1. Introduction
In recent years, several high-profile road tunnel fires have taken place across Europe. These fires, due to their great intensity, inevitably led to important structural damages and even loss of lives.

Among them, the most relevant ones were the fire in Mont-Blanc tunnel, joining France and Italy, which caused 39 casualties (1999); the fire in Tauern tunnel in Austria, in which 12 people lost their life (1999); and the fire in St. Gottard in Switzerland, which resulted in the death of 11 people (2001).

In all of these tunnels, national mandatory safety regulations were implemented. Nevertheless, disasters could not be averted.

Many other fires were not so serious and their consequences were not so relevant. They could be effectively put out by firefighters, avoiding both fatal victims and relevant damages on systems and structures.

The total length of tunnels continues growing year by year, the same as their intensity of traffic. In consequence, although the probability of occurrence of fires inside tunnels is relatively low, it is unavoidable that their frequency drastically increases.

Safety measures must be increased and improved in this kind of structure so that risky situations caused by fires become less frequent. In case they happen, they are extinguished thanks to higher safety standards that guarantee the physical integrity of users and emergency teams.

The analyses of the causes that brought about these fires and increased their intensity have provided engineers with a lot of information so as to design new safer tunnels and improve the safety of existing ones. These analyses also permitted to identify those factors that occasionally could contribute to the spread of the fire, exceeding the designed safety measures and causing dangerous situations in which life could be lost.

Despite these studies, the influence of some of these variables on fires is not completely understood and, therefore, their dangers could be undervalued. Some elements that in other situations would mean no risk could contribute to worsen the situation inside tunnels in case of fire. Under certain circumstances, these factors could lead to fatal disasters.

Fire brigades, as experts on risks on tunnel fires, have adapted and improved intervention techniques in order to tackle this kind of emergency in a fast and effective way.

Risk prevention services, which supervise and authorize safety projects for tunnels, have also increased safety requirements so that dangerous situations in any type of emergency are minimized.
Apart from a deep knowledge of safety and fire equipment within a tunnel that is subjected to a fire, it is also essential for firefighters to have a profound knowledge of the fire dynamics inside tunnels and the influence of all the elements that, to some extent, contribute to the fire.

One of the factors that modifies the behavior of fires inside tunnels is the type of road pavement. This recent study of the Spanish Technical Association of Firefighters shows that concrete pavements are inert elements and their interaction with fire is limited to the absorption of part of the heat generated. On the other hand, asphalt pavements are active elements that burn, releasing fumes and heat. In some cases, this material can modify the spread behavior of the fire, worsening evacuation conditions and complicating the work of firemen.

The document explains the special characteristics of fires inside tunnels and the advantages of concrete pavements in comparison with asphalt pavements in this kind of situations.

2. Fire dynamics inside tunnels

Safety systems within tunnels have improved significantly in the last years as a result of a more and more demanding European regulation.

Safety systems depend on the tunnel geometry, its length, the traffic intensity and the kind of freight transported through the tunnel. Thus, they can be classified into passive safety systems (general system) or active safety systems (ventilation systems).

The behavior of fires indoors is very different from the behavior of open-air fires. In a tunnel, a great amount of the generated heat remains inside contributing to fuel heating and speeding up combustion process. A key element of combustion dynamics is the presence of air that provides the fire with oxygen. In tunnels that are equipped with artificial ventilation systems, combustion progresses without any limit, reaching higher temperatures than in naturally ventilated tunnels. Another factor that contributes to increase the power of fires is the fuel distribution within the tunnel. Nevertheless, the most dangerous element for users and firemen is smoke, which reduces vision and suffocates people due to both the suspended particles and toxic fumes.

Regarding the dynamics of fires caused by heavy vehicles inside tunnels, three stages can be identified:

- **Initial spreading stage**, in which gases generated go up to the roof whereas the lower part of the tunnel remains free of smoke and heat allowing evacuation activities. This stage progresses slowly.

- **Exponential spreading stage**: in which heat transmission evolves from convection to radiation. Smoke goes through several hundred meters until it gets cool and goes down as it moves away from the seat of fire. This process complicates the evacuation activities and firemen access to the fire. Flames can also spread through dozens of meters to both directions from the seat of fire and heat power will increase steadily. When heat power reaches 30 MW, basically equipped extinction teams are not able to fight the fire. Heat radiation will only permit firemen to be as close as 10 meters from the flames during a very short period of time, limiting the chances to put the fire out. Smoke and heat control by ventilation systems are essential in this stage.

- **Progressing stage**: in which fire power exceeds 40 MW, heat is accumulated within the tunnel and artificial ventilation systems malfunction due to high temperatures. If this stage is reached, the surface of the pavement becomes essential to forecast the fire.
behaviour: concrete surfaces will absorb part of the generated heat and they will contribute neither to the fire spreading nor to the generation of fumes.

![Initial spreading stage](image1)
![Exponential spreading stage](image2)
![Progressing stage](image3)

Fig. 1: Stages of a fire inside a tunnel

3. **Pavement performance**

If the power of the fire exceeds 30 MW and artificial ventilation system is not able to absorb the generated fumes, flames could reach dozens of meters spreading through both sides of the vehicle and through the roof of the tunnel. In consequence, the temperature of the surface of the pavement will reach up to 300 °C and, under these circumstances, bituminous and concrete pavements will behave very differently.

**Concrete pavements**, thanks to their inert behavior, will only act as heat accumulators. During the first stage, heat will cause the evaporation of concrete water and the only effect will be that in which the surface of the pavement will become hotter and hotter reaching the inner part of the pavement. The good behavior of concrete at high temperatures will prevent the pavement to deteriorate, permitting extinction teams to access to the tunnel.

As asphalt is a combustible material, **bituminous pavements** may generate fumes at low temperatures although they do not burn below 485 °C. In that moment, asphalt would burn as long as the radiation is over 40 kW/m². Despite the fact that asphalt combustion generates a low amount of heat, the truth is that this heat is produced in the lower part of the vehicle, changing the dynamics of the fire and speeding it up. This generation of heat in the lower part of the tunnel makes the fire widespread and causes a sudden and dramatic increase of power, which can be observed in figure 2. Speeding up the fire will cause a significant increase of smoke together with the fumes generated by the combustion of the pavement. As a result of this, after the pavement starts burning, conditions around the fire will worsen quickly, preventing firemen to work in safety conditions.

![Figure 2: Sudden increase of power due to a change in the fire dynamics](image4)
Another consequence of this increase of power is the risk that the fire spreads to other vehicles, when it exceeds 50 MW. This effect may trap firemen between two fires, since they have to be as close as 20 meters from the original fire so as to put it out and new fires can be set behind them. Avoiding this sudden increase of power caused by the combustion of the asphalt pavement is essential to guarantee the safety of fire fighters.

Moreover, this combustion in the lower part of the tunnel may cause the explosion of the wheels of heavy vehicles, which represents an additional risk for firemen who are close to the fire. Besides, as asphalt is a thermoplastic material whose viscosity decreases with temperature, asphalt will significantly soften at temperatures between 150ºC and 180ºC, which are reached approximately 5 minutes after the beginning of the fire and at a distance of 45 meters from the seat. This distance is longer than the working distance of firemen and it difficulties mobility.

4. Firemen working conditions

As the fire progresses and spreads steadily moments after its beginning, it is essential to reach the fire before its power is higher than extinction capacity of firemen.

Numerical simulation techniques permit modeling and analyzing dynamics of fires inside tunnels. In the present study, four kinds of tunnels have been analyzed. Two of them have a domed geometry, with and without longitudinal ventilation, and the other two have a rectangular geometry, one with semi transversal ventilation and the other one with transversal ventilation. In all cases, the length of the analysis is 250 meters (125 meters in each direction) as relevant effects do not occur any further.

The main variable studied is the power of fire for every defined scenario and for both types of pavements, asphalt and concrete. When a concrete pavement is used, the power increase is much lower and, in consequence, extinction brigades will have more time to get to the fire and working conditions will be more favorable. This effect is common to all scenarios independently from the ventilation system. Figure 3 shows the differences.

![Figure 3: Power of fire for different scenarios](image)

If asphalt contribution to fire were limited to the energy generated by burning pavement, the power increment would be 4 MW, since the burning surface considered is 100 m² and the unit power emission is 40 kW/m². This power would represent the 8% of total fire energy and it should not significantly worsen working conditions unless fire dynamics changed completely.
Total energy generated will be the same, but emission rate drastically increases after the asphalt starts burning. Figure 4 shows the difference between both kinds of combustion processes depending on the type of pavement.

![Fig. 4: Differences in fire progress](image)

Asphalt pavement contributes to the combustion of the surrounding surface of the burning vehicle and additionally it worsens environmental conditions due to the heat generated in the lower part of the tunnel.

In a nutshell, in case of a fire inside a tunnel, the study proves that asphalt pavements increase significantly the power of the fire, whereas concrete pavements help improve working conditions of firemen.

5. **Evacuation conditions**

The main objective of ventilation systems is keeping proper environmental conditions inside the tunnel in order to carry out evacuation activities in a safety way. The most important factors that must be guaranteed or limited are toxic fumes, visibility, temperature and thermal radiation coming from flames.

The movement of smoke mass can be modeled by numeric simulation when power inside the tunnel is higher than 40 MW (see figure 5). An important growth of this mass can be observed when asphalt pavement begins to burn. However, results remain constant in case the pavement of the tunnel is made of concrete because the ventilation systems keep working efficiently.

Figure 6 shows the lack of visibility 400 seconds after the beginning of the fire at ground level in case the ventilation system is transversal. As it can be appreciated, the visibility is much better when the pavement of the tunnel where the fire is taking place is made of concrete.
Other parameters studied, such as oxygen concentration at a height of two meters above the ground or temperatures distribution along the tunnel; let us conclude that concrete pavements improve evacuation conditions inside tunnels in comparison with asphalt pavements.

The study also assesses the effect of the fire on systems and infrastructures, which can be very severe causing the tunnel to be out of service for a long period of time.

6. Conclusions

Some European regulations regarding the use of concrete pavements within tunnels whose length is over 500 or 1.000 meters (depending the country) is well grounded. The amount of fumes and heat released by burning asphalt surfaces is comparable to that produced by the combustion of a truck. The heat energy that asphalt surfaces may release, generated in the low part of the tunnel, can change the dynamics of the fire, leading to an increase of its intensity. In consequence, the fire could spread easily to other vehicles through the pavement. Additionally, the increment in the power of fires could mean that design load of ventilation
systems was exceeded, so that the fire was harder to fight resulting in a higher risk for people and for the structure.

This effect took place in some fires inside tunnels at the end of the 90’s in Austria, France and Italy and they all resulted in tragedies.

When fume extractors are insufficient to eliminate fire gases, heat will accumulate inside the tunnel causing other vehicles to catch fire and larger asphalt surfaces to burn.

In some extreme cases, the use of concrete pavements may be the key factor that permits keeping the amount of heat and gases under the design limits, so that the extraction system continues working until the situation is under control.

Evacuation proceedings and the action of emergency teams will never be affected in case the pavement is made of concrete. On the contrary, asphalt surfaces could complicate the situation.

Safety measures are designed for standardized fires, but in some occasions, the power of actual fires exceeds the designed values. In these cases, safety margins for both commuters and emergency teams are reduced to the minimum.

Any element that contributes to make the situation worse should be eliminated or minimized. During fires in road tunnels, a factor that definitely worsens the situation is the presence of asphalt in the surface.

Safety contribution of concrete pavements during fires in road tunnels is widely justified by professional fire brigades and, therefore, they strongly recommend the use of concrete pavements in any road tunnel independently from their length.