Experimental study on thermal and toxic hazards connected to different accident scenarios in road tunnels

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Tunnels have long been used for speeding up road and rail connections between places separated by natural barriers and for reducing traffic congestion in urban areas.
Not surprisingly, Italy with its particular orography and geographic position, has the largest tunnel length in Europe. In recent years serious accidents such as the fires in the Mont Blanc, Gotthard and Tauern tunnels have led to increasing attention to safety in tunnels. The transport of dangerous substances (inflammable and toxic) by road and rail is widespread in Italy and incidents involving this type of transport present an additional serious problem. Even if the last two decades have often seen drops in road accidents and a consistently high level of safety, recent accidents have shown that some types of commercial products, depending on their chemical composition, can cause large fires with severe evolving scenarios.
The objectives of the present paper are the experimental determination of thermal profiles inside and outside the gallery, under different thermal power emission and the qualitative and quantitative determination of toxic compounds of smoke from burning vehicles in a tunnel. Experimental techniques used to measure compounds from fire range in size from bench-top apparatus for testing small specimens, up to full scale tests. Regardless of the scale, it is important that fire reaction runs are carried out in conditions that closely replicate the type of fire to which the vehicle could be exposed. In particular, one of the main results of this work lies in providing an effective and reliable analytical methodology to optimize the analysis of toxic compounds of interest in tunnel fire scenarios.

1. Experimental material and methods

1.1. Tunnel modelling

Experimental runs were performed in a laboratory scaled tunnel, reproducing in scale the "Brasile" tunnel (located in the highway A7 Genoa-Milan stretch, Italy). The total length of the laboratory tunnel is 6.0 m, the internal radius is 0.15 m, the height from the floor is 0.2 m and the width at the floor level is 0.28 m. The model is made of fire-proof

concrete, with a Pyrex-glass made testing chamber (Fabiano et al., 2003). As summarized in the following, the physical model was properly modified and equipped in order to perform this study.
In the external surface of the tunnel, the model was equipped with two types of temperature sensors: internal temperature thermocouples chromel / Alumel (type K), with insolation oxide core and high heat insulated, sheathed in Inconel 600 with a diameter of 2 mm and length 800mm and external temperature thermal resistances type PT-100.
The model was also equipped with 4 tubes in glass placed on top of the vaulting, utilized as smoke sampling devices. The position of thermocouples type K was designed to detect the temperature profiles, considering four different heights and five thermocouples for each transversal section. The design was developed to ensure that it is possible to follow the stratification of smokes during the evolution of the fire.
The tunnel was divided into 4 sections, where section A corresponds to the flame and sections B, C and D equally spaced along the tunnel.

1.2. Analyses

The optimized sampling and analytical procedure was applied to the separation and quantification of different compounds in smoke. The smokes are passed into adsorbent systems properly selected, allowing the sequential sampling of different classes of substances.
The analytical methods are designed to characterize three classes of substances, namely:

- polycyclic aromatic hydrocarbons or PAHs through the use of PTFE and glass fiber filters and followed by a glass tube supporting XAD-2;
- inorganic acids were retained by a glass tube supporting silica gel;
- VOC and SVOC by a steel tube containing Tenax and subsequent thermal desorbtion.

In addition we used a real time monitor (Testo, Milan, Italy) allowing to detect carbon monoxide and oxygen profiles.

1.3. Pool fire

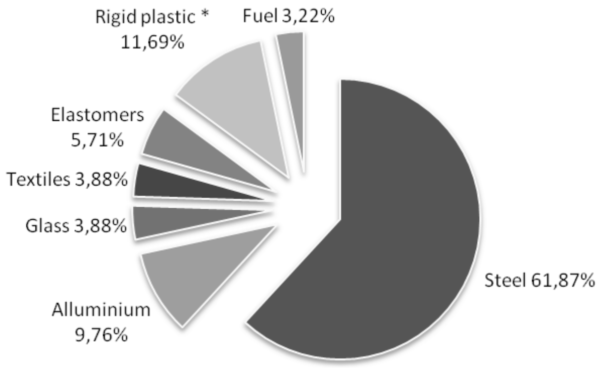
As already stated, one of the objective of this work is to study the thermal performance in a road tunnel during a fire. In order to perform the study, we used circles pools of white oil, designed to ensure constant flux during combustion. The estimate of kW emitted from a pool of known size was made assuming the presence of pool fire of white oil and a flame of cylindrical shape with its axis perpendicular to the plane of combustion, according to the well-known solid flame model (Marcon G., 2008).
The choice of the emissive power to simulate the tunnel accident scenario was made by elaborating literature and experimental data. The scaling method employed to extrapolate the data obtained from the model, in order to compare them with real scale results is known as Froude's method. The thermal power emitted from pools of oil were calculated, shows in table 1.

Table 1 Thermal power emitted from pools at different scales

Pool diameter [mm]	Fuel volume [mL]	Model thermal power [kW]	Thermal power of real fire [MW]
40	5	0.18	1
50	8	0.37	2
62	12	0.74	4
80	20	1.49	8
100	31	2.96	16

1.4. Test car

The focus of fire runs with scaled vehicles is to study the thermal evolution and the chemical composition of smokes developed after the fire of a car inside a tunnel.



*Rigid plastic: PP, PU, PE, PVC, PA, ABS, PS, PMMA, PET, PC

Figure 1 Prototype car composition at the laboratory physical scale 1:30

To this purpose, starting from car firms data, a detailed statistical analysis was performed allowing to characterize the average chemical composition of a real car. Starting from these results it was designed a prototype vehicle reproducing, at a physical scale 1:30, a real car in all its chemical materials including fuel and accounting for 12136 MJ and 480 kJ respectively for real and laboratory scale car. Figure 1 shows the percentage composition of the prototype car. In particular, in order to simulate the tank of a car we adopted a put fuel (1.85mL) in a 2mL polypropylene microvial (“Eppendorf”). The effect of such a technical solution during the evolution of the fire is to create a flash fire at the time of the opening of the tank.

The modeling approach developed according to the Froude similarity criterion and by the design of a prototype car represents, at least to our knowledge, a first attempt to characterize experimentally “realistic” fire evolving scenarios in road tunnels, at a laboratory scale.

2 Results and discussion

The results obtained are the thermal profiles of the oil-pools and prototype of the car and analysis of smoke generated by fire prototype of the car.

2.1. Thermal profiles

All experimental test with fire of different power, thermal profiles, detected in the four sections of the model, evidence similar trends. As can be seen in figure 2, section of A is characterized by very irregular thermal profiles. This feature is due to the fact that the thermocouples were positioned in line with the point of fire and therefore are to detect the temperature of the flame. The tunnel ventilation, either natural or mechanical, as well as non-stationary characteristic of the flame create a strong movement of the same affecting the thermocouple results. Temperature profiles of section allow appreciating the substantial difference between the combustion involving pools of oil and the prototype car. Indeed, in the test of pool a stationary temperature value was detected, contrarily to the trend during test car runs. The burning of oil is very stable and thus a constant temperature regime is easily reached. On the contrary, the combustion of the prototype car is not stationary, because the composition of the sample, the sequence of the combustion of individual components and the evolution of combustion varies over time, causing difficulties in the identification of a temperature regime. It must be noticed that the combustion time is strictly dependent on the average composition of the prototype car. The other sections of detection, are characterized by more regular temperature profiles. Here the thermal profiles are individually due to the stratification of smoke along the tunnel, while the nature of combustion exerts only slight influence.

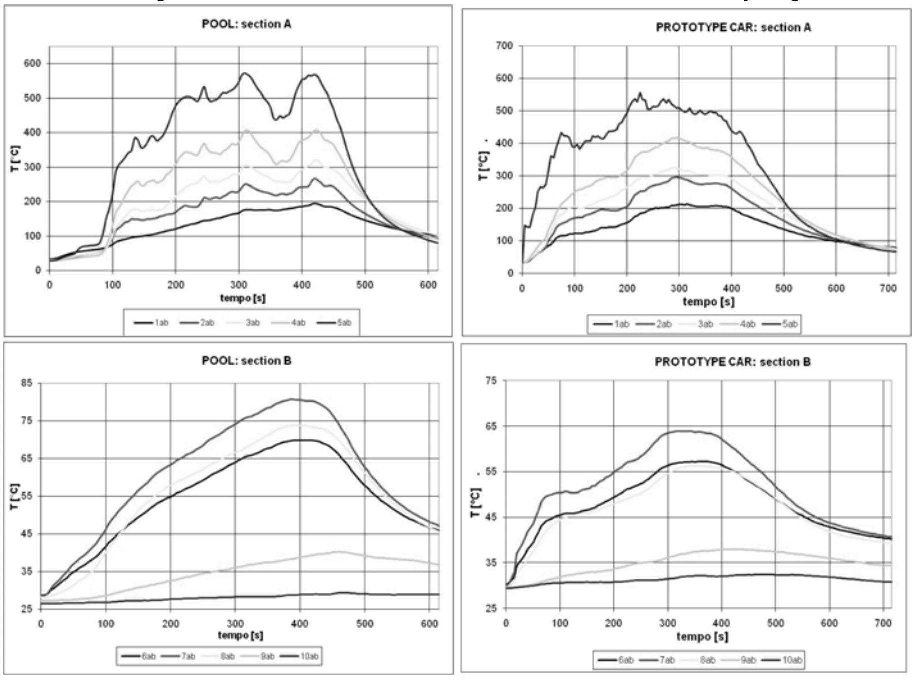


Figure 2 Detection sections A, B: oil pool, prototype car

Trends in temperature over time strongly depend on the fire heat (kW) of the fire and slightly on the nature of the released compounds during fire. Test characterized by similar thermal emissions showed similar values of temperature. This is valid also comparing test of oil and prototype cars and is consistent in all detection sections (with the already-mentioned exception of section A). As shown in figure 3, during all tests made, the temperatures recorded by thermocouples near vault are not the highest ones. In fact, it was experimentally verified a decrease of smoke temperature near the tunnel ceiling connected to enhanced heat exchange between flue gas and concrete and to stratification of the smoke on the vault. As hot smoke move outward under the vault it transfers energy by conduction to the adjacent ceiling surface that is rather cool and, by convection, to the entrained air. Information on the relative raise of temperature (dT/dt) can be derived from these data and can provide a valuable input to define properly a limit for a fire alarm. Globally, the growth rate is slower for the car fire, with an incubation time for the fully developed fire. Another common characteristic is the intersection between the curves of temperature at 2 cm and 5 cm from the vault. In all tests, in the section of the tunnel near fire, the high temperature is 2 cm from the vault while, at the end of the tunnel, the highest temperature is recorded at 5 cm.

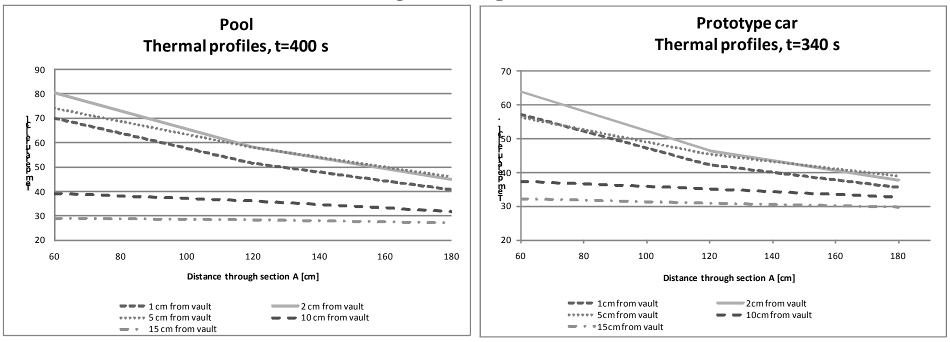


Figure 3 Thermal profiles at different heights of the pool of oil and car prototype

2.2. Smoke characterization

Analysis of smoke samples during the combustion evolution of the prototype cars are intended to obtain preliminary indications on the toxic load of smokes. The fumes produced are substances derived from combustible materials and their toxicity is linked to the nature of the origin material (e.g. the presence of elements such as chlorine, bromine, sulfur could result in particularly toxic chemical species). Another factor to be considered is that the combustion occurs in a constrained environment and the conditions of aeration highly interfere on the combustion product distribution. In particular, two types of thermal decomposition can be identified in the selected scenarios, namely well-ventilated flaming combustion, typical of pre-flashover fires and ventilation limited combustion typical of post flash-over fires.

The search for inorganic acids gave positive results for four acids: hydrochloric, nitric, sulfuric and fluoride. Hydrochloric acid is derived from thermal decomposition of PVC, polymer present in small part. Sulfates are connected to sulfur anhydrides in the vulcanized rubber tires. Dealing with IPA production we verified a predominant production of light IPA compounds. Gas sampling by Tenax allowed characterizing quantitatively following aromatics: benzene, toluene, ethyl benzene and xylene. The results show significant presence of paraffin (C4 to C16 and above) also branched, as well of a wide range of aromatics from benzene to phthalic esters.

In order to evaluate the lethal toxic potencies of smoke from tunnel fires, it seems advisable to compare LC_{50} values with results obtained on a material-by material basis. It must be noted that the toxic potency is dominated by the large amount of CO

produced during under-ventilated burning. As depicted in figure 3 and summarizing the results from the different experimental runs, the CO yield appears controlled by the oxygen shortage more than by the differences in the vehicle composition.
The threshold limit of 150 ppm for CO represents the selected value maintaining intact the physical and psychological state of an average person. The oxygen limit is indicated at the value of 19.5% (v/v). Summarizing, comparing results with toxicity indices, it seems more likely that the overall synergic effect of all products of combustion, mainly CO and the under- oxygenated conditions percentage of oxygen, make up the "cocktail" that is dangerous, in a characteristic context such as a tunnel.

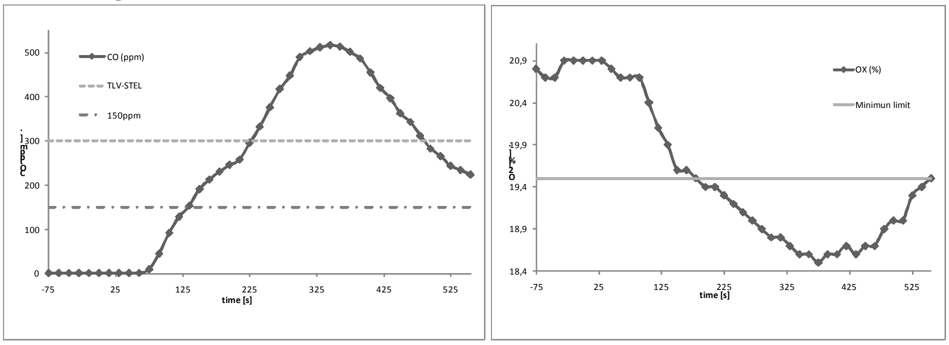


Figure 4 Carbon monoxide and oxygen concentration vs. time from fire start.

3 Conclusions

In this study experiments were performed to investigate thermal profiles considering different heat release rates. In particular, one of the main results of this work lies in providing an analytical methodology to optimize the analysis of toxic compounds of interest in tunnel fire scenarios. Starting from a statistical analysis of vehicles available on the market and of their main percentage composition in term of constructive materials, it was possible to define and realize a prototype vehicle. The experimental procedure for the investigation of combustion products was developed as an attempt to compare the product yields with those occurring in full-scale scenarios. In each experiment, three classes of compounds were identified with good accuracy and reproducibility, namely polycyclic aromatic hydrocarbons; inorganic acids and volatile and semi-volatile organic compounds. The results obtained under different heat release rates allowed evidencing the dependence of the yields of toxic gases upon the ventilation conditions and the heat release rate connected to the considered scenario. Based on the intrinsic toxicity data of each identified compound, it is possible to draw practical conclusions useful to assess the potential hazard associated to exposure to toxic smoke in road tunnel.

Reference

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