Environmental Aspects of Tunnel Ventilation

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ABSTRACT: A comprehensive methodology for computing the dispersion of air pollutants and immission levels for road tunnels is described. It is based on the combined use of a so-called Gaussian model and a three-dimensional simulation package. The combined model allows for a detailed analysis of very complex configurations, in particular within urban environments. A series of simulations carried out for Munich's ring road ("Mittlerer Ring") are used to illustrate the methodology and the results.

1. INTRODUCTION AND SCOPE

Road tunnels are frequently built in order to reduce the environmental impact of traffic, in particular in urban environments. The obvious advantages of the underground solution, in terms among others of noise and air pollution, are usually prevalent. Nevertheless, a locally increased impact close to the tunnel portals has to be taken into account. In case of a longitudinal or semi-transversal ventilation all the pollutants emitted in the tunnel are released into the environment through the portals, and seriously affect the environment within a radius of a few hundreds meters. The immission level in the portal area can therefore increase very significantly. This is easily illustrated by an example. For a tunnel of 4 km length the environmental impact in the portal areas is increased roughly by an order of magnitude with respect to an open road with the same traffic volume and characteristics.

The tunnel ventilation design can depend significantly on the immission levels in the vicinity of the portals. This is particularly true in sensitive environments, such as urban areas, where the efflux of polluted tunnel air has sometimes to be limited by means of expensive extraction systems and chimneys, or the adoption of more complex ventilation systems, such as transverse ventilations. Experience with many projects in several countries showed that it is essential to conduct a careful analysis of the environmental aspects already in the early phases of tunnel design, in order to increase the acceptance of the project and minimize the risk of delays.

Several approaches and methodologies for the analysis of the immission levels in the neighborhood of tunnel portals are available. Most of them are however seriously deficient with respect to the problem at hand, which is characterized by the following key requirements:

- ♦ Accurate modeling of all relevant pollutant sources, in particular of the tunnel exhaust.
- ♦ Analysis of a large area for identifying the “hot spots”.
- ♦ Refined analysis of all critical zones. In urban areas this can require a very detailed representation of the portal area.
- ♦ Account for all relevant conditions, in particular in terms of traffic and meteorology, in order to allow for a correct statistical analysis of the results.

A comprehensive methodology for the simulation of the dispersion of the air pollutants and computation of the immission levels is described in some detail. It is based on the combined use of a so-called Gaussian model and a three-dimensional simulation package. The former allows for a reasonably rapid and accurate estimate of large-scale effects and the identification of critical zones, while the three-dimensional approach yields a more detailed analysis of smaller domains. Consequently, large-scale effects as well as the particularities of the portal zones, such as buildings, noise-reduction barriers etc., can be taken into account with unsurpassed accuracy. The combined model allows for a detailed analysis of very complex configurations, in particular within urban environments.

The model was applied, after careful validation, for investigating the environmental impact of Munich’s new ring road (“Mittlerer Ring”). This project is used to illustrate the method and the results, as well as the implications on tunnel ventilation.

2. MAIN POLLUTANTS AND EVALUATION CRITERIA

National and international regulations and recommendations must be taken into account. Additional requirements are set for particular areas, for special protection of persons (e.g. health resorts) or nature. The wide spread of the different values makes a concise representation impossible. We will therefore summarize a few basic concepts.

Generally speaking the main air pollutants are (BUWAL 1997):

Pollutant	Main source
NOx (NO, NO_2)	Traffic
CO	Traffic
Ozone	Traffic, Industry
Particles, soot	Industry, Traffic
SO_2	Industry
Organic components (e.g. Benzol)	Industry
Heavy Metals	Industry

Table 1 Air pollutants and main sources.

The pollutants of primary interest for tunnel projects are:

- ♦ Nitrogen oxides NOx (NO and NO_2) – yearly averages and peak concentrations
- ♦ Soot or particles (total suspended and its small-size fraction, e.g. PM10) – yearly averages
- ♦ Benzol – yearly averages.

While its role is doubtless fundamental, Ozone is usually not taken into account. This secondary pollutant is generated through interaction between a number of precursors and sunlight. Its formation involves relatively long time scales and the main concentrations are usually not located in the portal neighborhood. A reliable prediction of its concentration is not yet possible.

Current regulations usually take into account both mean and peak concentrations. Common measures for the latter are the 95 or the 98-percentiles. These indicate values, which are, exceeded only 5% (about 438 hours yearly) respectively 2% of the time (about 175 hours yearly). The allowed immission levels are expressed in terms of total concentrations. This results from the superposition of a so-called background concentration with the additional load resulting form the tunnel portal.

3. POLLUTANT PROPAGATION AND COMPUTATION OF IMMISSION LEVELS

3.1. Approach

The analysis of the immission levels requires the following steps:

1. Modeling of all project-relevant pollution sources within the emission perimeter, in particular of the tunnel exhaust.
2. Calculation of the flowfield for all relevant meteorological conditions and wind directions.
3. Calculation of the pollutant dispersion for all relevant situations.
4. Statistical postprocessing for the determination of mean and peak immission levels.
5. Result analysis and recommendations.

Simplifications are possible, depending on the modeling level.

3.2. Pollution Sources

In order to assess the environmental impact of a given tunnel project, the most important information is the comparison between the pollution levels to be expected without and with the project, as well as a comparison between alternative solutions. The immission computation has to account for all project-relevant pollution sources. Other sources, which are not directly related to the project investigated, are taken globally into account as a background concentration. Households and industrial emissions, as well as the secondary road network, are accounted for in this global manner.

The most determinant parameters to be accounted for are traffic volume and composition and the specific emissions. Both aspects are critical and require a very careful evaluation, in particular because the values to be used are projections over a time horizonof the order of 5-10 years or more. While traffic volume tends to increase for most projects, the specific motor-vehicle emissions are rapidly diminishing. It is therefore essential to use the most up-to-date information available and revise projects as soon as new information becomes available. As an example, the recent revision of the emission data for Germany and Switzerland (UBA & BUWAL 1999) led to significant reductions of the expected immission levels over the time frame of interest. A new evaluation for several projects at different stages of planning allowed for substantial cost reductions.

3.3. Tunnel Portals

The correct modelization of the tunnel exhaust is obviously vital. Its intensity and variations with time can be estimated on the basis of the expected traffic conditions and ventilation operation. The tunnel exhaust behaves initially as a jet, whose behavior is dominated by the initial momentum and turbulence level. With increasing distance from the tunnel portals other effects become dominant, in particular the motion of the vehicles (in terms of turbulence generation and momentum exchange) and wind.

The available experimental evidence (e.g. Yoshizawa et al. 1994 and Vanderheyde 1994) suggests modeling the portal exhaust as a volumetric source, whose characteristics (height, width, length, intensity) depend on a number of parameters, among them traffic, wind and portal configuration. The correct modelization of the portal sources has a primary impact on the simulation results and should be handled with extreme care.

3.4. Pollutant Propagation

The theoretical background of pollution dispersion is exposed exhaustively by Fannelöp (1994), which develops the basic equations and engineering methods of investigation. Several levels of analysis could be adopted:

1. Empirical approaches.
2. Gaussian dispersion models.
3. Three-dimensional dispersion models.

Empirical approaches, such as MLuS (FSV 1992, 1996 and 2000), do not require a computation of the flowfield or pollutant propagation. They deliver rapid answers but are suitable only for a rough estimate of the possible immission levels and for a first screening of a given situation. Gaussian models are based on simplified solutions of the governing equations for the spread of pollutants and include a wide body of empirical information. They are computationally very efficient, but can take into account geometrical features (terrain shaping, building, particular portal configurations etc.) only in a simplified manner. The third approach is based on the direct numerical solution of the three-dimensional governing equations on a computational grid. This approach is usually restricted to small domains, because of the very high computational requirements.

The approach proposed herein is based on the combination of the second and third methodology. A Gaussian model is used first for a general screening of the overall investigation domain and the identification of the critical zones. The latter can then analyzed in more detail using the three-dimensional model, if this is justified by the results of the first level of investigation.

It is unfortunately not possible to obtain statistically meaningful values for the average and peak concentrations from a single computation. This is an obvious consequence of the non-linearity of the problem at hand. A comprehensive computation must be carried out in two steps:

- ♦ Computation of a sufficient number of representative episodes.
- ♦ Statistical evaluation for determining average and peak pollutant concentrations.

The pollutant propagation is carried out for a number of episodes. They account for different wind directions and intensities as well as for different atmospheric stability conditions. Variations of traffic level are also taken into account. The final step is always a statistical analysis of the results.

3.5. Postprocessing

The raw data are treated in a statistical manner in order to determine average and peak total distributions of all relevant pollutants. The steps involved for all inert pollutants are:

- ♦ Determination of the total concentrations.

- Statistical analysis of the concentrations.
- Result interpretation.

In the case of NOx an additional postprocessing step is the computation of the oxidation level of NO to NO_2.

3.6. An Interactive Approach to Tunnel Ventilation

The results of the study of environmental impact are often determinant for the choice of the ventilation system. If the immission levels are not acceptable the design has to be modified in a more or less fundamental manner. This includes:

- Modified operation of the ventilation system (e.g., in case of longitudinal ventilation, ventilation in the opposite direction if only one portal is critical).
- Realization of a portal exhaust extraction system with chimney.
- Choice of a more complex ventilation scheme, such as central extraction or transversal ventilation.

Experience with a number of projects consistently proves the importance of investigating the environmental impact already in the early steps of the ventilation design process.

4. GLOBAL ANALYSIS - GAUSSIAN MODEL

4.1. Modeling Approach

Gauss-type models proved to be both convenient in terms of computational and modeling requirements and accurate in terms of results. For this reason they form the core of HBI's immission computational procedure. Their physical fundaments and applicability are illustrated in Fannelöp (1994) and Turner (1970). In this case it was opted for the particular implementation developed by the American Environment Protection Agency (Petersen 1980), which is particularly well documented and validated and is internationally widely recognized. The original program was heavily customized by HBI based on its consultancy experience, in particular in terms of statistical analysis of the results (Zumsteg 1997).

The first step in the computation is the identification of relevant emission sources and their discretization. Experimental investigations show that the motor-vehicle exhausts are initially spread by the large-scale turbulence of the vehicles over a height of 2 to 8 m, depending primarily on vehicle speed and wind conditions. They are then carried by the wind and spread because of turbulence, depending on meteorological conditions. HIWAY-2 discretizes finely the sources and computes for each of them the spatial distribution of concentration in each point of the immission domain. This computation is carried out for all modeled sources and possible weather conditions. The computation is typically carried out on a grid with spacing of about 50 x 50 m. This typically results in roughly 400-500 computational points per km^2. This computation of pollution dispersion results in a large array of immission values for each location, which are analyzed statistically in a postprocessing step in order to determine representative average and peak immission levels.

4.2. Postprocessing

Meteorological conditions, in terms of wind velocity, direction and atmospheric stability are typically known in terms of hourly or half-hourly values over at least one year. The expected traffic volume and distribution is also well known, frequently in terms of distribution over the day, as well as dependence on weekday and month. On this basis the immission value can be computed for each point of the immission domain for each hour of the reference year. Particular attention has to be devoted to the analysis of windless episodes, in order to avoid spurious concentrations of pollutants.

The propagation of the nitrogen oxides, NO and NO_2, is carried out in terms of their resultant, NOx. The oxidation level is determined based on Romberg's (1996) charts, refined by Zumsteg (1997b) in order to account for particular Ozone conditions, such as low levels in urban areas and higher ones in rural environments.

The last computation step is the superposition of the computed immission values with the background concentrations for each episode and location. The statistical analysis of the results for the 8760 yearly episodes is carried out along the same lines used for experimental data.

4.3. Model Validation

This model was validated using two field experiments (Zumsteg & Haerter 1990 and Zumsteg & Graf 1993), and a wind-tunnel investigation (Zumsteg 1997a). The results showed that the accuracy delivered by the model is mostly adequate and is typically limited by the availability of reliable forecasts for the input data, in particular traffic characteristics and vehicle emissions.

5. REFINED LOCAL ANALYSIS - MISKAM

5.1. Modeling Approach

Gaussian models can account for complex configurations only in an approximate manner. Improvements can be achieved through the numerical solution of the well known governing equations for the motion of airflow and species propagation. This was impractical in the past, because of the high requirements in terms of computer resources, but is now becoming increasingly accessible owing to the impressive evolution of computing hardware and software. MISKAM is a three-dimensional non-hydrostatic package for the simulation of wind distribution and pollutant concentrations in urban environments. Its practical applicability is restricted to small domains, typically a few 100 m. Its main advantage is the possibility of accounting for geometrically complex configurations, such as portals located in urban environments or particular features, such as noise-reduction walls. Turbulence is accounted for by means of the two-equation E-ε (or k-ε) turbulence model.

The program is commercially available and is described in detail in Eichhorn (1989, 1998). Additional information on its physical background is given in Zenger (1998).

5.2. Analysis

The main phases of the analysis are the following:

- Domain modeling and grid generation.
- Flowfield computation for all relevant wind directions and meteorological conditions.
- Computation of the propagation of pollutants.
- Statistical postprocessing.

While the statistical postprocessing can be carried along the lines exposed for the Gaussian models, important differences emerge in terms of modeling and simulation. The most critical issue is certainly the modeling of the computational domain (i.e. the identification and representation of all crucial features of the computational domain) and grid generation (i.e. the discretization of the computational domain using small control volumes, which are used for the solution of the governing equations). They both require specific knowledge and good engineering judgment, and have a fundamental impact on the final results. Examples are known, where misjudgments in the modeling phase led to wrong conclusions with devastating consequences on large tunnel projects.

The main limiting factor for the adoption of this approach are the computational resources. Good accuracy requires large grids, which easily reach 10^6 cells. The CPU requirements for one single simulation on a state-of-the-art high-end PC can be on the order of one week or longer. The model is therefore applicable only to relatively small computational domains with a few 100 m with.

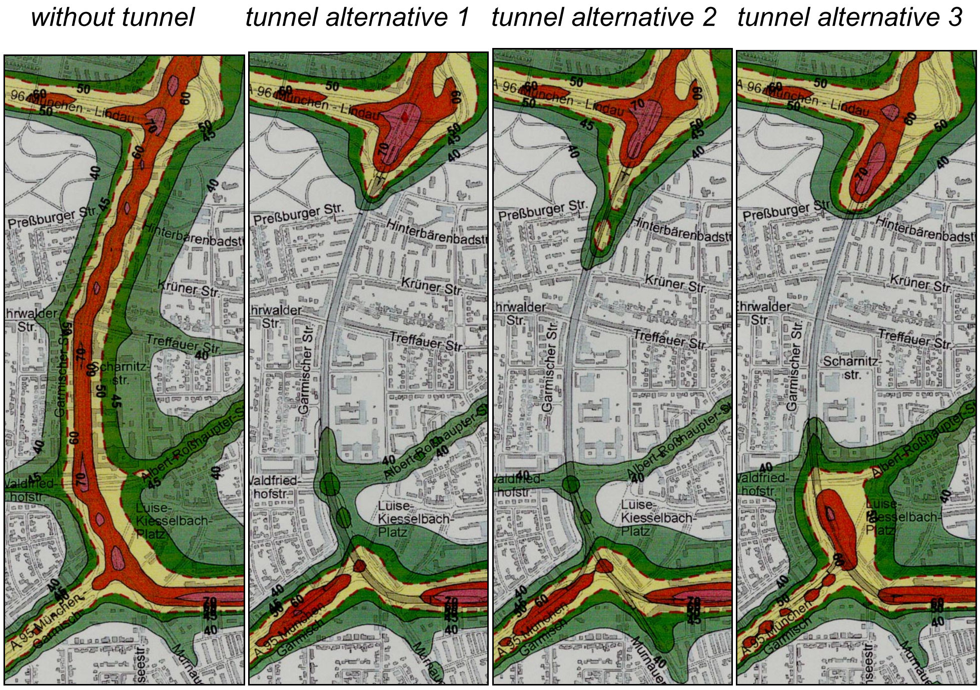

Figure 1: Mittlerer Ring southwest - Annual mean concentration of NO_2, situation without tunnel and with three different tunnel designs, year 2010.

5.3. Model Validation

Before application the model was carefully validated, both in-house and as part of international efforts (e.g. Eichhorn 1996, Schädler et al. 1995). The validation cases ranged from basic configurations (e.g. one single point or line source) to comparison with wind-tunnel results for modeled urban environment and large-scale measurements.

6. APPLICATION - MITTLERER RING MÜNCHEN

6.1. Introduction

The „Mittlerer Ring“ is the main artery for the individual traffic in the Bavarian metropolis. Its present and future function is the distribution of local and incoming traffic. The traffic on this artery amounts to roughly one seventh of the whole traffic volume of the city. The impact on the adjacent residents, in terms of noise, pollution as well as traffic jams at some critical points, is a major source of concern.

Following a plebiscite of the year 1996, planning for an expansion of the capacity of the “Mittlerer Ring” was resumed. Four tunnels, all in the urban area, are planned: the Petuel Tunnel (length 1.5 km) in the north, an eastern tunnel (1.5 km) and two tunnels in the south-west (1.2 and 0.6 km). These tunnels will increase the Ring’s capacity and reduce the environmental impact of the artery.

HBI’s effort consisted in the analysis of the immission levels in proximity of the tunnel portals and the design of the tunnel ventilation. It provided in particular pollution-dispersion calculations for a variety of tunnel alternatives and a number of different pollutants. Prognoses have been made for NO_2 (yearly averages and peak values in form of 98 percentiles), benzene and soot (yearly averages) as well as for the additional impact of small particles from vehicle engines emissions. The prognoses of the pollution in the vicinity of the tunnel serve as a basis of the decision-making process and are necessary for obtaining the final design approval.

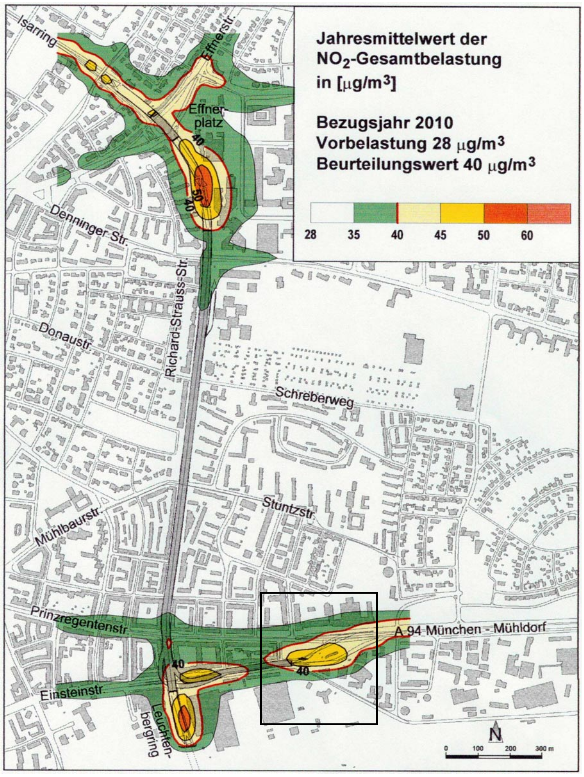

Figure 2

Mittlerer Ring east - Annual mean concentration of NO_2, year 2010. Calculation with the Gaussian model

6.2. Example 1 – Investigation of Design Alternatives using the Gaussian Model

This example illustrates a typical investigation of project alternatives for the southwestern sector. The immission study was carried out for the situation without tunnel and for a number of alternatives. Some results are presented in Figure 1, in terms of yearly averages of the NO_2 concentration. This kind of investigation is best carried out using the Gaussian model.

6.3. Example 2 – Identification and Detailed Investigation of Critical Areas

This example illustrates the combined use of the Gaussian and the three-dimensional models in the eastern sector. The Gaussian computation for the whole domain of interest is illustrated in Figure 2. A number of questions concerning the southeastern portal arouse, because of the relatively high immission levels and high density of population. It was decided to investigate this area in more detail. Because of the complexity of this configuration, characterized by a number of relatively tall buildings, it was decided to carry out an additional investigation using MISKAM. The computational domain is marked in the lower part of Figure 2. The results are presented in Figure 3.

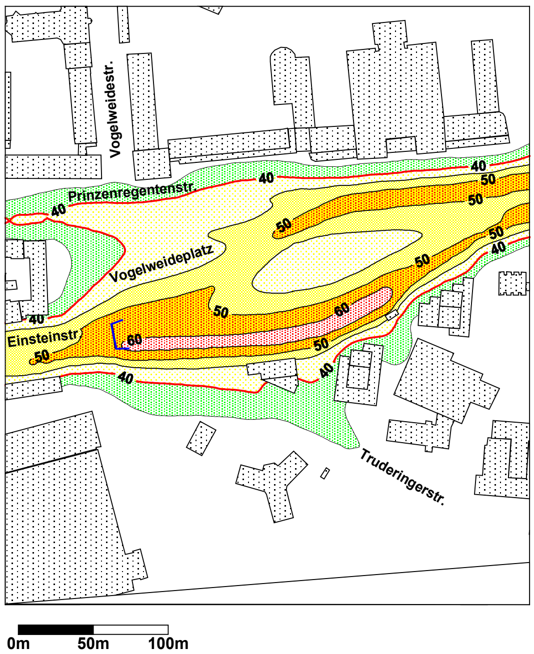

Figure 3

Mittlerer Ring east - Annual mean concentration of NO_2, year 2010. “Hot spot” investigated using MISKAM.

6.4. Conclusions

A large number of immission simulations were carried out, in order to identify the best design options. The combined use of Gaussian and three-dimensional models allowed for both a quick screening of options and a detailed analysis and optimization of the most promising ones. Today, HBI Haerter Ltd serves as the technical expert for tunnel ventilation and air quality during the approval of the tunnel design by the German authorities. The project is being refined for final approval.

7. CONCLUSIONS AND OUTLOOK

The combined model presented herein combines the advantages of Gaussian models, notably good accuracy at relatively low computational cost and applicability to large domains, with the unsurpassed modeling accuracy of three-dimensional numerical simulation. Because of its high cost and limitation to relatively small domains, the second modeling step is justified only for analyzing the “hot spots” identified by means of the Gaussian approach. The combined model allows for an unsurpassed flexibility and modeling accuracy also for very complex portal configurations, in particular in urban environments.

The flexibility and accuracy level, which can be achieved through the combined use of both approaches, is far superior to that of any one of the models alone. However, a high level of expertise is required form the responsible engineer. Examples are known, where modeling misjudgements (e.g. in the modeling of the tunnel exhausts) led to design errors, which cannot be easily corrected.

Experience shows, that it is increasingly important to carefully investigate the environmental impact of a project from the early design phases. The ventilation design process should be tightly coupled with the environmental investigation, in order to reduce the number of costly iterations.

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