# ON THE AERODYNAMIC CHARACTERISTICS OF PARTLY OPEN GALLERIES IN CASE OF FIRE

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## ABSTRACT

Galleries completely or partly opened on one side are very common in the Alpine area, where they provide protection against natural dangers (avalanches, landslides and falling rocks) while allowing for a fair level of natural lighting and ventilation. The strong natural ventilation does also influence smoke propagation. However, from a normative point of view, galleries often fall into a grey zone, treated neither as open road nor as closed tunnel, engendering uncertainties about the required safety equipment.

The effect of the side openings (“windows”) of galleries on smoke propagation is investigated based on CFD simulations and on experience from a real fire event. The results are evaluated especially in terms of need for safety equipment, particularly emergency exits, and compared to fully closed tunnels. The results show, that requirements on self-rescue facilities for partly open galleries are generally lower than for tunnels. On the other hand, steep galleries coupled to tunnels do not show the tendency to mitigate the effects of incidents.

*Keywords: gallery, fire safety, smoke propagation ventilation design*

## 1. INTRODUCTION

This papers deals with the operational safety of galleries in case of fire, from the point of view of self-rescue and intervention. The primary focus is on road infrastructures but the main findings and conclusions apply also for galleries on railway networks.

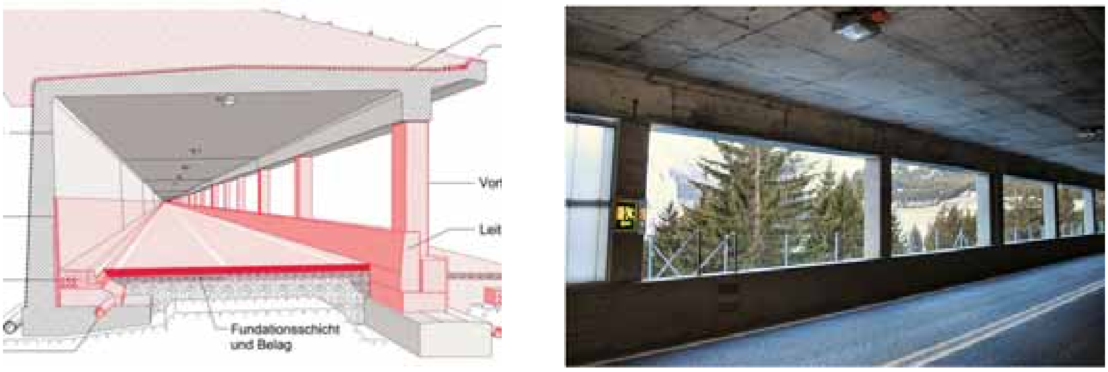


**Figure 1:** Typical Swiss protection gallery investigated in this paper

Galleries are a very common feature of roads and railway lines in the Alpine area. Schellenberg (2009) reviews more than 350 existing protective galleries in Switzerland. About 300 are located on the national, cantonal or local road network, while about 50 are part of the railway network. The primary function of galleries is generally protection against natural dangers, particularly avalanches, landslides, falling rocks or mudflow. The typical structure of protection galleries is presented in Figure 1. In most cases, they are entirely closed on the top and on one side while they are partially or entirely open on the opposite side. Galleries are frequently combined with tunnels, for offering an optimum compromise between protection of the infrastructure, investment and operating cost. Galleries are particularly interesting because of the high level of natural lighting and ventilation. Noise-protection galleries in urbanized areas could be structurally different but share many common elements in terms of smoke propagation and requirements on safety facilities.

A large body of literature is available on the structural behavior of galleries in case of rock fall and avalanche. Knowledge on smoke propagation and the resulting conditions for self-rescue and intervention is very limited. Mayer et al. (2012) investigated the requirements for certain safety equipment in galleries with lateral openings and ceiling openings based on quantitative risk analysis. They concluded, that the influence of emergency exits on the risk level is reduced with lateral openings, especially if the inner clearance is increased or if the ceiling is inclined towards the lateral opening.

Most current regulations do not distinguish between tunnels and galleries. The European directive 2004/52/EC defines “tunnel length” as ”the length of the longest traffic lane, measured on the fully enclosed part” and NFPA 502 defines a road tunnel as “an enclosed roadway for motor vehicle traffic with vehicle access that is limited to portals”. The French regulation (2000) is an exception because it provides explicit guidance on this subject: the national regulation on road-tunnel safety is not applicable to enclosures with openings larger than 1 $m^2$ per lane and m length. Most protection galleries have significantly larger openings.

The lack of specific regulations, coupled with poor physical understanding of smoke propagation in partly enclosed traffic infrastructures, result in significant uncertainties concerning the level of safety facilities required for user protection in galleries, particularly emergency exits. These issues, largely related to smoke propagation shall, be addressed here. This paper focusses on galleries with comparatively large side openings, of the order of at least 1/3 of the side surface or more (Figure 1). Most existing galleries fall into this category.

## 2. THEROETICAL INVESTIGATION OF KEY PARAMETERS

In normal operating conditions, the combined effect of vehicle motion (piston effect and pressure fluctuations) and external wind generally allow for an excellent air exchange in galleries. An entirely different situation arises in case of fire, where the exchange with the exterior is dominated by thermal effects and where much of the smoke should be expelled through the side openings over a short distance, for ensuring a proper level of safety.

A simple model about the thermal exchange over the sidewall can be used for illustrating the underlying physics. Consider an enclosure opened on one side subject to an arbitrary temperature difference. The air velocity through the opening can be expressed as

$$u = \sqrt{\frac{2}{\rho_i} \cdot (p_i - p_o)} \approx \sqrt{2 \cdot g \cdot y \cdot \left(\frac{T_i}{T_o} - 1\right)}$$

where the symbols denote: $y$ = vertical coordinate, $p$ = pressure, $\rho$ = air density, $T$ = air temperature, $g$ = gravitational acceleration, $i$ = inside, $o$ = outside.

This simple approximation shows, that a substantial air exchange through the side openings can be expected in case of fire, with air speeds of the order of 2-3 m/s or more. Further significant differences compared to tunnel fires are:

- The airflow available for combustion in the case of galleries is virtually unlimited and fires are most likely to be fuel limited.

- The longitudinal airflow below the smoke layer in direction to the fire plume, which tends to destabilize the smoke layer, is limited.
- The “stack” effect, generating a longitudinal airflow, is limited by the loss of buoyancy due to the smoke leaving the gallery and due to the openings, which prevent the creation of a longitudinal pressure difference.
- The potential for using mechanical ventilation is very limited (creation of longitudinal pressure difference is not possible) and cannot be seen as efficient safety measure in open galleries.

The physics of smoke propagation in galleries is largely determined by the key geometric parameters (width, height, open height, lateral and longitudinal slope) and by the vertical thermal gradients.

## 3. APPROACH AND CASE STUDIES

### 3.1. Approach

The authors investigated a number of real-life galleries in the past few years, covering a wide range of relevant parameters. While not systematic, these investigations are quite representative for two-lane galleries in the Alpine room. All investigations were carried out based on CFD simulations carried out using the commercial software package FDS. FDS (http://www.nist.gov/el/fire_research/fds_smokeview.cfm), combined with its own visualization tool, is considered by many tunnel specialist as the preferred software for investigating tunnel fires and smoke propagation.

All case studies presented herein refer to existing infrastructures and are based on real investigations carried out by and for the responsible road authority. The identification and localization of the different objects is immaterial.

### 3.2. Small longitudinal slope

An existing urban gallery is used as prototype for illustrating the simplest situation, a gallery with small longitudinal and characterized by the following parameters:

- Length: ca. 200 m
- Slope: 0.6%
- Width: 9.5 m (2 lanes)
- Height: 5.7 m
- Average side-opening height: 3.7 m.

A HGV fire on the inner lane with idealized HRR curve was considered, which rises linearly to 30 MW within 5 minutes. The gallery structure and smoke propagation in absence of wind are illustrated in Figure 2. Smoke stratification and visibility conditions within the gallery are excellent during all the phases of the fire.

Galleries are frequently exposed to wind. A specific investigation was therefore carried out with an external wind of 1.4 m/s orientated at 45° with respect to the tunnel axis. The results are presented in Figure 3. They show that external wind does not change the previous conclusion. Although the wind does generate some turbulence around the pillars of the openings, the visibility conditions are deteriorated only locally, close to the burning vehicle. Self-rescue conditions are pretty good over a long time period. It was concluded that the initially planned emergency exits are not needed.

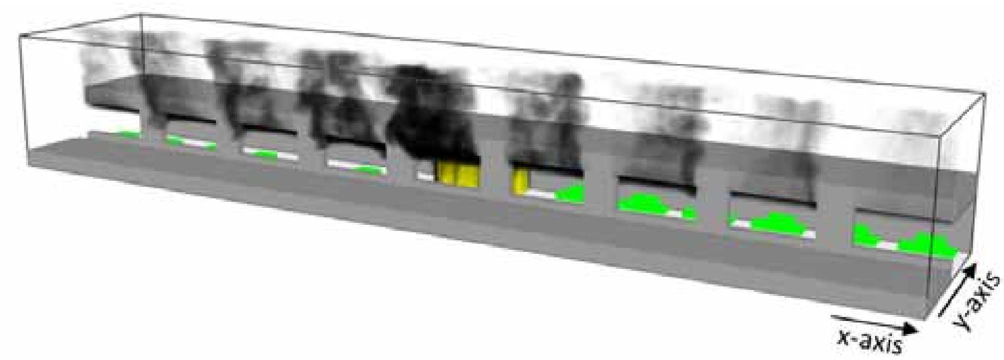


**Figure 2:** Smoke propagation and visibility in the gallery 4 minutes after start of fire (no wind).

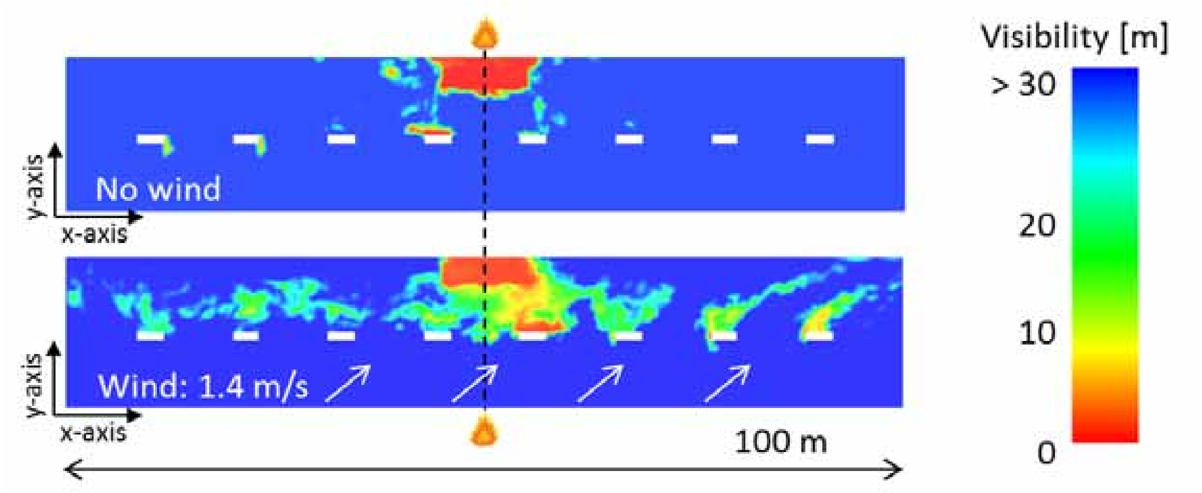


**Figure 3:** Visibility conditions in the gallery at 2 m height for a 30 MW fire, 4 minutes after start of fire, for different wind situations (white rectangles are pillars)

### 3.3. Large longitudinal slope

Particularly in mountainous areas, longitudinal slopes in excess of 3% are frequently encountered. Many existing galleries even exceed the now commonly accepted threshold of 5%. The influence of longitudinal slope is well known for closed tunnels. The difference between tunnel and a partly open gallery shall be illustrated based on a gallery characterized by the following parameters (Figure 1):

- Length: ca. 600 m
- Slope: 6.1%
- Width: 9.5 m (2 lanes)
- Height: 5.7 m
- Average side-opening height: 3.7 m.

Further assumptions are: all vehicles at rest, vanishing initial air velocity, no external wind.

The results are presented in Figure 4, which shows the visibility conditions computed for two geometrically identical structures, the gallery presented in Figure 1 and the tunnel resulting if the sidewall is completely closed. The openings in the gallery prevent the development of a strong stack effect with a high longitudinal velocity and allow smoke to leave the gallery over the side openings. A significant fraction of the buoyancy flux is lost and the stack effect is significantly reduced, as shown in Figure 4. The stratified layer is stabilized and the propagation velocity of the smoke front is reduced. Compared to a closed tunnel, the self-rescue conditions are significantly better.

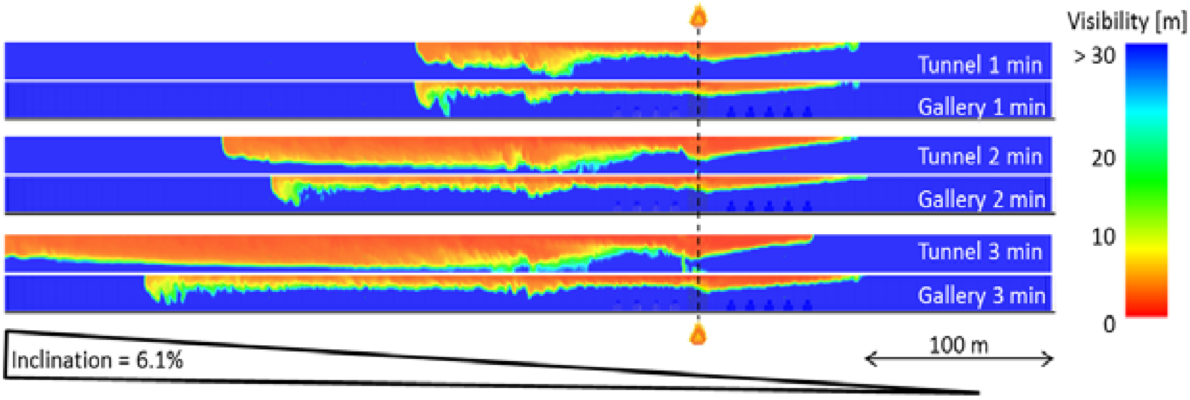


**Figure 4:** Smoke propagation in tunnel and gallery with identical shape (6.1% slope)

The openings do not only allow smoke to leave the gallery, they also reduce the longitudinal velocity towards the fire source in the "fresh air" layer below the smoke layer. The smoke layer is thus much more stable, even if the temperature in the smoke layer decreases. This effect is characterized by the specific Froude number, which is defined as:

$$\mathrm{Fr} = \frac{u_{avg}^2}{\sqrt{g \cdot H \cdot \Delta T_{cf} / T_{avg}}}$$

According to Nyman and Ingason (2012), a stratified smoke layer is expected for $\mathrm{Fr} < 0.9$. Due to the vanishing longitudinal velocity in the gallery (no generation of longitudinal pressure difference) in the fresh air layer below the smoke layer, the Froude number is obviously smaller than in the tunnel, or in other words, smaller temperature differences between smoke layer and fresh air layer are possible without loss of stratification.

A further advantage is, that local disturbance and mixing of the smoke layer with the lower fresh air layer has no impact on self-rescue conditions further away. Usually these disturbances are convected towards the fire source. The missing longitudinal air velocity prevents the transport of such disturbances.

### 3.4. Interaction between tunnel and gallery

Techno-economical project optimization in mountainous areas frequently leads to road sections with continuous sequences of tunnels and galleries without entirely open sections in between. Galleries are also very common at the ends of tunnels, as a compromise between safety and excavation cost. The slope is frequently high to very high and frequently exceeds 5% in existing infrastructures. The situation is investigated based on the following real-life example: a tunnel, which is coupled to a gallery at the upper portal, both with a longitudinal slope of 6.1%. The properties of the gallery are in fact identical to the one presented in chapter 3.3. The tunnel has a length of about 550 m and is not ventilated mechanically.

Due to the thermal effect and to the tunnel slope, airflow towards the upper portal with high velocity is generated, destroying smoke stratification. The configuration with a gallery tends to have a slightly higher longitudinal velocity in the beginning due to the shorter tunnel and smaller friction losses (Figure 5), and thus a slightly faster smoke propagation. At the boundary Gallery – Tunnel, smoke is already distributed over the whole tunnel cross section. Looking at the further development of the smoke propagation, the positive effect of the gallery can be observed. The smoke propagation velocity is slowed down and smoke density is lower in the gallery if compared to a geometrically identical tunnel. However, the differences between gallery and tunnel are small and self-rescue conditions are not improved in a manner that would lead to a reduction of the required safety equipment. The loss of stratification in the tunnel cannot be reversed and the high smoke propagation velocity is mainly based on the longitudinal airflow driven by the stack effect in the tunnel.

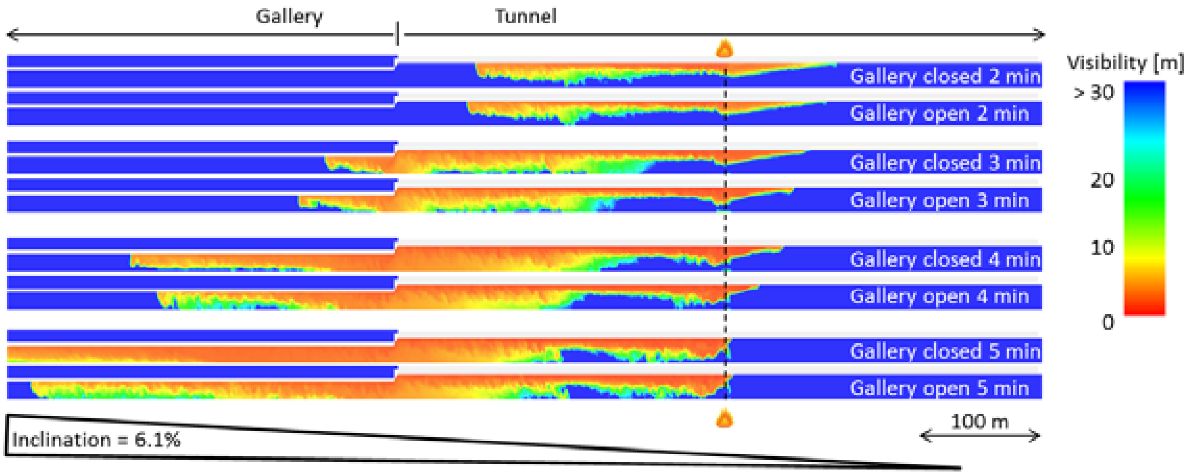


**Figure 5:** Smoke propagation in case of fire in the tunnel with adjacent gallery, slices called tunnel are fully closed in the gallery section too.

### 3.5. Fire position in relation to open side and influence of aspect ratio

The fire position has been identified as a possible influence factor for smoke propagation and characteristics of the smoke layer, especially in wide galleries. An example where the focus has been laid on temperature distribution and development shows that the influence of fire position (close to the open side or close the sidewall) can be neglected. If the fire is placed close to the open side, the conditions are slightly less favorable, due to the local disturbances at the closed sidewall.

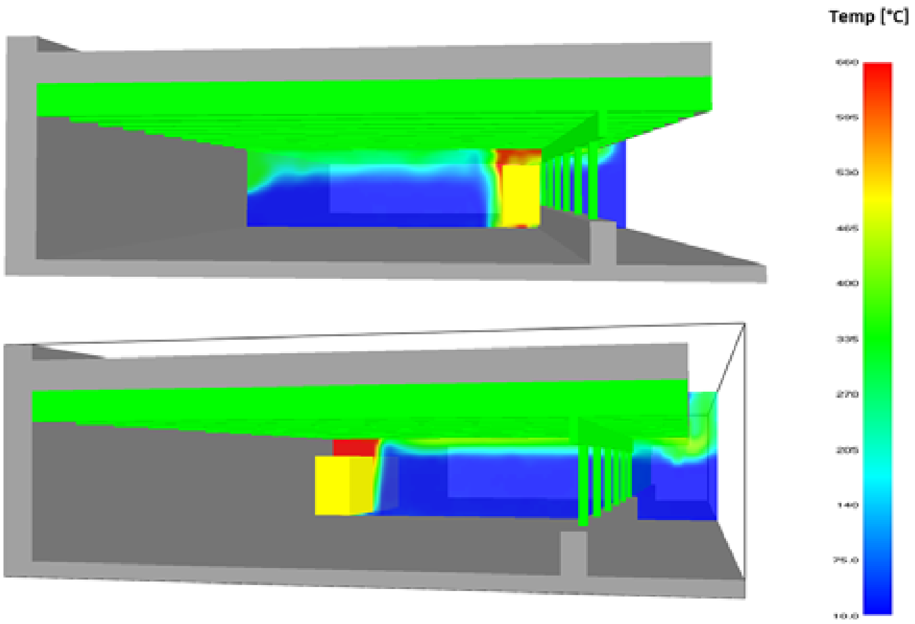


**Figure 6:** Different fire positions in a wide gallery (temperature distribution)

## 4. FINDINGS FROM REAL EVENTS

Two fires confirm and further illustrate the findings from the simulations presented in the previous chapters. The first example is a bus fire, which occurred in the year 2002 in a 2.2 km long combined system consisting of tunnels and galleries with 5.7 to 6% longitudinal slope. The fire occurred in a 231 m long tunnel, whose upper portal is directly connected to a 432 m long gallery. The upper part of the gallery during the fire is presented in Figure 7. The available documentation and direct witness reports indicate a considerable amount of smoke being released through the side openings of the gallery. Nevertheless, a large amount of optically unstratified smoke was expelled at high speed through the upper portal of the gallery. Intervention was only possible through the lower portal. This confirms the simulation results presented in chapter 6, showing that in case of fires in a tunnel with adjacent gallery, the gallery has only limited influence on the smoke propagation and stratification.

**Figure 7:** Smoke propagation during a bus full fire (2002). View of the upper gallery portal and image of the bus after the fire in the inlay at the left lower corner.

A full fire of a medium-size personal car occurred in the year 2015 at the lower end of the same tunnel-gallery system, consisting of a 424 m long gallery connected through its upper portal to a 541 m long tunnel equipped with longitudinal ventilation with jet fans. The intervention services reported a variable level of smoke stratification within the gallery and very bad visibility at the interface between the tunnel and the gallery. After fire detection, the jet fans in the tunnel were operated towards the gallery (lower tunnel portal) for protecting the tunnel against smoke propagation. This clearly shows that the interface between tunnels and galleries is extremely important and needs to be investigated in detail.

## 5. DISCUSSION OF FINDINGS AND PRACTICAL IMPLICATIONS FOR DESIGN AND OPERATION

Smoke propagation in case of fire in galleries was analyzed for a variety of configurations using CFD and the most important observations could be confirmed on a real fire. The main findings and conclusions are as follows:

- In case of small longitudinal slope, and excellent exchange with the exterior is observed also in case of external wind, resulting in good visibility and favorable conditions for self-rescue and intervention.

- Larger gallery aspect ratios and different fire locations within the gallery do not change in a significant manner the previous conclusion.
- In case of fires in galleries with large longitudinal slope, a reduced stack effect, slower smoke propagation and fair stratification are observed compared to the corresponding tunnel configurations. This virtually corresponds to a smaller heat-release rate, because a significant part of the buoyancy is “lost” through the sidewalls. Again, this results in favorable conditions for self-rescue and intervention.
- Fires in a tunnel continuing at its upper portal with a gallery represent a major safety problem. The “stack effect” results in a large longitudinal air velocity within the tunnel, with full loss of optical stratification at the lower portal of the gallery. Under these conditions, loss of stratification within the gallery cannot be prevented. The propagation speed of the smoke front is much higher than in case of a fire with identical characteristics but located in the gallery.
- Significant smoke destratification can occur at the interface between tunnels (frequently protected against smoke penetration by mechanical ventilation generating airflow towards the fire) and galleries with longitudinal slope, where the gallery is located at the upper portal of the tunnel. Simulation and real fires showed that these locations are critical for both self-rescue and intervention.
- Fires in galleries are most likely to be fuel controlled, because of the virtually unlimited availability of air. Proper liquid collection is required at least in case of transportation of liquid fuels.

It should be noted that most simulations were carried out considering idealized conditions, ignoring e.g. vehicle motion or external wind. The experience gained from smoke propagation within different types of galleries allows drawing some conclusions about the need of emergency exits. Galleries, which are not coupled with a tunnel, show improved characteristic compared to tunnels. The distance between emergency exits can be reduced or emergency exits can even be completely eliminated. Careful investigation is required in case of galleries coupled to tunnels. In case the tunnel has a large longitudinal slope, the side openings of galleries do not influence smoke propagation in way that would allow reducing emergency exits.

The specific characteristics of galleries have a profound impact on safety design, which should be based on specific analysis and regulations rather than on rules developed for tunnels.

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