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AIR QUALITY MODELLING OF ROAD PROJECTS USING A 3D COMPUTATIONAL FLUID DYNAMICS (CFD) MODEL

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Abstract: The air quality impact analysis is an important part of the regulatory studies (noise impact, landscape impact, hydrogeology, wildlife impact…) of a road project. When the project includes urban areas, the impact on human life quality is one critical point. It is necessary to demonstrate the air quality impact assessment on human health of the road project based on traffic-induced air pollution dispersion modeling in urban areas. In complex road configurations (tunnels, buildings, hilly topography, acoustics panels, crossroads, roadway design…), the air pollution dispersion from road traffic is influenced by complex and turbulent wind flows. Indeed, it is well recognized that dilution is an important mechanism governing the near-road air pollutant concentrations. From the accuracy of the flows simulation the correct estimation of the near road pollution impact is possible. Simulations through CFD approach provide the accuracy expected by taking into account all the 3D element influences. Parameters considered for the 3D dispersion model are altitude curves, street width and length, building heights, wind-rose data (velocity and direction), ambient air temperature, background pollution, traffic volume, vehicle type and speed. This framework for assessing and visualizing urban pollution levels has been used for the level crossing of Molsheim, France. This spot is representative of the complex design of roads across a city. The modeling results of this case have been compared to the local NO_2 measurements which included each time 20 different points around the road project. The comparison between 3D modeled concentration and measurements campaign has shown good agreement. The results from the 3D air modeling have provided valuable information for pollution impact analysis of those projects. Moreover it shows that CFD modeling can become a valuable tool in the roadway designs process by providing important information to decision makers for air quality assessment and management.

Key words: *Road traffic pollution, air quality, 3D CFD software; fluidyn-PANROAD*

INTRODUCTION

The French transcription of the European directive in terms of air quality near transport infrastructures and land planning projects (law 96-1236) requires from all project leaders working on land planning either by designing a new road or by modifying an existing road infrastructure to study the impact of their project on the local scale air quality and on health of nearby populations.

The latest guide to work on this impact study is the inter-ministry circular DGS/SD7B/2005/273 on impact studies for air quality and health applying to every new road project and every modification of the existing road network. This guide defines the following objectives for the impact study:

- Evaluation of traffic pollutant emissions for the existing and future infrastructures included in the framework of the urban project
- Qualification of the initial state of the air quality by modelling the dispersion of these emissions coupled to an experimental campaign on site
- Appraisal of the air quality in future, 10 and 20 years from the current year with and without the projected modifications to the network and comparison to the initial state
- Comparison of the projected modifications, if several competing projects, in terms of air quality impact
- Comparison to the European standards in terms of air quality
- Evaluation of the sanitary impact on nearby inhabitants
- Analysis of the collective cost of the pollution.

The software used for the qualification of the initial state as well as the estimation of pollutant dispersion are generally of Gaussian nature. However, the Gaussian software cannot take into account strong declines (mountain areas) or urban context with many obstacles (buildings but also trenches and tunnels) which is where the strongest health impact is expected.
To quantify the impact of a road modification, 3D CFD software are therefore more adapted to the urban context.
3D CFD models are able to model the 3D wind field pattern on hilly terrains and over complex obstacles by solving the Navier-Stokes equations for atmospheric flow in a RANS formalism. It includes mass, momentum and enthalpy conservation, state law and equations for advection-diffusion.

Such a use of a 3D CFD software, fluidyn-PANROAD, is presented here in the context of the modification of a railway crossing in the city of Molsheim in France. The whole impact study will not be presented here, rather focussing on the dispersion models and results.

ROAD PROJECT

On the road network around the city of Strasbourg in the East of France, the nodes at the town of Molsheim are of primary importance on the local and regional level. The railway crossing of Molsheim is a focal point in terms of environmental impact, risks and delay in traffic (figure 1). Major modifications are therefore under way, mainly by the creation of a lower or upper passage.
The implications on the air quality, the benefits and nuisances have to be analysed on three scales: current status, status expected in 2012 and in 2022.

Figure 1. Aerial view of the planned project (railways tracks crossing in Molsheim)

The simulation of the intervening processes in atmospheric pollutant transport and dispersion requires the consideration of many parameters. These are:

- Topography and ground roughness parameter of the study area according to different ground occupation parameters,
- Emission sources made up of roads,
- Weather conditions.

Amongst the numerous pollutants that have to be studied in the European regulatory context around road infrastructures, two are presented here, NO_2 and C_6H_6. They have been chosen because they are the main contributors to air quality and experimental measures have been done for these two chemical species.

NUMERICAL TOOL: FLUIDYN-PANROAD

The software *fluidyn*-**PANROAD** developed by TRANSOFT International has been used here. This software is specifically dedicated to the traffic pollutant dispersion by solving 3D fluid mechanics equations (Navier – Stokes equations).

The resolution of the fluid mechanics equation is done on a curvilinear unstructured embedded mesh, capable of following closely the differences in altitudes or terrain elevations to take into account their effects on the dispersion and to represent in detail the major areas in the study zone. In the current study, the influence of the relief is not negligible since the project itself is based on 3D features such as overheads or tunnels. It is thus essential for the mesh to represent the terrain along these curves.

Besides, the terrain roughness, the effect of ground occupation parameters on the wind field is also modelled with respect to the areas crossed (urban areas, empty terrain, forests…).

Two types of turbulence have an influence over dispersion: mechanical turbulence (vortices created by the difference in velocity of air masses or by the movement of air in contact with these objects), and the thermal turbulence (vortices created by the difference in temperature of air masses in the atmospheric layer). The turbulence model k-ε, adapted for the flow calculations over complex topography terrain has been used for these simulations and a micro meteorological model provides the initial atmospheric wind, turbulence and temperature profiles based on Monin Obukov similarity theory.

The velocity profile in the boundary layer is determined by a logarithmic law. This allows to take into consideration the local roughness on the forests and urban areas. The gravity forces are neglected.

NUMERICAL MODEL OF TERRAIN

Geometry

The simulation domain is determined by the roads directly or indirectly affected by the project. Moreover, the boundaries have been chosen far enough from the considered site to reduce their impact on the results. The domain is therefore square with 1.5 km sides (figure 2).

The simulation domain is globally flat but the projected land planning requires local modifications of the terrain by road fills and excavations. These configuration differences have been taken into account in the different terrain models detailed for each variation. From this information, the terrain objects have been introduced into the numerical terrain model, thus taking into account the important parameters in the study domain.

The information from the topographical database is either converted into area with a roughness coefficient depending on the land occupancy (urban areas, forests, fields, water bodies, open spaces, etc.) or is explicitly described in the model. In the current study, each building near the railway crossing has been integrated in 3D. The others have been included in the form of built areas with an appropriate roughness coefficient.

Finally from the varied information provided by the city planning, the road sections represented in the study domain have been localised and integrated in the numerical model of the terrain.

Figure 2. Aerial view of domain with roads (left) – numerical model of terrain (right)

Once the terrain model has been generated, *fluidyn*-PANROAD builds a 3D unstructured embedded mesh, curvilinear and refined at and around road levels where a high precision is required and where the obstacles and terrain features will considerably modify the windfields and pollutant dispersion.
The following pictures present a top view and a 3D isometric view of the mesh. The number of cells in the computational domain is 225000 distributed along the three axes. The finer cells are mainly located near the road sectors and are of the order of a few meters.

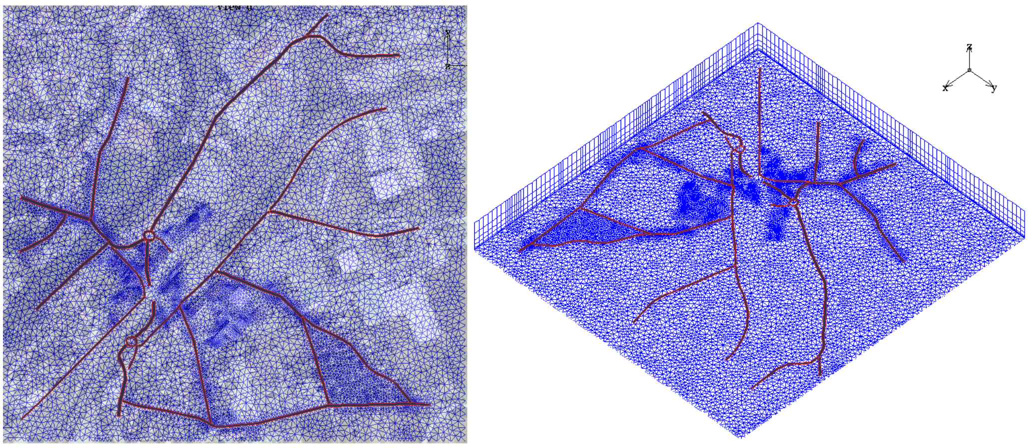

Figure 3. Mesh – top view (left) and isometric view (right)

Weather conditions
The transport and diffusion vectors of the atmospheric pollutants are air and its movements. It is thus important to define weather conditions to be simulated. These are then applied to the computational domain boundary, and the software defines the wind fields (velocity and direction) at any point in the domain by solving the fluid mechanics equations. Since the calculation is three-dimensional, the weather conditions are different with respect to altitude and are influenced by the numerical model of terrain: buildings, urban areas, topography and fields.

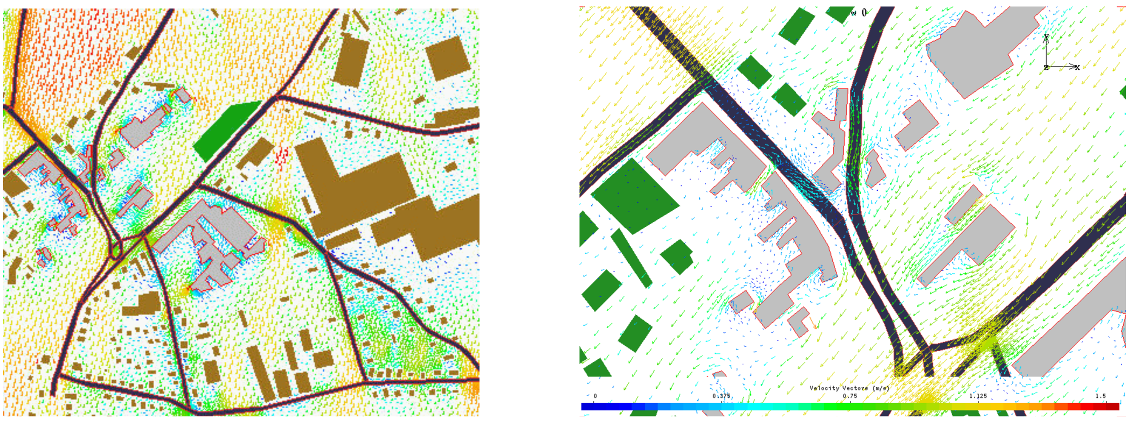

Figure 4. Wind vectors on the ground plane (left) – zoom view (right)

In the framework of an air quality impact study, it is imperative to use a sufficient number of weather conditions in order to represent an average situation. For this reason, the methodology depends on the construction of mean annual exposures by the weighted summation of the results obtained for the chosen wind conditions. The maximum exposures are obtained by individual examination of the concentrations for each condition.
The selection of the weather conditions for the simulation has been done from the wind rose obtained from Meteo France along the following criteria: the winds taken into account are those with velocities greater than 1 m/s. The least frequent winds (less than 1%) have not been considered due to their limited effects on the mean annual impact. Thus a number of 35 wind sectors have been extracted representing a total of 90.1% of wind rose. These were then brought to a total of 100 % to calculate the mean annual impact.
Figure 4 shows an example of wind field for a North wind of 2m/s at a height of 10 m. The wind vectors are presented on the 1.5 horizontal plane. The influence of topography and obstacles can clearly be seen, for example in the recirculations behind the buildings and acceleration between buildings.

Emissions
The traffic data was extracted from the survey results and traffic modelling done by the city planning services. The calculation of the pollutant emissions in the atmosphere from traffic data has been done with the software IMPACT-ADEME version 2.0. This software tool is an adaptation of the COPERT III methodology for the quantification of the consumptions and emissions induced by a given flow of vehicles on a given infrastructure at a given horizon in France.
It uses an emission and consumption database for each vehicle category of the current and future vehicle park and a dataset of the annual structure of the park, elaborated by INRETS.

Experimental campaign
The analysis of the initial state is defined by an on-site measurement campaign by passive tubes. According to the CERTU methodology, the NO_2 constitutes a reference index for traffic pollution. A series of measurements for BTEX (benzene and other hydrocarbons like toluene, ethylbenzene and xylene) has also been done.
7 measurement points of NO_2 and benzene have been chosen and each point has 2 NO_2 tubes (doubled) and one BTEX tube.
The distribution of the sample points has been defined in order to cover the entire study domain by:

- Measurements on different road axes near traffic
- Measurements in urban areas in order to evaluate the dispersion of emissions from road traffic and from urban background (used for the modelling)

Numerical results
From the weather conditions and road traffic emissions established on the traffic database and the emission factors, the mean annual concentrations are modelled by solving the advection-diffusion equations. The resultant concentration maps show a representation of the air quality that can be related to the road for the various pollutants and years considered.
This section presents a sample of results obtained. The first table shows the experimental campaign results with the comparison with numerical results obtained for the annual average at current status in the cell containing the measurement spot as well as the standard deviation. The standard deviation for NO_2 concentration results are between, 2 and 23% with an average at 10%. The standard deviation for benzene is a bit higher ranging from 65 to 0%. These results are quite good considering that the experimental results were done over a period of 15 days whereas the numerical results have been produced for a yearly average (both for weather and traffic data).

Table 1. Comparison of experimental measures with numerical results

Monitor	**Experimental results**		**Numerical results**		**Standard deviation**	
	NO_2 concentration (µg/m³)	**C_6H_6 concentration (µg/m³)**	**NO_2 concentration (µg/m³)**	**C_6H_6 concentration (µg/m³)**	**NO_2 (%)**	**C_6H_6 (%)**
1	28.7	1.5	35	1.05	19.8	33.4
2	44.3	2.1	35	1.1	23.5	64.5
3	58.4	2.3	55	1.35	6.0	53.8
4	36.8	1.3	43	1.15	15.5	11.8
5	65.2	2.8	67	1.7	2.7	49.9
6	38.2	1.5	37.4	1.1	2.1	29.5
7	37.6	1.2	32.6	1.05	14.2	16.6
8	31.0	1.0	31.8	1	2.5	0.1

The following set of pictures in figure 5 shows concentration contours of NO_2 at ground level for two wind conditions at 0° and 180°N and 3 m/s. This type of results can be used to discriminate between the proposed layouts for the railway crossing.
The simulation indicates that the benzene levels exceed the air quality norms in current status (year 2008) but this is localised near the road. No other pollutant from road traffic exceeds the norms specified by the air quality directives.
By comparing the future references 2012 & 2022 to 2008, the benzene emissions decrease by more than 50%. NO_2 decreases by 30% on the entire domain. Even if the traffic for 2012 and 2022 is more important than in 2008, the more severe air quality emission norms for new vehicles, fuel specifications and the technological evolution of motors, estimated to be less polluting and more environmental friendly in future years have contributed to this decrease.
As a direct consequence, a decrease in the maximum concentration of pollutants between 2008 & 2022 can be seen. For 2022, only NO_2 exceeds in limited points the threshold values of air quality norms.

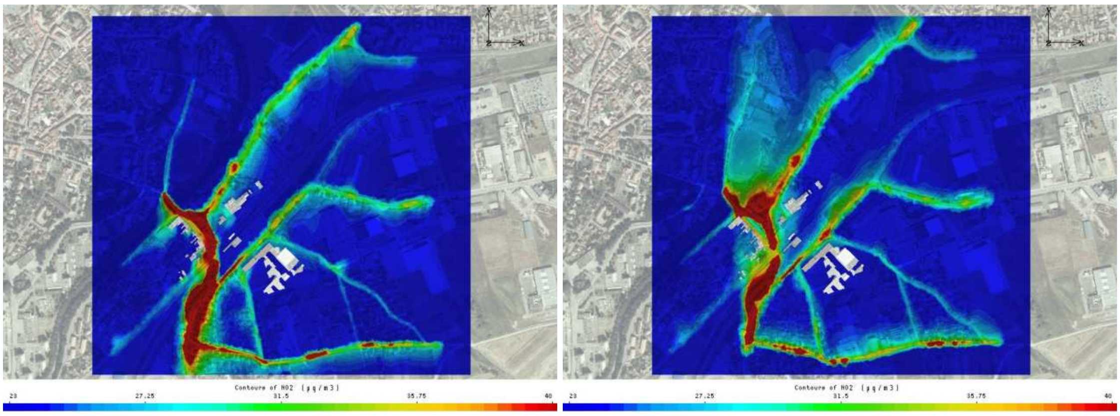

Figure 5: NO_2 concentrations contours at 1.5 m for a wind velocity 3m/s and a wind direction 0°N (left) and 180°N(right)

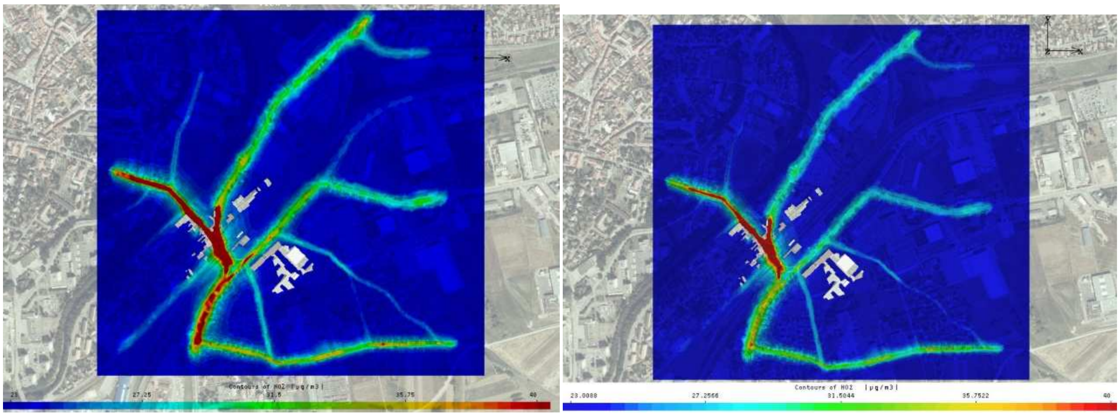

Figure 6: Yearly average of NO_2 concentrations contours for 2008 (left) and 2022 (right)

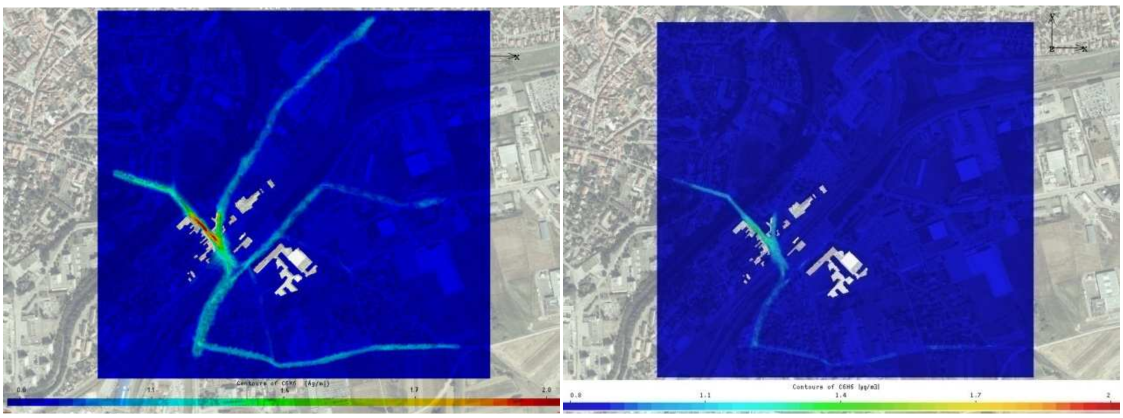

Figure 7: Yearly average of C_6H_6 concentrations contours for 2008 (left) and 2022 (right)

CONCLUSION

This paper presents the results of the evaluation of air quality impact due to the construction of the railway crossing at Molsheim done with the 3D CFD dispersion model, Fluidyn-PANROAD. According to the specifications of the inter-ministry circular DGS/SD7B/2005/273 on air and health impact of road infrastructure projects, the study presents the results of road traffic pollution dispersion simulation in the study domain conducted for reference years 2008, 2012 and 2022 for several modifications of the project.

The comparison of numerical results with experimental measurements has shown that the simulation results are realistic even though a direct comparison is not possible. The comparison of each project has helped to provide insight on the air quality impact of crossing above or under the railroad.

The 3D CFD models can therefore be used for great advantage as a tool to comply with the European directive on air quality.