations large reductions of up to -25 µg/m³ AM NO_2 result. However, the noticeable extent of portal plume emissions results only within the first 60 m from the portal. At the official air quality monitoring station *M0* the reduction is -0.9 µg/m³. Only about 2 % of the simulated AM NO_2 at M0 is attributable to tunnel portal emissions and about 75% is attributable to open roads emissions. The remainder (23%) is due to the background concentration level. The portal region is dominated within the first 30 m by the impact of tunnel emissions on total *AM NO2*. Thereafter the concentration pattern is dominated by open roads (line sources). However, given the low wind speed conditions in the study area, traffic induced momentum may push significantly polluted air from the portal towards the official AQ station (*M0*). This may lead to higher portal emission contributions than represented by the model simulations. Consequently, higher mitigation may be obtained in case portal emissions can be reduced as in the scenario discussed. Another major uncertainty is the applicability of the Romberg approach within street canyons and close vicinity of tunnel portals. The shadowing within the street canyon may impact on NO to NO_2 conversion and extremely high NO concentrations as found near the portal may lead to complete O_3 titration during night time or winter time inhibiting further NO to NO_2 conversion. Consequently, NO_2 is overestimated using the Romberg approach.

Finally, due to the strong impact of open road sources a scenario with 50 % overall traffic reduction was assessed as well (Figure 5). The background concentration was kept constant. However, even 50 % traffic reductions are not sufficient enough to fulfil current air quality standards.

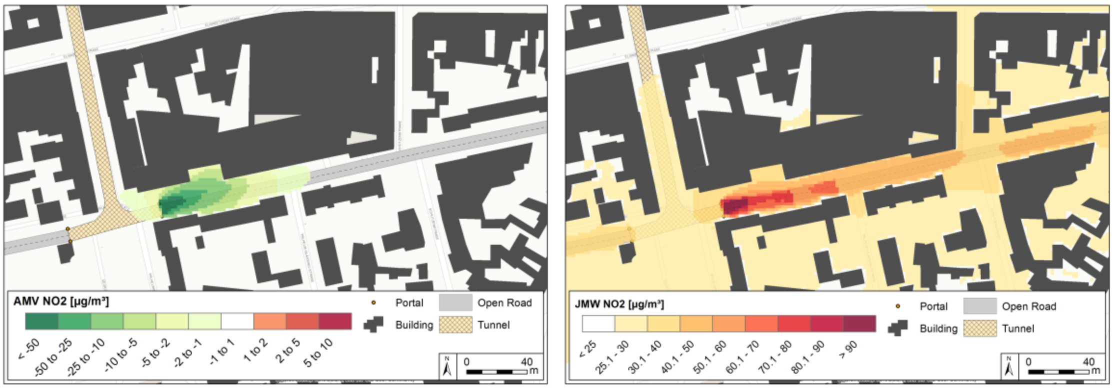

Figure 5. Difference AM NO_2 portal air management mitigation scenario – base (left). AM NO2 for 50 % traffic reduction scenario (right).

CONCLUSIONS

Micro-scale simulations were carried out using the Lagrangian particle model GRAL to represent complex dispersion processes within a street canyon and tunnel portals. NO_x/NO_2 source attribution was applied for open roads and portal emissions respectively. Within 30 m near the portal, the tunnel related NO_x/NO_2 pattern dominates versus the open roads one. The other road sections are dominated by emissions from open roads. Two scenarios were evaluated, a zero portal emission scenario and a 50 % traffic reduction scenario. In both scenarios large reductions in AM NO_2 were obtained. However they are still not sufficient to fulfil current air quality standards. In total, a local 65 % light vehicles traffic reduction would be required to fulfil current AM NO_2 limits. Potential diesel car access restrictions would affect fewer vehicles as the share of diesel light vehicles the main NO_x emitter is 34 %.

The simulations undertaken were challenging with respect to NO_x emission modelling, the representation of flow/turbulence in street canyons and near the tunnel portal as well as the practical applicability of a Romberg type conversion formula.

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