Interaction of Forced Ventilation and Traffic Induced Flow Field in a Road Tunnel: Eulerian-Lagrangian Computational Model.

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Introduction

Ventilation system of road tunnels must fulfil several requirements:
1. to keep the air pollution inside the tunnel below threshold values
2. to ensure an emergency ventilation in case of a fire
3. to protect the area in the neighbourhood of the tunnel outlets from increased pollution and to guarantee the air quality.

Namely the last point requires to be addressed with all the efforts since this is the most important aspect to be judged by local authorities when licensing the traffic construction. Local authorities always require that the tunnel will not negatively affect the air quality in the close vicinity of the tunnel. In case that the tunnel is equipped with a central exhaust shaft they often require that no pollutants leave the tunnel through its portals. It's very difficult to prove it unless we have available a good predictive tool. Otherwise a physical model must be built which is very expensive, the experiments are time consuming, and often it is very difficult to correctly design moving belt with model vehicles. Another problem is the similarity between the physical model and the actual tunnel in the situation with moving vehicles.

When designing the ventilation system we have to consider the flow field induced by moving vehicles. A well-designed ventilation system should profit from the induced flow. Sometimes the requirements of hygienic services are contradictory. In order to keep pollution inside the tunnel below certain level we need a large amount of air to dilute emissions. But this also means that this air must leave the tunnel. Measures must be taken to prevent as much as possible the polluted air from leaving the tunnel through its portals from where it disperses under almost no control into surrounding area. To design correct measures, the designer must have knowledge about the flow field inside the tunnel and how the traffic, i.e. mainly speed of cars and traffic rate influence the ventilation of the tunnel.

In this contribution, ventilation of a vehicle tunnel and the air flow rate induced throughout is solved. Several issues are addressed:

- A quasi-steady approach to moving objects on the basis of which the entrained flow is calculated. This approach is a combination of Eulerian approach to the continuos phase of the ambient air and Lagrangian approach to discrete moving objects (1). This model is capable to take into account not only the speed of vehicles but also traffic rate and type of vehicles and/or one- or multi-lane traffic with different velocities of vehicles in individual lanes.

- Traffic induced turbulence originating from the interaction between moving vehicles and the ambient air.

The model just mentioned was applied to the ventilation system of the road tunnel Mrazovka in Prague. The tunnel has the system of longitudinal ventilation with one central shaft close to the end of one tunnel tube, booster ceiling fans and Saccardo nozzle located in the north tunnel portal. Its purpose is to mainly avoid emissions from leaving the tunnel portal. The model of moving vehicles was integrated into the commercial CFD code StarCD.

Brief Mathematical Formulation and Solution Procedure

The set of equations for the conservation of mass, momentum, energy and passive scalar is solved for the steady-state, incompressible turbulent flow. The equation for a general variable ϕ has the form:

$$\frac{\partial}{\partial x_i}\left(\rho u_i \phi\right) = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_i}\right) + S_\phi + S_\phi^P \tag{1}$$

Equation (1) contains an additional source term S_ϕ^P that results from the interaction between ambient air and discrete moving objects. The interaction is treated using a modified Particle-Source-In-Cell (PSIC) technique by Crowe et al.(2). The standard k-ε model of turbulence is employed in which the equation for kinetic energy is modified with additional source term originating from the interaction between both phases. The whole procedure is described in details in (1).

Results and their Discussion

The tunnel Mrazovka in Prague has two parallel tubes of the length of 1310m. Only one of them - east tube - was solved. From the point of ventilation, the north portal is crucial. There are several extraction slots located in side walls of the tunnel portal from which the polluted air is guided through the ceiling into the west tunnel tube which is at its end equipped with a central shaft and stack. In the north portal, Saccardo nozzle is used with the aim to bring fresh air and mainly to prevent the polluted air from being extracted by moving cars from the tunnel to the surrounding area. It means that the air from Saccardo nozzle is directed opposite to the direction of traffic. Also ceiling fans lead the air in the opposite direction to the traffic. The main goal of the calculations was to predict what percentage of emissions is extracted by traffic from the tunnel to the outside and how to arrive at the situation in which the extract of the emissions from the tunnel is close to zero. Also we want to know whether the ceiling fans working in the opposite direction to the traffic can create such a situation. Several scenarios were solved that differ in traffic rate, speed

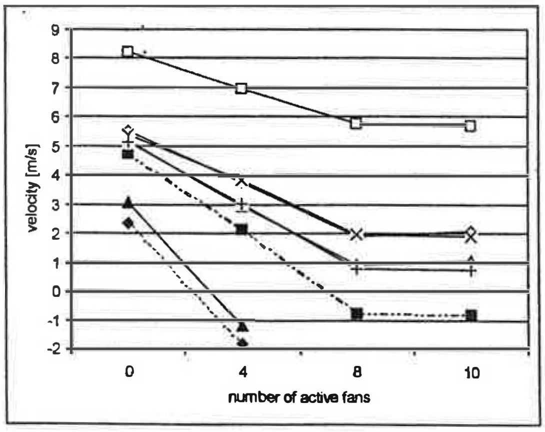

Figure 1. Outlet mean air velocity

of cars in individual lanes and amount of extracted air by the ventilation system in the outlet portal - see Table1. In the Figures 1 and 2 there are calculated air outlet mean velocity and concentrations as a function of number of operating ceiling fans. As can be seen only in the variants #5, 10 and 11 the direction of the flow reverses inwards the tunnel. These variants are characterised by a low traffic rate and/or speed of cars in the combination with a high extracted amount of air. For all remaining variants the air flows outwards from the tunnel and extracts pollutants. It can also be seen that increasing the number of working fans has no positive effect. As soon as we reduce the amount of extracted air by the ventilation system while maintaining the traffic rate and speed, the air flow reverses out of the tunnel (compare variants 9 and 5). Or if the traffic rate is increased while maintaining the extracted amount of air (compare variants 4 and 5) the flow again reverses out of the tunnel. Moreover if the amount of the extracted air is reduced, the mean flow rate out wards of the tunnel is further increased (see variant 2). The worse situation is encountered when there is a high traffic rate (see variants 13 and 14) even the ventilation system extracts the maximum air flow. We can conclude that high traffic rates are difficult to be handled with counter-flow ceiling fans and Saccardo nozzle and that a novel design would be needed to fulfil requirements of "no emissions" leaving the tunnel.

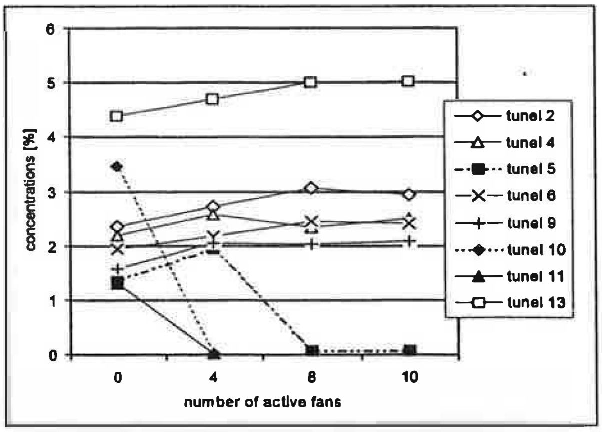

Figure 2. Outlet mean concentrations

Table 1. Scenarios

Traffic lane	Speed [km/hour]	Traffic rate [car/hour]	Extracted air [m^3/s]	Speed [km/hour]	Traffic rate [car/hour]	Extracted air [m^3/s]
Tunnel 2				**Tunnel 4**		
Speed	90.0	480	135	90.0	480	275
Middle	68.4	480		68.4	480	
Slow	50.4	480		50.4	480	
Tunnel 5				**Tunnel 6**		
Speed	95.0	180	275	95.0	180	0
Middle	84.0	312		84.0	312	
Slow	72.0	504		72.0	504	
Tunnel 9				**Tunnel 10**		
Speed	95.0	180	135	48.0	180	275
Middle	84.0	312		42.0	312	
Slow	72.0	504		36	504	
Tunnel 13, 14				**Tunnel 11**		
Speed	70.0	1750	275	95.0	90	275
Middle	70.0	1750		84.0	156	
Slow	70.0	1500		70.0	252	
Entrance ramp	40.0	1500				

Acknowledgement

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