# A CASE STUDY: DISPERSION OF NITROGEN OXIDES IN THE VICINTY OF THE PLABUTSCH TUNNEL PORTAL IN GRAZ

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**Abstract**: High resolution $NO_2$ concentration maps have been computed for the city of Graz using the Lagrangian particle model GRAL (Graz Lagrangian Model) in the frame of the time extension application for $NO_2$. The model suggests non-compliance with the EU air quality standard (annual mean of 40 µg/m³) in some city areas. Especially in the vicinity of the southern tunnel portal of the Plabutsch tunnel (10 km length) yearly mean $NO_2$ concentrations reach values far beyond the threshold. To verify these simulations, air quality monitoring has been carried out 40 m away from the portal for several months. Subsequently this data has been used to get some more insight in the special dispersion conditions found near the portal, and to conduct sensitivity analysis of model results in dependence on exit velocity of the tunnel jet. In dispersion applications for regulatory purposes this parameter is usually not available on an hourly basis, but is critical in simulations, especially for high percentiles of concentration distributions. In contrast to sources like roads, peak concentrations near the Plabutsch tunnel portal were found for wind speeds around 3 m/s and not - as usual - in low wind speed conditions. Such behaviour is also suggested by GRAL, which uses a specific algorithm to compute dispersion from tunnel portals described in Oettl et al. (2002).

***Key words:*** *GRAL, Dispersion, Tunnel portal, Lagrangian Dispsersion Model, Nitrogen Dioxide*

## INTRODUCTION

Due to non-compliance with the European Air Quality standard of 40 µg $m^{-3}$ at the monitoring station Don-Bosco in the Styrian capital Graz (Austria), the government applied for time extension in 2011. A comprehensive modelling study was undertaken in 2010 (Oettl and Pongratz, 2010) in order to assess the main contributors, to discuss possible reduction scenarios and to provide an estimate of the total area above the limit value. Very high yearly average $NO_2$ concentrations were suggested by GRAL (Graz Lagrangian Model) in the vicinity of the southern tunnel portal of the Plabutsch road tunnel (10 km length). Thus, the local authority of Graz asked for further investigations in that area. Between July and November 2011 a mobile air quality monitoring station (AQM) was placed approximately 40 m southeast of the tunnel portal (Figure 1).

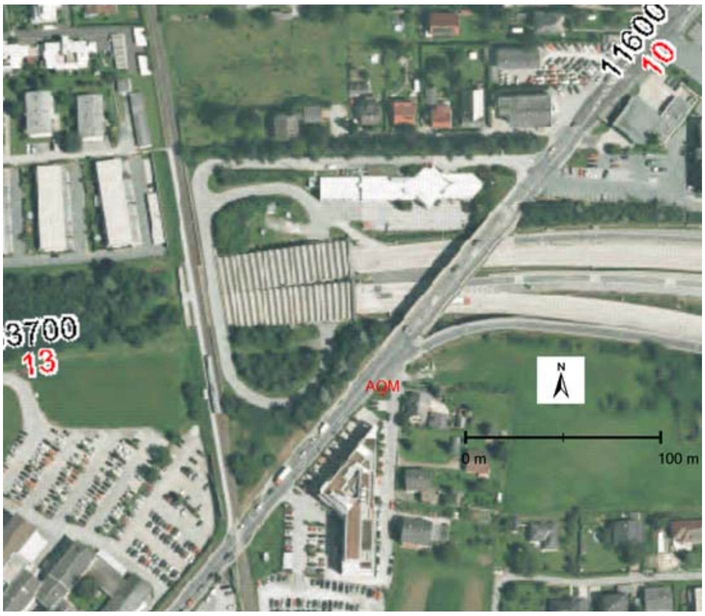


Figure 1. Location of the southern tunnel portal of the Plabutsch tunnel and the air quality monitoring station (AQM)

By comparing observed $NO_x$ and $NO_2$ concentrations close to the portal with those from other fixed monitoring stations in Graz, annual mean $NO_2$ concentrations for 2006 and 2010 were projected as 62 µg $m^{-3}$ and 54 µg $m^{-3}$, which confirmed the modelled concentration based on the year 2006 of 65 µg $m^{-3}$ (Oettl and Pongratz, 2010).

In this study the focus is on the specific dispersion conditions from tunnel portals taking $NO_x$ observations close to the southern portal of the Plabutsch tunnel as an example. To do so, only wind directions between 300 and

300 deg. were considered, to ensure that the observed concentrations were mainly influenced by tunnel emissions. All in all about 1,000 different dispersion situations were available for evaluating model performance.

## METHODS

As outlined in Oettl et al. (2002), the dispersion of pollutants from tunnel portals is strongly influenced by the excess temperature of the tunnel air, the exit velocity of the tunnel jet, and the ambient wind direction fluctuations. Simulations with a microscale non-hydrostatic prognostic Eulerian model showed (Oettl et al., 2002) that the plume out of a tunnel more or less quickly changes its direction towards the ambient wind direction. Especially in low wind speed conditions ambient wind directions fluctuate over a wide range due to meandering (e.g. Hanna 1983). As a result, a tunnel jet will also be spreaded over a large area in such conditions, effectively enhancing the dispersion from an Eulerian point of view. GRAL provides a specific tunnel module, which takes into account these effects. It is evaluated against five different tracer experiments taken in Austria and Japan (Oettl et al. 2002, Oettl et al. 2003, Oettl et al. 2004). Over the years the tunnel module has been refined and partly simplified, therefore it is outlined in the following (see also Oettl, 2012):

The horizontal position of the tunnel jet is modelled by simulating the along and cross wind component of the jet, which depend on the ambient wind:

$$\frac{dU_p}{dt} = -K\frac{\partial^2 U_p}{\partial y^2} \tag{1}$$

$$K = 0.3 \cdot t \tag{2}$$

$$\frac{dU_{nS}}{dt} = \frac{1}{2}\alpha U_{nA}^2 \tag{3}$$

$$\alpha = 1.0 \tag{4}$$

| | |
|---|---|
| $U_p$ : | Along wind component of the tunnel jet [m s$^{-1}$] |
| $K$ : | Turbulent exchange coefficient [m² s$^{-1}$] |
| $t$ : | Dispersion time [s] |
| $U_{nS}$ : | Cross wind component of the tunnel jet [m s$^{-1}$] |
| $U_{nA}$ : | Ambient wind component perpendicular to the tunnel jet [m s$^{-1}$] |

It is straightforward to account for ambient wind fluctuations, because the wind direction and –speed can be taken different for each released particle according to observed or parameterized standard deviations of the horizontal wind component fluctuations. A Gaussian distribution is assumed in GRAL for the probability density function of the horizontal wind components. As soon as the jet stream slows down, the cross-sectional area has to increase in order to fulfill mass conservation. This is accounted for by increasing the width of the jet stream direct proportional to the decrease of the velocity along the x-axis of the centre-line. The vertical extension of the jet stream is not changed, because the mathematical treatment of the buoyancy (see below) does not allow for an additional vertical velocity to be incorporated in the model formulation. A similar treatment was performed as soon as the jet stream changes its orientation, where particles on the inner arc move slower compared to particles at the edging arc, to keep the mass balance fulfilled. Buoyancy effects of the tunnel jet are taken into account by modifying dissipation rates within the tunnel jet dependent on the temperature difference between tunnel air and ambient air.

$$dW = -\frac{W}{T_W}dt + \varepsilon_W^{0.5} d\omega_W \quad , \tag{5}$$

The dissipation rate is determined according to:

$$\varepsilon_W = 0.06 \cdot \frac{U_p^2}{T_W} \tag{6}$$

$$\varepsilon_W = Max\left(\frac{\varepsilon_W}{10 \cdot Max\left(0.1, \Delta T^2\right)}, \varepsilon_W \cdot 0.01\right) \quad for\ \ \Delta T < 0,$$

$$\varepsilon_W = \varepsilon_W \cdot \sqrt{1 + \Delta T \cdot 0.5} \quad for\ \ \Delta T \geq 0 \tag{7}$$

$W$ is the vertical speed of a particle, $T_W$ is the Lagrangian time-scale for the vertical motion, $\varepsilon_W$ is the dissipation rate, $\omega_W$ are random numbers with zero mean and a variance equal *dt*, $\Delta T$ is the temperature difference between the jet stream at the portal and the ambient temperature. The Lagrangian time-scale for velocity is assumed to increase with time (Hernan and Jimenez, 1982). Note that $U_p$ decreases usually with time:

$$T_W = 2 \cdot \frac{z}{U_p} \tag{8}$$

As soon as the orientation of the tunnel jet is very close to the ambient wind direction, $\varepsilon_W$ is set equal to $\varepsilon_A$. In contrast to the dispersion from e.g. point sources, dispersion from tunnel portals differs as maximum concentrations do not generally increase with decreasing wind speed, but, according to simulations with GRAL, show a maximum for medium wind speeds (Figure 2).

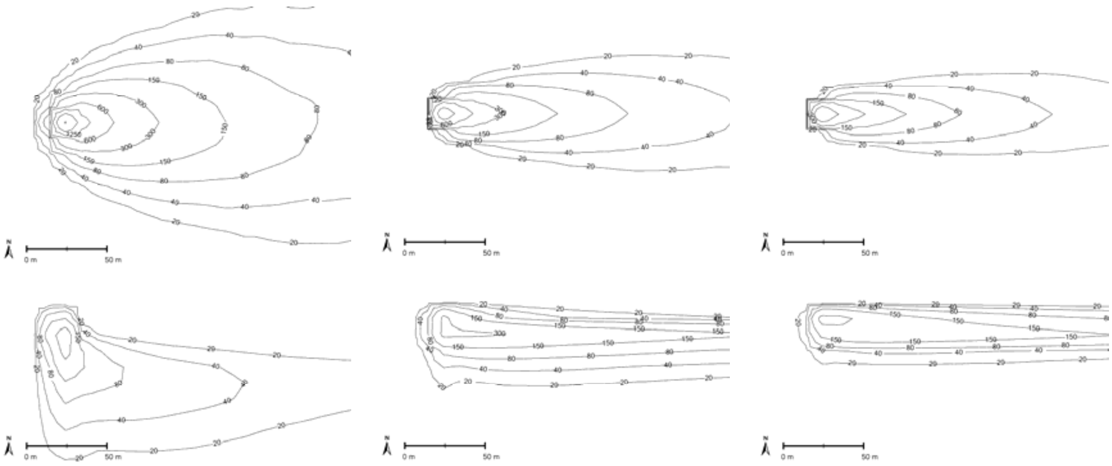

Figure 2. Comparison of computed concentrations from a point source near ground (top) and a tunnel portal (bottom) for three different wind speeds (left: 1 m s$^{-1}$; middle: 3 m s$^{-1}$; right: 5 m s$^{-1}$)

Traffic emissions were computed with the Network Emission Model NEMO 2.0 developed by the Graz University of Technology (Rexeis and Hausberger, 2005). NEMO requires annual average daily traffic, share of HDV, mean driving speed, and a characterisation of traffic situation. On average 16,272 passenger cars and 2,496 heavy duty vehicles drove out of the southern portal of the Plabutsch tunnel per day, causing about 161 kg d$^{-1}$ $NO_x$ emissions. In the surroundings the air quality monitoring station Graz-West (urban background station), which is not directly influenced by traffic emissions, was selected to provide a rough estimate of background concentrations. Observed $NO_x$ concentrations at the AQM close to the tunnel portal and at Graz-West were 227 µg m$^{-3}$ and 33 µg m$^{-3}$, respectively.

Wind speed and –direction observed at the AQM near the tunnel portal at 10 m above ground level was used as input for GRAL. In addition stability classes computed according to the SRDT-method described in US-EPA (2000), but slightly adapted to Austrian conditions (Oettl, 2012), were necessary to run the model. Horizontal resolution was set to 5 m, and buildings were taken into account with a microscale prognostic wind field model implemented in GRAL (Oettl, 2012). The model domain extended in the east-west direction 1,000 m and 700 m in the north-south.

**RESULTS**

First, the period with the highest observed $NO_2$ concentrations is being discussed (Figure 3). Here, it is interesting to note that the peak concentrations close to the portal (red curve) occurred at wind speeds around 2-3 m s$^{-1}$ contrasting observed concentrations at the traffic AQM station Graz-Don Bosco (brown curve) taken here for comparison purposes. This is in line with the outlined hypotheses about the dispersion of pollutants from tunnel portals implemented in GRAL (Figure 2). Though, it simply could also have been resulted from a traffic jam in the vicinity of the monitoring station. As hourly traffic data were available neither for all nearby streets nor for the highway in and out of the Plabutsch tunnel, there is no way to proof this further.

Second, $NO_x$ concentrations were computed taking not only into account portal emissions, but also all other nearby roads. Note again, that hourly/daily traffic data wasn't available, except for the highway out of the Plabutsch tunnel, where daily figures were provided by the Austrian highway company (ASFINAG). In applications for regulatory purposes, GRAL is typically provided with an estimate about the average exit velocity of the tunnel jet, while the excess temperature of the tunnel jet is usually set zero. It will be referred to as standard scenario from here on. In addition, based on daily traffic figures in combination with assumed typical daily variations of traffic, hourly traffic volumes and exit velocities of the tunnel jet were estimated using the well known traffic piston equation (“Scenario 2” from here on):

$$\left(1+\zeta_e+\lambda\frac{L}{D}\right)U_0^2=\frac{A_m\,n}{A_t}\left(V_t-U_0\right)^2 \tag{9}$$

| | |
|---|---|
| $\zeta_e$ | tunnel entrance loss coefficient (~ 0.2) |
| $\lambda$ | tunnel wall friction loss coefficient (0.017) |
| $L$ | tunnel length (10,000 m) |
| $D$ | hydraulic diameter of the cross-section (= $4\cdot{A_t}/{C}$ = 6.7 m) |
| $C$ | circumference of the cross section (m) |
| $A_t$ | tunnel cross sectional area (49 $m^2$) |
| $V_t$ | traffic speed in the tunnel (27.8 $m\ s^{-1}$) |
| $U_0$ | exit velocity ($m\ s^{-1}$) |
| $n$ | number of vehicles in the tunnel, and |
| $A_m$ | equivalent resistance area of the vehicles ($m^2$) |

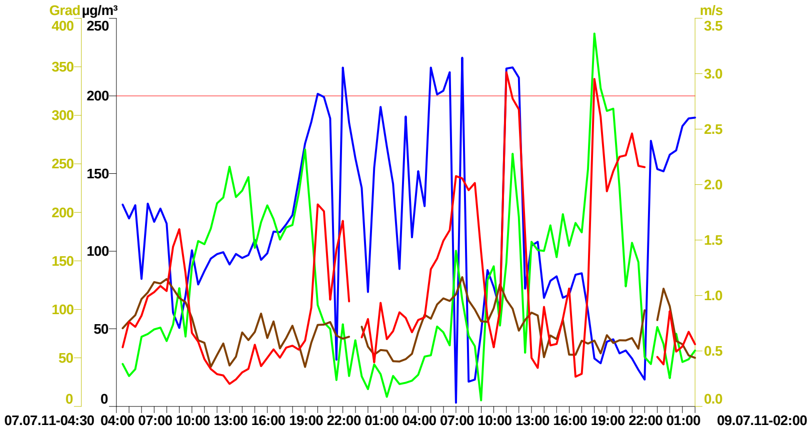


Figure 3. Observed $NO_2$ concentrations (red curve) near the Plabutsch tunnel (south portal) and at a curb site in Graz (brown curve); wind speed (green curve) and –direction (blue curve)

Using a constant exit velocity (standard scenario) leads to an overestimation of $NO_x$ concentrations during daytime, also peak concentrations are overestimated by a factor of two. Applying hourly changing exit velocities (Scenario 2) improves both the average diurnal and peak concentrations (Figure 4).

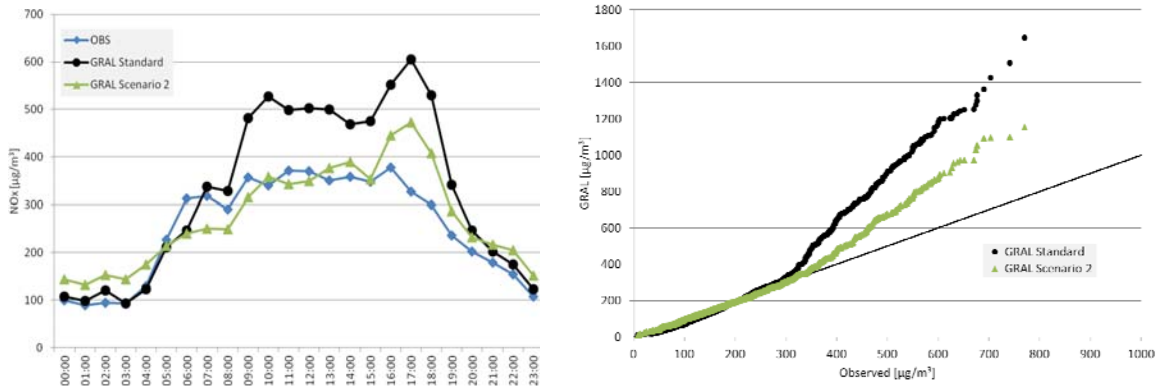


Figure 4. Comparison of observed and modelled average diurnal $NO_x$ concentrations (left); Quantile-quantile plot (right)

Table 1 lists some common statistical measures for both scenarios. Chang und Hanna (2004) suggested using an upper bound for the NMSE of 4.0, and a maximum fractional bias of +/-0.3 as criteria to define acceptable model performance. Although GRAL is well within those bounds in both cases, the correlation is rather low, which might be attributed to unknown hourly traffic data as well as exit velocities (there were just roughly estimated), and exit temperatures. Further, concentration gradients are typically found to be extremely high close to portals making a dispersion model prone to large errors, whenever the modelled plume position does not match the real one exactly. Tracer experiments gave evidence that concentrations sometimes vary up to a factor of ten over a distance of only 50 m (Oettl et al., 2002). Simulated average concentrations in this study (Figure 5) show also very strong gradients around the AQM station, such that the correct observed concentration value can be found just within a few metres distance to the AQM station.

Table 1. Statistical measures for the two different scenarios

| | Mean [µg m$^{-3}$] | Max [µg m$^{-3}$] | Fractional bias | Normalized mean square error | Correlation |
|---|---|---|---|---|---|
| **Observed** | 227 | 770 | | | |
| **Standard** | 295 | 1645 | -0.26 | 0.93 | 0.63 |
| **Scenario 2** | 257 | 1154 | -0.12 | 0.61 | 0.54 |

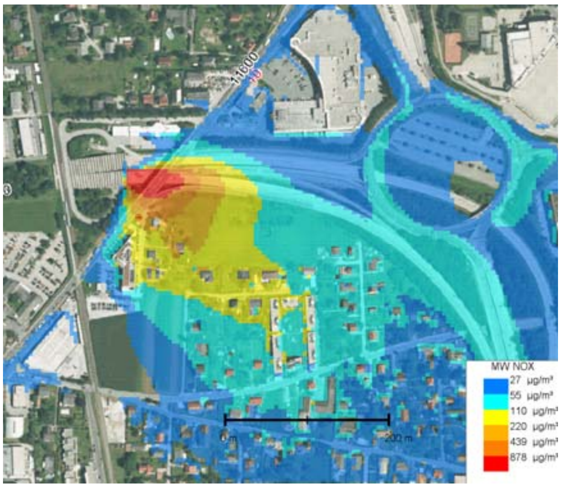


Figure 5. Modelled average $NO_x$ concentrations in the vicinity of the southern portal of the Plabutsch tunnel (Scenario 2)

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