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DISPERSION OF TRAFFIC EMISSIONS IN THE LEOPOLD II ROAD TUNNEL IN BRUSSELS UNDER THE COMBINED INFLUENCE OF THE VENTILATION SYSTEM AND THE VEHICLE MOTION

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Abstract: The present study was undertaken within the frame of the EU LIFE+ PhotoPAQ project in support of a field campaign, which was organised in order to demonstrate the applicability of photo-catalytic surface covering materials, as an effective means for the abatement of air pollution inside road tunnels in urban areas. The main objective was to quantify the combined effect of the vehicle motion and the ventilation system under heavy traffic conditions on the dispersion mechanism inside the Leopold II road tunnel in Brussels, Belgium, focusing on the section of tunnel which was selected as a test area for the aforementioned field campaign. Measurements for the volume flow rates of the ventilation ducts, the diurnal variation of the traffic flow, the speed of the vehicles and their average travelling time, served as boundary conditions for the numerical simulations and were provided by the Belgian Road Research Center (BRRC). The simulations were conducted in two stages. During the first stage the dispersion of traffic emissions was simulated inside the entire tunnel, taking into account only the effect of the ventilation on the distribution of air pollution along the tunnel. During the second stage the field trial test section was isolated and the dispersion of traffic emissions was simulated taking into account the combined effect of the ventilation system and the vehicle motion in order to quantify the expected levels of air pollution during the field campaign. Results reveal a significant effect of both the ventilation system and the motion of vehicles on the mixing levels inside the tunnel due to the generation of additional terms of turbulence and the enhancement of advection, by entraining masses of air in the direction of the vehicle movement.

Key words: *Road tunnel, moving vehicles, ventilation, traffic emissions, turbulence, pollutant dispersion.*

INTRODUCTION

The EU LIFE+ project PhotoPAQ as *"Photo-catalytic remediation Processes on Air Quality"* aims at demonstrating the usefulness of a range of photo-catalytic TiO_2 based materials for the abatement of air pollution in urban areas. Their de-pollution performance for building façade covering applications towards the improvement of the urban air quality has already been assessed within the frame of numerous studies over the past decade (Moussiopoulos et al., 2008; Maggos et al., 2008). However, in addition to their application on building facades, these materials may contribute to the significant reduction of air pollution inside road tunnels. Towards this aim, a field trial was organized in the Leopold II road tunnel in Brussels, in an effort to quantify the effectiveness of the aforementioned type of materials as a viable means for the reduction of the exposure of the population in road tunnels in urban areas across Europe.

Although road tunnels in urban areas are usually well ventilated and the air inside them is renewed relatively frequently, previous research has shown that they suffer from elevated concentrations associated with road traffic emissions mainly during the rush hours (Indrehus and Vassbotn, 2001). In particular, as they are partially enclosed they tend to give rise to intense entrapment of road traffic emissions due to poor dilution and especially under low vehicle speeds during the rush hours, a situation which may promote elevated exposure of the population, with serious adverse health impacts (Kagawa, 1984; Schwartz and Morris, 1995). The tunnel ventilation and the extra terms of turbulence generated by the motion of vehicles inside it dominate the transport of traffic emissions downwind to the tunnel exit where elevated concentrations are normally diluted. More specifically, boundary layer separation from the moving vehicle's solid surface gives rise to large transient aerodynamic forces, particularly in the case when the vehicle is moving close to the tunnel's side wall (Diedrichs et al., 2004; Barmpas et al., 2011). At the same time the generation of continuous pressure disturbances propagating downstream of the vehicle's body further enforce the impact of the piston effect on the dispersion of traffic emissions inside the tunnel (Zanini et al., 2006; Barmpas et al., 2011).

In view of these findings and in support of the measurement campaign, a numerical study was undertaken by the Laboratory of Heat Transfer and Environmental Engineering in order to quantify the combined effect of the vehicle motion and the ventilation system on the dispersion mechanism inside the Leopold II road tunnel under heavy traffic conditions and estimate the expected NO_x concentration levels in the test area selected for the measurement campaign. The main objective of this study was to account for the effects of the ventilation and the aerodynamics of the flow around the moving vehicles on the mixing levels and the dispersion of traffic emitted NO_x inside the tunnel.

METHODOLOGY

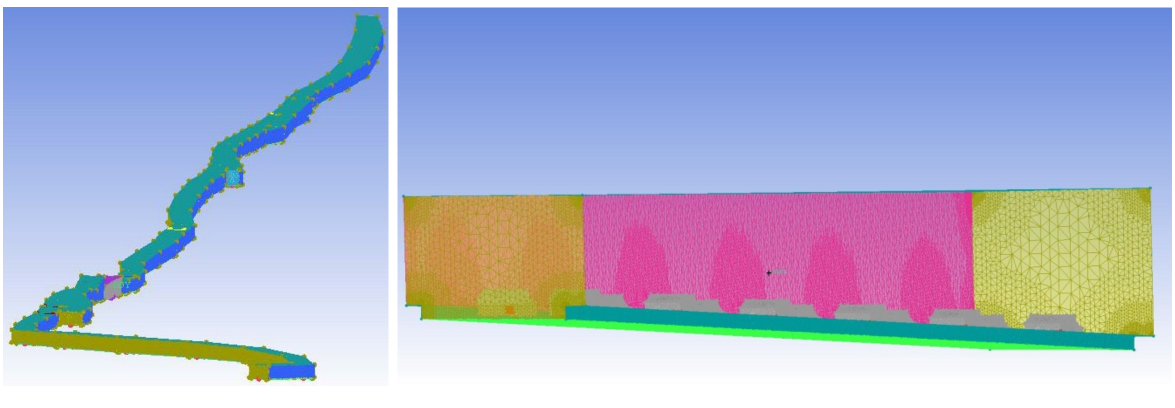
The Leopold II road tunnel is a bi-directional tunnel located in the Brussels city centre along the Basilica – Midi axis, within a densely built urban environment (Figure 1). Its geometry is highly complex as it is about 2.3 km long and consists of two segments separated by a wall, with varying cross sectional areas along each direction. It should be noted that as the two segments are separated by a wall, each one can be considered as a one-directional tunnel. The segment of the tunnel which runs along the direction from the Basilica to Midi has a total of three entrances and three exits and its ventilation system includes three injectors and four extractors, with one of the extractors however being operated in cases of emergency only. The selected area where the measurement campaign will be realized is 110m, with an average height and width of 7.4 m and 8.4 m respectively.

According to the information which was provided by the Belgian Road Research Center (BRRC), the ventilation system is normally operated during the rush hour periods between 06:30 and 10:30 in the morning. The total volume flow rates for the three extractors and the three injectors in operation are 300 m^3s^{-1} and 260 m^3s^{-1} respectively. Furthermore, based on measurements which were made on the 13th of October 2009 between 07:00 am and 09:00 am, the average traffic flow in the direction from the Basilica to Midi is 2300 vehicles per hour, with an average residence time for the vehicles of 6 min.

Figure 35. The Leopold II road tunnel (red) in Brussels city centre

In order to quantify the effect of the vehicle motion on the air pollution in the selected field trial section, a series of three dimensional numerical simulations were performed using state of the art Computational Fluid Dynamics (CFD) tools in two stages. During the first stage the dispersion of road traffic emissions was simulated over the entire segment of the tunnel running along the direction from Basilica to Midi which also includes the selected field trial section, for a period of 6 min, for two different scenarios, employing both steady and unsteady Reynolds Averaged Navier Stokes (RANS and URANS respectively) techniques. The simulation period corresponds to the average residence time of the vehicles inside the tunnel. According to the first scenario it was assumed that the ventilation system is not operating ("reference scenario"), while during the second it was assumed that the ventilation is in operation ("ventilation" scenario). The objectives of this stage were to identify the effect of the ventilation system on the distribution of NO_x concentrations downwind the tunnel towards the exits, to estimate the expected levels of air pollution in the field trial test section and provide boundary conditions for the numerical simulations in the next stage. In all cases considered the traffic emissions were calculated using COPERT 4.0 (Ntziachristos et al., 2009), based on the measured traffic flow and taking into account the fleet composition at a national level, excluding Heavy Duty Vehicles (HDV) as they are forbidden to enter the tunnel. During the second stage the dispersion of traffic emissions was simulated in the field trial test section only, for a period of 20 s, which corresponds to the average residence time of the vehicles inside it. The main objective of this stage was to quantify the expected levels of air pollution during the measurement campaign by taking into account the combined effect of the ventilation system and the vehicle motion, employing both URANS and LES formulations. Numerical results from the first stage for the velocity and the turbulence profiles at the entrance of the section and the average pressure at its exit were used as inflow and outflow boundary conditions respectively. Based on the information for the traffic flow, the speed and the geometrical characteristics of the vehicles, their average residence time in the tunnel, the number of traffic lanes and the tunnel's length, it was estimated that a total of 12 vehicles are present in the field trial tunnel section, with an average distance of 15 m between two consecutive vehicles.

For the generation of the mesh the commercial ANSYS ICEM CFD code was employed. In all cases considered, an unstructured tetrahedral mesh with sufficient refinement close to the solid walls was set up in order to resolve the important features of the flow (Figure 2). For the needs of the first stage the optimised mesh comprised of 6×10^6 cells, with a minimum cell size of 0.04 m close to the solid surfaces and an expansion factor of 1.2. For the needs of the second stage however, a refined mesh with a total of 11×10^6 cells was generated with an expansion factor varying from 1.12 to 1.2 and inflated boundaries at points of interest such as sharp body corners and areas of high gradients. The geometrical characteristics of the modelled vehicles correspond to the average shape of a medium sized passenger car, without tyres.



(a) (b)

Figure 2. Tunnel geometry and mesh for (a) the entire segment from Basilica to Midi and (b) the field trial test section with vehicles

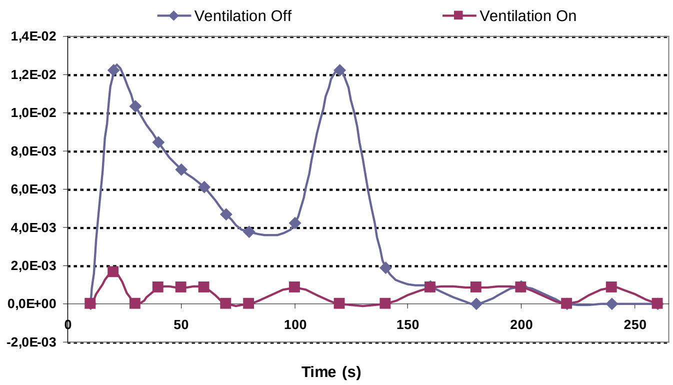
All numerical simulations were performed with the commercially available general purpose Computational Fluid Dynamics (CFD) code ANSYS CFX. This code uses a flexible multi-block grid system and an automatic unstructured hybrid element mesh generator with an adaptive mesh refinement algorithm. The conservation equations for mass, momentum and scalar quantities like temperature, turbulent kinetic energy and any number of species are solved. The numerical solution is based on first-order in time and second-order in space discretisation (the discretisation method is based on the Finite Volume approach). The basic discretisation technique adopted is a conventional Upwind Difference Scheme (UDS) with Numerical Advection Correction (NAC) for the advection terms in the momentum and energy equations. The Reynolds stresses and turbulent fluxes of scalar quantities can be calculated by several linear and nonlinear turbulence models. Accurate modelling of the flow around simplified vehicle bodies inside tunnels is challenging due to certain characteristics of the aerodynamics and mainly the decelerations and accelerations of the flow about the nose and the tail of the vehicle, the generation and growth of boundary layers, the separation and formation of free shear layers and the chaotic wake flow. Therefore, for the needs of the study, the κ-ω Shear Stress Transport (SST) two equations turbulence closure model (Menter, 1994) was selected, since it can account for the transport of the turbulent shear stress and can give highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients. In addition, for the field trial test section only, simulations with the Smagorinsky LES WALE model (Nicoud and Ducros, 1999) were also performed. The reason is that the flow dominating the dispersion in the presence of vehicles was expected to be unstable, with large scale flapping of shear layers and vortex shedding and hence details on the structure of the turbulent flows were required which cannot be obtained through traditional RANS approaches.

RESULTS AND DISCUSSION

Numerical results for the non-dimensional concentration of traffic emitted NO_x are presented according to the following formula:

$$C^* = CUA_t / (Q_s / A_S) \quad (1)$$

where C^* is the non-dimensional concentration, C is the predicted pollutant concentration, U is the reference velocity at the tunnel inlets, A_t is the average cross sectional area of the tunnel, Q_s is the emissions rate along the entire segment and A_s is the area of the emissions source. As a first step, results for the average non-dimensional concentration over the entire tunnel were extracted for a period of 260 s, at a step of 10 s both for the reference and the ventilation scenarios. Comparison of results between the two cases reveals that steady state is reached 48% faster in the case of the reference scenario. The estimated average non-dimensional concentration in the tunnel is approximately 1000 for the reference and 560 for the ventilation scenarios. Only very small fluctuations around these values were observed during the simulated period, which ranged between 0% and 0.012% for the former and 0% and 0.0017% for the latter scenario (Figure 3). Further comparison for the average non-dimensional concentration in the tunnel after steady state has been reached shows that in the case when the ventilation system is not in operation the concentration is 44% higher. Therefore, one should expect significantly lower concentrations in the field trial section for the case of the ventilation scenario. However, results extracted at various horizontal levels in the field trial test section show that after steady state has been reached, the average concentrations in that level are lower in the case of the reference scenario. Figure 4 illustrates the non-dimensional concentration distribution on a horizontal level in the field trial test section at a height of 4 m from the floor, which corresponds to 50% of the tunnel height. It is evident that the operation of the ventilation leads to increased concentrations in that area. This is due to the fact that this specific area is located between an injector and an extractor, so that when the ventilation is operated tunnel air together with air pollution which is emitted from the traffic upstream is forced through that area towards the extractor, where then part of it is flushed out and the rest is diluted.



(a) (b)

Figure 3. Non-dimensional concentration fluctuation in the direction Basilica – Midi over a period of 260 s

Figure 4. Non-dimensional concentration distribution along the field trial test section (shown in red) for the reference scenario on top and the ventilation scenario on bottom

During the second stage, dispersion on the selected field trial test section was simulated for a period of 20 s, which corresponds to the average residence time of a vehicle in that part of the tunnel, under the same traffic conditions assumed during the first stage. For the needs of this simulation the Smagorinsky LES WALE formulation was employed due to the intense fluctuations and the flapping expected in the presence of the moving vehicles. Results were extracted for the average non-dimensional concentrations both over the test section volume and at selected horizontal levels, for the entire simulation period at a step of 1 s. The estimated non-dimensional concentration in that section of the tunnel was found to be approximately 1300. As in the case of the first stage simulations, the estimated concentration fluctuations were very small, of the order of 0.01% (Figure 5). Figure 6 presents the concentration distribution at a horizontal level at a height of 0.8 m from the ground, which corresponds to half the height of the vehicles, at different simulation periods. These results reveal that in the presence of moving vehicles a large amount of the traffic emissions is forced on the sides of the vehicles and towards the tunnel walls, promoting intense entrapment phenomena and poor dilution. As a result, compared to the first stage during which the effect of the vehicle motion was not considered, significantly higher non-dimensional concentrations averaged over the entire field trial area of the order of 26% are observed. Previous work has shown that separation of air about a moving vehicle's tail inside a road tunnel gives rise to large transient aerodynamic forces (Diedrichs et al., 2004). Therefore, elevated concentrations in the field trial test section in the presence of moving vehicles could be attributed to the generation of continuous pressure disturbances propagating alongside the wake regions of the vehicles, leading to intense entrapment phenomena inside these regions. However, these observations seem to be limited only within the wake regions, where large coherent turbulent structures such as large eddies dominate the flow and increase the mixing.

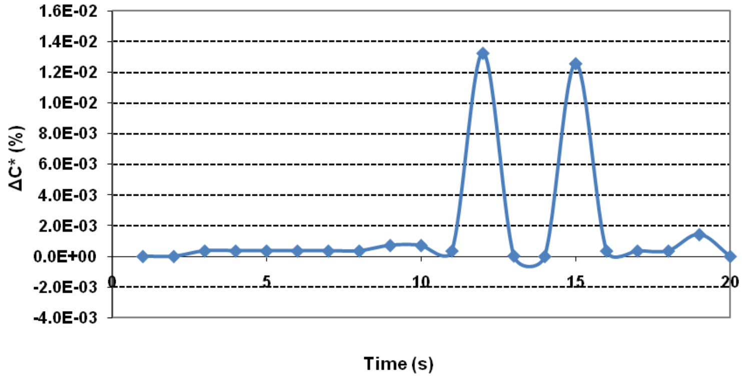


Figure 5. Non-dimensional concentration fluctuation in the field trial section of the tunnel over a period of 20 s

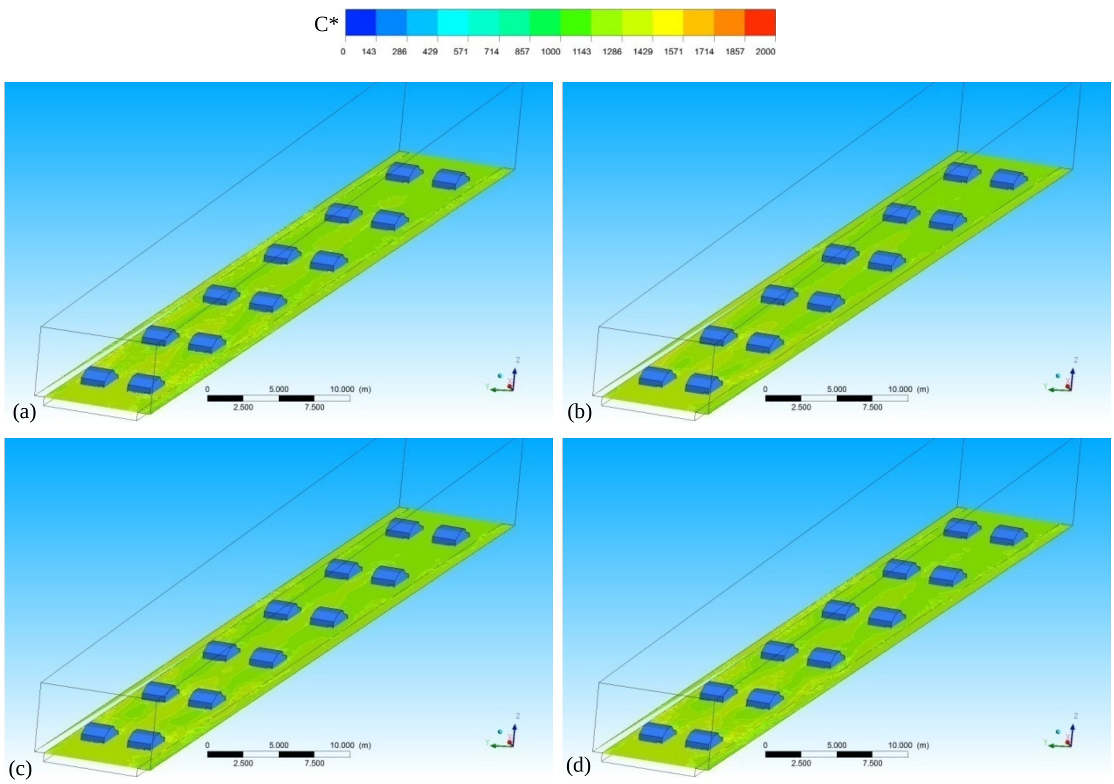


Figure 6. Non-dimensional concentration distribution along the field trial test section in the presence of moving vehicles at half the height of the vehicles at T = 5 s, T = 10 s, T = 15 s and T = 20 s

CONCLUSIONS

The numerical results have confirmed the strong dependence of the dispersion mechanism inside a road tunnel on its ventilation system and the complex aerodynamic effects due to the motion of vehicles. More specifically, the operation of the ventilation system may have a strong impact on the distribution of the traffic emitted air pollution downwind the tunnel towards the exits where the tunnel air is normally diluted. Specific areas inside the tunnel can be adversely affected from a concentration level point of view, depending on their location with respect to the extractors and the injectors of the ventilation. In addition, the motion of vehicles in these areas significantly adds to air quality deterioration, especially under heavy traffic conditions, as it promotes strong entrapment and poor dilution. The simulations that were conducted using simplified models of moving vehicles have shown that the concentrations of traffic emitted pollution at locations which lie in the wake of these moving vehicles can be largely affected. In particular, the flow separation at the wall side of the vehicle models and the resulting aerodynamic forcing can lead to a considerable increase in the tunnel wall concentrations. However, considerably more research on the field is necessary, since the current issue which is addressed depends on many other parameters, which for the needs of the current study have not been taken into account, such as the accurate representation of the vehicle shapes in accordance with their type and the fleet composition.

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