ENVIRONMENTAL CONSEQUENCES AND RISK FACTORS AFTER A FIRE IN A ROAD TUNNEL

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Abstract. Nowadays the world is facing increasly road traffic, due to high number of cars running on the street ant not highways. This is, unfortunately a very important source of pollution for the environment. Although there are many laws and projects, discussions and rules regarding environmental protection. The pollution from automotive industry mainly, for at least few decades, one of the major challenge for the next generation. In this context, the closed and semi-closed spaces will be affected by this kind of the pollution. Road tunnels can be framed in the category above mentioned, being exposed to a high traffic, because most of them are 20-30 years old and were built for the traffic estimated of those times. A simulation using Pyrosim software is based on the physical model in which one electrical fault accident involving a car appear. The accident, consisting in a fire event at one stationary car, is modeled at 1.5 m from height. Considering an electrical fault followed by a fire, we obtained temperature and CO₂ fields depending on time in this tunnel. These information allow us to realize an appropriate impact on the event in aim of minimizing the time for a promptly intervention. Also, with these size field parameters we may check even fresh air flux that can be dislocated.

Keywords: environmental pollution, road tunnel fire, heat release, Pyrosim software.

1. INTRODUCTION

Cars engines, either diesel, petrol or LPG are pollutant and emit noxious. Road tunnel pollution depends on the tunnel characteristics (length, ventilation systems, fire protection systems), number of cars, time of the day and year etc. One of the greatest level pollution that can be reached in a road tunnel occurs in a fire event.

There are, also, others major pollution sources developing as factories, power and chemical plant etc., but the automotive industry is increasing, also the pollution due of it. With all new trends in behalf of replacing classic pollution fuels (diesel and petrol) in favour of unconventional fuels (electricity, as an example), the next decades of internal combustion using and exhausted burning gases will affect the road tunnels and semi-closed spaces of them. The pollution involving exhausted gases is really felt in the tunnels, this increasing drastically when accidents and fire events occurs. In this situation, a traffic block with high release of pollutant substances per tunnel volume unit. The O₂ level may decrease at a dangerous concentration for human being and animals.

It can be related then open spaces such road and highways represent most important pollution spaces, both closed and semi-closed ones also can be pollution areas. One of these is represented by road tunnels, which involve a high density of traffic each day.

A very important factor to be considered is that most of the road tunnels existing today are 20-30 years old, so they were built in terms of traffic estimate at that time. In the past 10-15 years, the number of cars running on the roads significantly increased and the road tunnels built are practically the same. These conditions given, the pollution rate registered in road tunnels nowadays is higher than usually. It is also known that diesel vehicles are more polluting than petrol ones, due to diesel burn properties.

Measures taken over time indicated, in the morning and evening rush hours values of monoxide carbon just over 100 ppm and peak values up to 500 ppm were recorded at times [1]. Oxides of nitrogen were determined in some of the experiments and there was always more nitric oxide than nitrogen dioxide, experiencing eye irritation to users, also the cause of it was not analysed. The concentrations of pollution in the road tunnels do
not appear to be high enough in order to create any special hazards for short-term exposures. The atmosphere may though became very dirty sometimes and involve an additional concentration of carbon monoxide, dioxide and nitric oxide that can produce some effect over a period of several hours of continuous exposure. In order to keep the total emission of pollution from road vehicles in normal limits, measures including jet fan mounting are priority to be taken and followed, in 500 m or long road tunnels, according to specific law. By far the most dangerous situation that involves polluting is represented by fire. Unfortunately, in case of a fire occurring in a road tunnel, the pollution level increases much over the standard values. Due to this fact, the question of tunnel adaptive traffic management raises.

With these considerations in view, the tunnel ventilation control system may make use of the following measurements [1]: concentration of the different pollutants in each part of the tunnel, proper utilization of the natural resources, through flow rates in the tunnel sections, mean speed and traffic flow in each section, wind velocity and its direction, alarm-signals of smoke and fire detectors, there should be proper filtration process of the harmful gases, the materials used should be eco-friendly.

Based on the above mentioned findings, this article aims to analyse some of the circumstances and pollution conditions due to a fire taking place in a road tunnel, using Pyrosim software in order to simulate a real fire situation in given conditions.

2. GENERAL ASPECTS REGARDING FIRE POLLUTION IN ROAD TUNNELS

Although most road tunnels are placed in open spaces, between localities and in mountain areas, most pollution rate is registered in small tunnels, in towns, where traffic density recorded is very high. Due to many tunnels existing and the traffic, construction and later during the full life cycle of the tunnel, the surrounding environment is sensitive to undesired effects in case of an accident or a fire event.

As long as tunnels can be used by hundred thousand vehicles per day in busy areas, in case of a fire, extinguished can contaminate not only the near environment, but also they can leak into the ground water or be transported by sewage disposal systems.

It is well known that it is always better preventing than treating, so, even the pollution can’t be complete removed, it must be maintained at a minimum level.

Traffic represent one certainly way of environmental pollution, having a harmful impact on health but also indirectly affecting the quality of life by disturbing the eco-system, destroying our natural beauty and many more. Despite of all efforts and all kinds of recommendations to reduce, especially in large cities, traffic flow and pollutant emissions may be expected for the next few decades.

All types of vehicles fuels (diesel, gasoline, LPG, CNG etc.) and engines produces a lot of toxic substances which affect the environment.

On the Figure 1 we may observe that following a fire in a road tunnel, the polluting fluxes interaction with the local environment, resulting toxic product for it, which can be summarized as illustrated in Figure 1 as follows: direct gaseous and particulate emissions to the atmosphere, spread and deposition of atmospheric emissions, soil contamination and aquifer contamination. There are also observed fire effluents that go to the tunnel ceiling and those going to the network utilities, as corrected agents to be treated.

The figure shows us, that the pollution rate is much higher in tunnels that in the open spaces, given the location and any utilities meaning water supply, sewerage system, gas etc. that can cross the tunnel site. In this case, the location of the specific utilities must be caution provided, in aim to ensure a proper operation and access. Those pollutant substances are due to limited spaces existing in the road tunnels.

The specific pollutant compounds produced by traffic into the road tunnels are:

- Carbon dioxide (CO₂) is the main product of the combustion of a fossil fuel [2]. The substance is responsible for the “greenhouse effect”. Although a non-negligible amount of the produced CO₂ has to be taken on account of the traffic, the problem has a world-wide importance which is not specific to road tunnels ventilation.

- Carbon monoxide (CO) is produced in a reducing atmosphere, either by an overall shortness of the combustive or by a local deficiency due to the no homogeneous character of the mixture of fuel with air. The substance is present at all incomplete combustion.

- Nitric oxide (NO), mixture of NO and NO₂, of which the latter is a very toxic substance, is often referred to as NOx. Experiments showed that traffic contributes for about 60% to the entire NOx pollution. At high temperatures, its two main compounds combine to form NO (together with small amounts of N₂O) and this reaction is sufficiently fast enough to produce a measurable quantity. On the other hand, the cooling down after
the combustion process is too fast to allow a reversible dissociation of NO into its two compounds. A small amount of this NO is then transformed by oxidation into NO\textsubscript{2} at the exhaust pipe of the vehicle. The rate of oxidation is mainly dependent on the NO concentration, and thus the formation of NO\textsubscript{2} is favored by a higher pressure and a lower temperature (<160\degree C).

Fig. 1. Ways and sources of pollution in case of fire in a road tunnel.

3. CASE STUDY. ROAD TUNNEL FIRE SIMULATION USING PYROSIM

3.1. FDS model and stability criteria

FDS (Fire Dynamics Simulator), a software developed by NIST (The National Institute of Standards and Technology – U.S.A.), is a computer programme of fluid dynamic simulation, particularly of the heat flow released during a fire; it uses the high definition computer language “Fortran 90” and solves the governing equations of fire dynamics [3]. “Smokeview” program, written in “C/OpenGL” is the pair program that produces images and animation of the results.

Mathematical model adopted by is adapted on the fire development in which the fluid dynamics, the heat transfer and combustion occur. Though these equations are not recent the way they are numerically solved is updated and uses complex mathematical models which describe the evolution of the fire in time and space.

FDS computes the temperature, density, pressure, velocity and chemical composition within each numerical grid cell at each discrete time step. In addition, FDS computes on the solid surfaces the temperature, heat flux, mass loss rate and various other quantities.

Typical output quantities for the gas phase include: gas temperature, gas velocity, gas species concentration (water vapours, CO\textsubscript{2}, CO, N\textsubscript{2}), smoke flying particles and visibility estimation, space pressure, heat release rate per unit volume, mixture fraction (or air/fuel ratio), gas density, water droplet mass per unit volume contained in the atmospheric moisture, the walls and sprayed particles.

Pyrosim (meaning ‘pyro simulator’) represent the software that use FDS as a unit work in order to simulate fire burning mode and estimate involved parameters evolution [4].

Classical equations developed by FDS:

- Conservation of mass:
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = \dot{m}_b^{\text{in}},
  \]
  with: \( \rho \) – the density, in g/cm\textsuperscript{3}; \( t \) – the time, in s; \( \mathbf{u} \) – the velocity, in m/s; \( \dot{m}_b^{\text{in}} \) – the net heat flux from thermal conduction and radiation, in kg/s/m\textsuperscript{3}.

- Conservation of momentum (Newton’s second law):
  \[
  \frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) + \nabla p = \rho \mathbf{g} + \mathbf{f}_b + \nabla \cdot \mathbf{\tau},
  \]
  with: \( p \) – the pressure, in Pa; \( \mathbf{g} \) – the gravity acceleration vector, in m/s\textsuperscript{2}; \( \mathbf{f}_b \) – the external force, in N; \( \mathbf{\tau} \) the stress tensor, in N/m\textsuperscript{2}.
Conservation of energy (first law of thermodynamics):

$$\frac{\partial}{\partial t}(ph) + \nabla \cdot ph\mathbf{u} = \frac{Dp}{Dt} + q'''' - \dot{q}_b''' + \nabla \cdot \mathbf{q}'''' + \varepsilon,$$  \hspace{1cm} (3)

with:  
- $h$ – the enthalpy, in J/kg;  
- $q''''$ – the heat release rate per unit volume, in W/m$^3$;  
- $\dot{q}_b'''$ – the energy transferred to the evaporating droplets, in W/m$^3$;  
- $\mathbf{q}''''$ – the heat flux vector, in W/m$^2$;  
- $\varepsilon$ – the dissipation rate, in W/m$^3$.

3.2. Input data used in fire simulations

The geometry of the virtual space is similar to a real road tunnel. The geometrical data of the subway station is presented in table 1 and different views of the layout in FDS/ Pyrosim are given in figure 2 and 3.

Fire scenario: it is considered that the fire occur at one stationary car caught inside the tunnel, 3 m from one exit and 2.5 m from the other exit due to an electrical fault at the engine. The car is about 4 m long, 1.5 m high and 1.5 m width. The car is considered being made of steel, and the road tunnel walls from concrete. The burning develops a heat release rate (HRR) value of 400 kW/m$^2$, being square shape fire source with dimensions 0.36 m × 0.83 m.

Total simulation time is 50 seconds. The vitiated air and smoke evacuation is carried on through both tunnel outputs. The main objective of the paper is to study the amount of different values end the evolution for each parameter.

Figure 2 shows the car position and the tunnel architecture, in which the thermal processes occur.

According to Figure 3, the temperature field develops the gradient on the vertical up to 120 °C for around 1.8 m height. Also on the ceiling of the tunnel the temperature reaches 70 °C for an approximately length of 30 cm, which for a short time is acceptable.

**Table 1**

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational domain</td>
<td>Simulation volume</td>
<td>A presumed road tunnel, designed in the program, by taking geometrical data from given dimensions</td>
</tr>
<tr>
<td></td>
<td>Dimension of the volume containing road tunnel</td>
<td>10 m × 8 m × 5 m (in order on (0x), (0y) şi (0z) axes)</td>
</tr>
<tr>
<td>Numerical data</td>
<td>Cells per mesh, uniform division</td>
<td>30 × 35 × 15 cells</td>
</tr>
<tr>
<td></td>
<td>Dimension of one cell</td>
<td>0.5 × 0.5 × 0.25 m</td>
</tr>
<tr>
<td></td>
<td>The total number of cells</td>
<td>15.750</td>
</tr>
<tr>
<td></td>
<td>Boundary conditions for the simulation volume</td>
<td>The boundaries of the domain were both open. The whole structure of the road tunnel was considered of concrete.</td>
</tr>
<tr>
<td>Other data</td>
<td>The fire burner</td>
<td>Imported from the FDS library, HRR (heat release rate) of 400 kW/m$^2$, square shape fire source, dimensions 0.36 m × 0.83 m</td>
</tr>
<tr>
<td></td>
<td>Environment values</td>
<td>20 °C, relative humidity 40 %, atmospheric pressure 101.325 Pa, no air currents selected</td>
</tr>
<tr>
<td></td>
<td>Simulation time</td>
<td>50 seconds</td>
</tr>
<tr>
<td>Fan - wind current generator</td>
<td>Window (tunnel exit) of dimensions 5 × 8 m</td>
<td></td>
</tr>
</tbody>
</table>
Also the Figure revealed the thermal chart in the tunnel. It can be observed that on the horizontally direction the temperature is maximum on a distance of 0.5 m from the fire core. On the other hand, the base of the fire is at 1.5 m height so the hot gases at the tunnel ceiling are around 70 °C.

Figure 4 shows the axial temperature developed on the vertical. This allows us to decide concerning the ventilation system of the tunnel. The axial temperature remains almost stabilized in the ceiling tunnel zone, at about 70 °C.

According to Figures 5 and 6, the evolution of HRR is presented on the graphs below. We observed that the peak of 350 kW appear at 3 seconds and the period with a high temperature gradients is around 1.5 seconds. After 4 seconds up to 50 seconds, the HRR is stabilized at about 110 kW.

The simulation visible smoke results are presented at Figure 7. It can be observed that the tunnel gap is obturated by the smoke progressively as follow: after 25 seconds the percentage is about 30% filled with smoke at the zone of gap tunnel section. On the other hand, after 50 seconds, the gap tunnel section is about 50% filled with smoke, at the tunnel ceiling, where the temperature is also higher than it is at the tunnel base. These figures direct us to a location of the ventilation systems at the tunnel ceiling. If the fire continues, the smoke will reach 1.5 m of the tunnel base, which represents a real danger for the tunnel users.
We divided in 2 zones according how the software works with in aim to obtain a higher precision. The right side shows us the CO₂ concentration. We may observe that concentration reach about 0.9 kg/m³, in the vicinity of the fire core. In about 0.3 m from the burning area, the CO₂ concentration decreases up to 0.5 kg/m³. According to Figure 8, a maximum CO₂ concentration of 1 kg/m³ is reached after 40.8 seconds from the fire ignition.

The standard air has 21% molar O₂, with a concentration of 1 kg/m³ CO₂ (the air is considered to be only with C equivalent). Due to the combustion, CO₂ concentration in the local atmosphere may reach 1 kg/m³. The burning process occurs in the fire core and there can be reached even 1 kg/m³ concentration of CO₂ which at 117 °C is equivalent with 60% CO₂ volume, meaning 40 % pure air, meaning 8 % O₂, which becomes very dangerous for human life. According to Figure 9, a maximum value of 6.5 ppm vol. CO₂ is reached in about 50 seconds of simulation.

4. CONCLUSIONS

Tunnels are building considering their functional and constructive nature, therefore, to prevent fatal and enduring consequences of accidental pollution resulting from a fire, the taking measures must be pro-active, starting from prevention, preparedness, response and restoration at the initially stage.

It will take into account the category of the tunnel, prioritizing measures in sensitive areas and assessing the risk of fire and oil dispersal. Also, existing technologies in-situ (treatment in the existing environment), ex-situ (contaminated material transported outside environment and treated later) and on-site (contaminated material treated in a plant / environmental specialist) will be considered. From the above mentioned aspects, it can be said
that a fire at a road tunnel is severe (large scale) and can inclusive pollute considerably the environment.

The present article used a Pyrosim simulation in order to highlight the CO$_2$ values considering a fire occurring in a road tunnels in given conditions. Recourse to one car near an tunnel exit, it can be realize than in a real situation, involving many cars and a long tunnel, the environmental effects will be much higher.

From the simulation, were obtained important information about temperature evolution on the tunnel height and we arrived at 117 °C at the fire core level, respectively 70 °C at the tunnel ceiling level. This range of values allows checking the air circulation in the studied tunnel in aim to avoid the disagreeable values for traffic and life protection in road tunnels construction. The CO$_2$ concentration in some points of the tunnel gives us useful data for the ventilation system sizing (draught ventilation). Also, the fact that the time starting with fire ignition is an important parameter allow us to size a fire extinguish system which may be triggered in time thus limiting the damages.

References


