

SMOKE RECIRCULATION AT ROAD-TUNNEL PORTALS

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ABSTRACT

In case of fire in twin-tube tunnel systems, the parallel tube is commonly used as a haven for self-rescue and plays an essential role for intervention. This requires a high level of protection against smoke penetration through cross connections and tunnel portals. Structural (e.g. shifting of portals or anti-recirculation walls) and technical measures (primarily appropriate ventilation control) are commonly adopted for preventing portal recirculation. Anti-recirculation walls are frequently unwanted, mainly because of their visual and operational impact as well as cost. Project-related detailed investigations showed that the benefits from anti-recirculation walls are at times lower than expected. This paper provides guidance for screening and detailed assessment of requirements and benefits. Appropriate numerical simulations can help to avoid large structural measures with low effectiveness.

Keywords: Road tunnel, portal smoke recirculation, anti-recirculation wall.

1. INTRODUCTION AND OBJECTIVES

In case of fire in twin-tube tunnel systems, the parallel tube plays an essential role as a haven for self-rescue and as access and working area for intervention. This requires a very high level of protection against smoke penetration through cross connections and tunnel portals. This paper focuses on portal smoke recirculation in twin-tube road tunnels.

Constructional and technical measures are commonly adopted for preventing portal recirculation, such as shifted portals or anti-recirculation walls. National regulations and international recommendations often provide specific prescriptions or functional guidance. Such measures can be invasive and are typically unwanted mainly because of their visual impact and cost. Technical reasons, such as load on bridges or viaducts directly connected with tunnel portals, might also play an important role in special cases. Portal recirculation is intimately related to geometric, operational and environmental conditions. Detailed analyses carried out for specific project-related configurations show widely variable benefits from anti-recirculation measures. While they play an essential role in most cases for ensuring a proper safety level, they only show marginal benefits in others.

The first part of this paper focuses on the phenomenological description of portal recirculation and discussion of relevant issues, requirements and design objectives, normative prescriptions and state-of-the-art. The second part provides specific guidance for the evaluation of practically relevant situations and describes methodological approaches for screening and analysis. Finally, representative real-life examples illustrate the approach for verifying the need and the effectiveness of anti-recirculation measures and how appropriate numerical simulations, involving coupled 1D and 3D simulations, can help to avoid costly constructional

measures with low effectiveness. The main focus here is set on methodological aspects rather than on technical details such as simulation technology and setup.

2. PHENOMENOLOGICAL DESCRIPTION AND SAFETY IMPLICATIONS

In twin-tube tunnels, self-rescue in case of a relevant accident is generally based on cross connections. Evacuees reach the parallel tunnel tube, where they can safely wait for rescue. The non-incident tube also plays an essential role in terms of intervention. Depending on the specific intervention strategy adopted by the first responders, it might host the bulk of the intervention effort or at least be used for the secondary intervention. Persons requiring emergency support and medical attention are generally carried into the parallel tube. The requirements on safety and air quality within the non-incident tunnel tube play therefore a central role in the overall safety concept. Smoke penetration through cross connections or through the portals must be prevented at any time. It is important to note that comparatively low levels of smoke penetration, resulting in smoke concentrations well below health-relevant thresholds, can have a significant impact. Persons escaping through a cross connection might perceive a partly smoke-filled parallel tunnel tube as unsafe and return to the fire tube. An additional requirement is the protection of the portal areas against noxious impacts, as evacuees may receive medical assistance or just wait in the immediate vicinity of the portals. The areas reserved for supporting and coordinating intervention are also located nearby.

In principle, portal recirculation can occur whenever smoke flows or is actively expelled from a tunnel portal. This phenomenon is particularly intense in case of air inflow into the parallel tunnel tube, unless the axial or lateral distance between the tunnel portals is sufficient. Portal configuration, wind and wind exposition also play an important role. The length of the influence area at the exhaust portal can generally be assumed to be in the order of 100 m. This can be significantly longer in case of smoke expulsion at high velocity (jet-type portal outflow with low thermal effects) and shorter e.g. in case of large fires coupled with comparatively low air velocity, where the hot smoke tends to rise rapidly at the portal. The area of influence at the inlet of the parallel tunnel tube is significantly shorter, in the order of 20 to 30 m. For this reason, portal shifting in axial direction is a very effective constructional measure against portal recirculation. This requires a prolongation / displacement of the exit portal by at least 30 m or of the entry portal by at least 100 m. An effective alternative is a roughly 30 m long separating wall between the two tunnel portals.

Tunnels equipped with longitudinal ventilation systems are particularly critical in terms of portal recirculation because of the steady smoke outflow from a portal during practically the whole duration of the emergency. The appropriate ventilation strategy in this case is flow reversal in the safe tunnel tube with an air velocity of at least 1 m/s. This measure is generally not sufficient for keeping the portal area free from smoke but effectively prevents smoke penetration into the safe tunnel tube. Flow reversal typically requires a few minutes, mainly because of the natural ventilation generated by the vehicles leaving the tunnel. Some level of smoke penetration during this initial stage cannot be entirely prevented by ventilation alone, particularly for long tunnels and in case of fires located close to the exit portal. Ventilation systems with smoke extraction are significantly less critical because smoke outflow from the tunnel portal only occurs during the first minutes after fire onset, before smoke confinement is effective, or in case of a fire located in the immediate vicinity of the exit portal, for which longitudinal smoke expulsion is typically the strategy of choice. Issues and prevention strategies are similar as in case of longitudinal ventilation.

Portal recirculation in short, naturally ventilated tunnels is significantly more complex. Different effects impact natural ventilation in the two tunnel tubes at different levels and at

different times. This particularly includes the initial traffic impact, the fire stack effect, which typically increases within the first minutes of a fire incident, and environmental effects, such as temperature difference, portal wind or barometric pressure difference. These environmental effects can vary rapidly during a fire incident and are likely to act in very different ways depending on season and meteorological conditions. These challenging conditions shall be addressed in more detail in Chapter 5.

For the purposes of this paper, it will be distinguished between transient (short-term) and sustained smoke recirculation. The former only occurs in the very first minutes of a fire scenario, e.g. before automatic fire ventilation can implement the proper fire ventilation strategy. Conversely, sustained portal recirculation is more or less a steady-state phenomenon, due e.g. to inappropriate ventilation strategy or to the combined action of natural ventilation and wind.

3. REGULATIONS AND STATE-OF-THE-ART

The risk of smoke recirculation at the portals of a twin-tube tunnel has found its way into the regulatory requirements in some countries, while other ones, e.g. France, just mention the issue and call for appropriate solutions without specification. National prescriptions are quite similar. The German RE-ING prescribes an offset between the portals of 30 m or a 30 m long anti-recirculation wall with the same height as the portal. The Swiss guideline for ventilation in road tunnels (ASTRA 13001) bases its requirements on the concept of an exhaust zone stretching 100 m from the exit portal and an intake zone for 30 m ahead of the entry portal. This results in largely similar requirements to the German guideline albeit accounting for the difference between air intake and expulsion jet behaviors. The Brazilian regulation requires a physical separation between the exhaust of the fire tube over a length of 100 m and the intake of the safe tunnel tube over a length of 30 m at each portal. Specific measures include a minimum lateral distance of 60 m between the portals, a longitudinal shift, the construction of anti-recirculation walls or combinations thereof.

Real-life experience and simulation proved that the normative prescriptions are generally effective. In several countries, e.g. Switzerland, anti-recirculation walls are a standard component for new or retrofitted tunnels. In other countries this issue has low or no priority.

4. RELEVANT PARAMETERS AND CLASSIFICATION

Various factors impact the risk and severity of portal recirculation in a twin-tube tunnel with a given portal arrangement, such as tunnel length, longitudinal slope, cross section, fire heat release rate, meteorological conditions, ventilation system, traffic volume, etc. This study mainly focuses on sustained portal recirculation that can have a relevant safety impact in terms of self-rescue or intervention. Tunnel length and tunnel ventilation system are two key parameters for smoke recirculation. Though countries differ in the details, the choice of ventilation system generally correlates directly with its length. Short tunnels allow for natural ventilation, intermediate ones are equipped with a longitudinal ventilation system using jet fans or Saccardo nozzles and long tunnels are equipped with smoke extraction systems. For twin-tube road tunnels with unidirectional traffic the classification of length is assumed herein to be roughly according to the following categories: short tunnels reach up to 1 km, intermediate ones up to 3-5 km and long tunnels beyond that. For the present purposes this simplified correlation is sufficient. Further key parameters include longitudinal slope, portal configuration and meteorological effects, such as wind, barometric pressure differences and natural thermal effects. Further parameters, such as traffic volumes and characteristics or

tunnel cross section, might play a role in some situations but are generally less relevant. Longitudinal slope, coupled with fire heat release rate, directly impacts longitudinal air velocity and smoke propagation. For these reasons, portal smoke recirculation shall be discussed primarily in terms of tunnel length / ventilation system and longitudinal slope in the fire tube. Fire intensity is subject to rapid variations in time and varies from case to case. It should be treated as range, with assumptions on the (traffic-dependent) likely maximum and development time.

A first rough categorization and ranking in terms of risk of portal smoke recirculation is summarized in Table 1. The classification “High” suggests that smoke recirculation is likely to be an issue deserving appropriate attention. “Low” suggests that it might be possible to evaluate deviations from normative requirements if they result in excessive functional, aesthetic or economic constraints.

Table 1: Categorization of tunnels in terms of risk of portal smoke recirculation

Tunnel categorization and expected risk of recirculation		Longitudinal slope		
		< -3%	-1.5% to 1.5%	> 3%
Tunnel length / Ventilation systems	< 1 km Natural ventilation	Low	Medium	High
	1 - 5 km Longitudinal ventilation	Medium	Medium	Medium
	> 5 km Smoke extraction	Low	Low	Low

5. SHORT TUNNELS WITH NATURAL VENTILATION

Short tunnels allow generally for short self-rescue times and natural ventilation is frequently the accepted solution. As a result, airflow is purely driven by a complex combination of traffic-related and natural effects. At times of high traffic, the airflow is mainly driven by traffic and at other times mostly driven by the wind. Barometric pressure differences and stack effect due to natural temperature differences are frequently negligible. In the event of a fire in a short tunnel, traffic influence quickly disappears, and transient portal smoke recirculation is virtually negligible. The driving parameters are in most cases external wind and stack effect.

In case of small tunnel slope (typically below 1%), the aerodynamics of smoke recirculation is largely governed by wind. Both tunnel tubes behave in a similar manner, the airflow in both tunnel tubes is generally in the same direction and the risk of relevant sustained smoke recirculation is low.

The situation in case of significant tunnel slope is more challenging. As fire develops, the incident-tube’s airflow will be driven by the fire’s stack effect and smoke will propagate towards the upper portal. In case of slopes over 2-3% and HGV fires with substantial heat-release rate, wind impacts on the incident tube will be relatively weak to negligible. Conversely, the non-incident tube will develop an airflow that depends on portal wind. This represents a significant risk, as this can easily lead to substantial airflows in the two tubes going in opposite directions for a tunnel that lacks mechanical ventilation to oppose these trends. The potential for strong, sustained smoke recirculation at the upper portal is therefore significant. Conversely, the lower portal will only experience short-term (transient) recirculation for up to 2-3 minutes with fire in the tube with descending traffic. Considering typical fire-development curves, this is mostly negligible. For fires in the tube for ascending

traffic, recirculation at lower portal is reduced/eliminated even further. There is hence potential for removing the anti-recirculation wall at the lower portal.

The risk of portal recirculation at the upper portal depends on the complex interaction between portal configuration and wind characteristics. Anti-recirculation walls should not be removed without a detailed analysis carried out considering the specific portal geometry and the local wind rose. Examples are presented in Chapter 8.

6. INTERMEDIATE TUNNELS WITH LONGITUDINAL VENTILATION

In principle, longitudinal ventilation systems provide ideal conditions for transient and sustained portal smoke recirculation. With the possible exception of extended traffic congestion, the preferred ventilation strategy is generally to support the natural airflow induced by the traffic in the tunnel using e.g. jet fans, resulting in opposite flow directions in the two tubes. The accepted ventilation strategy for mitigation of portal-recirculation into the safe tunnel tube is flow reversal. This can be assumed to work safely, independently of meteorological conditions and traffic, as long as ventilation is correctly designed. Smoke outflow can begin immediately in case of fire close to the tunnel exit or take up to roughly 15 minutes in case of a fire at the entrance of a 5 km tunnel. Flow reversal in the safe tunnel tube can typically be achieved in 5 to 10 minutes. An illustrative example (tunnel with length 4 km, slope 2.5%, 2 traffic lanes, longitudinal ventilation with jet fans, traffic per direction 1000 vehicles/h at 100 km/h, 50 MW fire developing within 10 minutes, no portal pressure differences) is presented in Figure 1. Fire is detected 2 minutes after onset and ventilation reaches full power 1 minute later. Under these specific conditions, significant smoke recirculation may occur between roughly 3 and 7 minutes after fire onset.

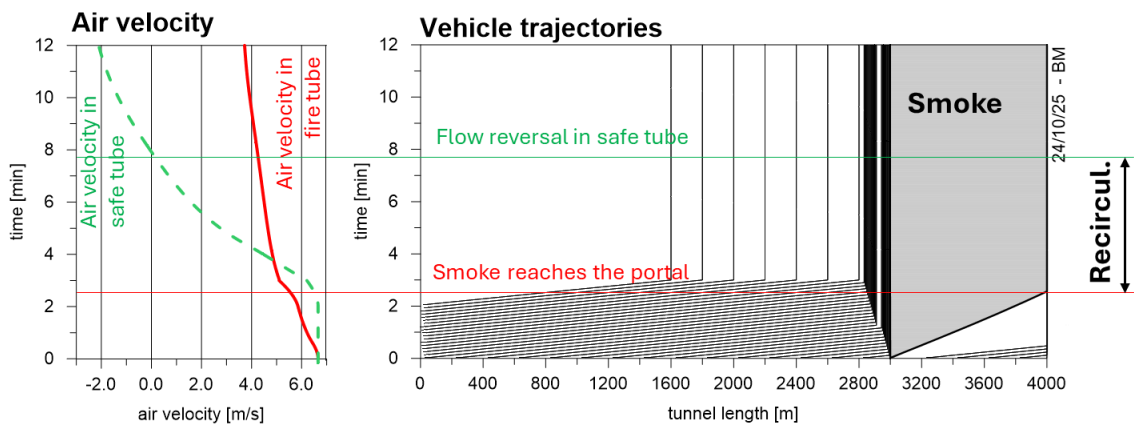


Figure 1: Vehicles trajectories and smoke propagation (right) and air velocity (left) [1].

Transient smoke recirculation into the safe tunnel tube might therefore last for at most 5-10 minutes. Depending on the specific conditions and considering typical fire heat-release rates in road-tunnel fires, this might be deemed acceptable, and one could consider eliminating the corresponding anti-recirculation walls. Under these conditions, smoke outflow from the fire tube might last for typically 30 to 60 minutes or longer. Appropriate considerations on specific portal configurations, and specifically the location of emergency meeting points and intervention points, are suggested, since smoke impact on these facilities would typically last for the whole duration of the fire. As a general conclusion, removal of accepted anti-recirculation facilities should only be considered, if they represent a real issue.

7. LONG TUNNELS WITH SMOKE EXTRACTION

The preferred smoke-confinement strategy in case of transverse or semi-transverse ventilation with smoke extraction is concentrated smoke extraction in the immediate vicinity of the fire. Smoke extraction systems greatly alleviate the risk of sustained recirculation of smoke at the portals. Smoke extraction systems are designed to extract all smoke produced in the fire, thus preventing smoke propagation beyond the extraction. Smoke is therefore generally not expected to reach a portal in significant quantity/density. Hence, the risk of smoke recirculation in long tunnels only concerns smoke released at early stages, before smoke extraction reaches nominal operation, or for fires located close to the exit portal, where emergency ventilation cannot prevent smoke exhaustion at the portal. There is therefore generally no risk of sustained portal smoke recirculation once flow conditions in the tunnel system have reached steady state.

Fires located close to the exit portal (typically up to 200-300 m) represent a very important exception, since direct portal blowout typically represents the preferred strategy. The relevant phenomena in case of fire at the tunnel exit are analogous to the case of longitudinal ventilation, with the following particularities: under such conditions, smoke reaches the tunnel portal very rapidly and flow reversal in the opposite tunnel tube can take up to 15-20 minutes, the time required for traffic effects to decay to a level compatible with the capabilities of longitudinal airflow control. Self-rescue can therefore be inhibited by smoke penetration from the beginning and for a significant time period. This may also have a severe impact on intervention in the case of major tunnels with their own firefighting stations located by the tunnel portals (St. Gotthard, San Bernardino, Mont Blanc, Fréjus etc.).

The impact of transient smoke recirculation in case of a fire located farther away from the tunnel exit is generally very limited, despite the comparatively long time required for achieving smoke confinement. Self-rescue could be impacted by smoke recirculation, but only after several minutes, because of the time required for smoke to reach the portal and from there the cross connections used for self-rescue or intervention. Meteorological effects and tunnel longitudinal slope are also unlikely to have a significant impact, in spite of possibly very large barometric pressure differences of the order of several 100 Pa, since state-of-the-art ventilation systems are designed for mastering such effects.

8. ANALYSIS – METHODOLOGICAL APPROACH AND REAL-LIFE APPLICATIONS

8.1. Methodological approach

The preferred approach for assessing issues related to transient and sustained portal recirculation varies from project to project and is largely driven by the specific objectives of the investigation. Nevertheless, experience shows that the following general approach is appropriate in most cases:

1. Clear identification of the objectives of the investigation
2. Systematic gathering of all relevant tunnel, traffic and environmental conditions and identification of the specific scenarios which are relevant for portal recirculation
3. Preliminary screening based on 1D-simulation of relevant scenarios (airflow, smoke propagation and people movement) and engineering assessment
4. Detailed investigation of the potentially critical scenarios (if any) identified in the previous step

Based on the identified scenarios that pose a potential risk for portal recirculation, the airflow in the two tubes can be evaluated through 1D-simulation (step 3). A comprehensive model for this can already estimate the evolution of the smoke propagation in the incident tube. Together with the simulation of the non-incident tube, this provides a clear indication of when recirculation is possible (simultaneous smoke exhaustion at one portal and air intake in the parallel one). This leads to a prioritized list of scenarios and might lead to a conclusive evaluation for part of them.

The detailed investigation of the leading scenarios (step 4) needs to be based on 3D-simulation of smoke propagation in the tunnel and primarily in the area around the portals. This step enables full consideration of portal design in the evaluation, which is not feasible in the previous step. The conditions in the two tubes have been derived in the previous step and can be implemented into the boundary conditions of the 3D-simulation. Portal design as well as the surrounding landscape need to be appropriately represented in a 3D-model and included in the simulation with adequate accuracy (meshing and modeling of local wind conditions) and geometric extension, making these analyses quite expensive.

8.2. Application – Very short tunnel with large slope and natural ventilation

This example focuses on a short and very steep, short tunnel (length 280 m, slope 9%, 5 cross connections, daily traffic lower than 20'000 vehicles/day with low HGV percentage). Portal-recirculation patterns are clearly dominated by the interaction between portal wind and stack effect. Based on screening and 1D-simulation, the risk of sustained recirculation at the lower portal could be ruled out as virtually negligible and the corresponding anti-recirculation wall could be removed.

The analysis of the upper portal is much more complex because of the significant risk of sustained portal recirculation due to stack effect and unfavorable wind patterns. A screening procedure identified the most critical statistically relevant wind conditions. The corresponding scenarios with and without anti-recirculation wall were analyzed in detail using FDS [2]. The results without and with recirculation wall are shown in Figure 2 and Figure 3-The color contours represent visibility at 2 m height, ranging from 0 m (red contours) to 30 m or more (blue). The acceptable range, 10 to 20 m, is represented in green.

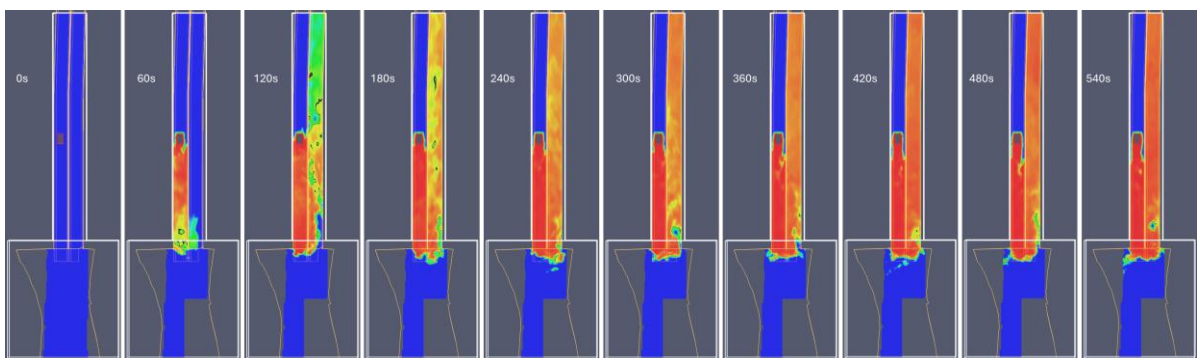


Figure 2: Smoke recirculation at upper portal without anti-recirculation wall.

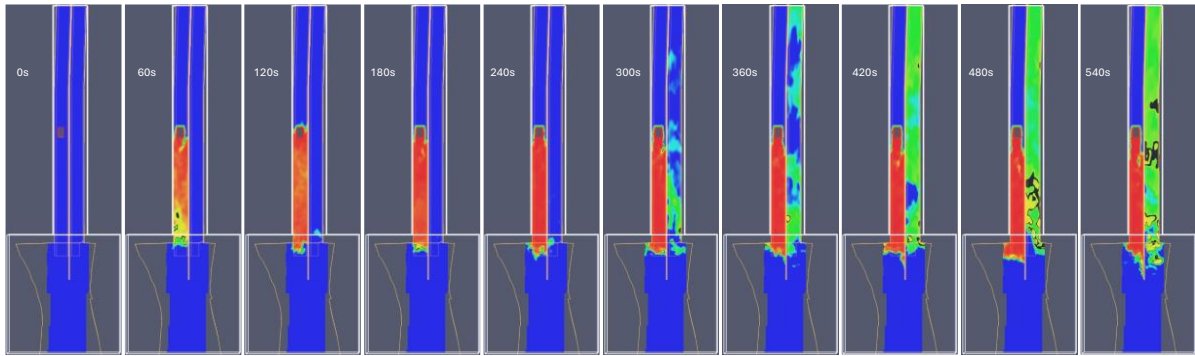


Figure 3: Smoke recirculation at upper portal with anti-recirculation wall.

The results clearly show that the anti-recirculation wall is required and very effective. Detailed analysis showed that its length can be safely reduced to 15-20 m.

8.3. Application – Tunnel with natural ventilation and low slope

A detailed investigation on smoke recirculation for the Swiss Riedberg tunnel (length 537 / 565 m, slope 1.2%, traffic volume 16'000 vehicles/day with 10% HGV) was carried out by Guetg et al. [3]. The realization of anti-recirculation walls in a very exposed area posed serious visual and static challenges, with tunnel exit on a bridge on one side. This is a typical example of a complex situation, where many different recirculation patterns result from complex portal configurations and wind conditions. A statistical approach was selected, based on a) Identification of specific potential damage patterns, b) Detailed analysis of all relevant scenarios, c) Identification of cases with strong / mild / minor recirculation and damage assessment and d) Consolidation in terms of expected number of fatalities and injuries per year. The final decision was based on a cost/benefit analysis.

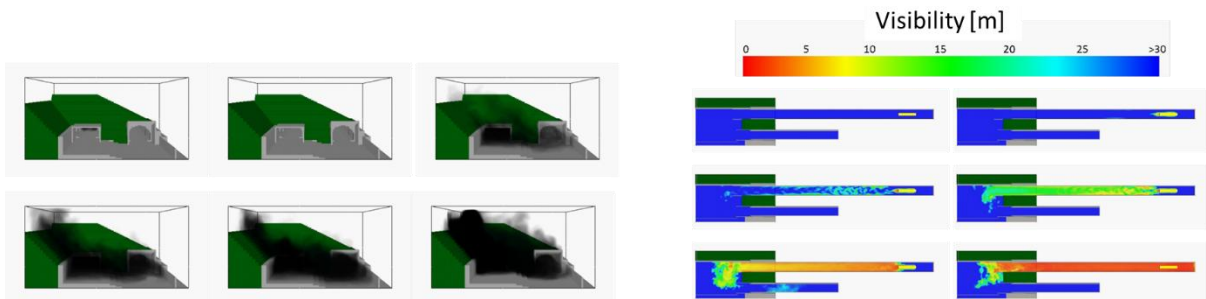


Figure 4: Leading smoke-recirculation scenarios for Riedberg tunnel [3].

9. SUMMARY AND CONCLUSION

Structural and technical measures against smoke recirculation through tunnel portals in case of fire are well established in several countries but are widely ignored elsewhere. Regulatory prescriptions, as they are formulated in several national regulations, are generally very effective but fail to catch the particularities and specific needs of each project. Short and intermediate-length tunnels with natural or longitudinal ventilation generally pose the highest requirements. Specific project-related investigations are strongly recommended.

The overall impact from structural measures can be very significant, particularly for urban tunnels. Simple screening procedures and detailed analysis as outlined herein help to establish project-specific requirements and to achieve tailored solutions for critical situations. As shown in the examples illustrated herein, the potential for preventing onerous measures with low effectiveness by means of appropriate screening and analysis is significant.

10. REFERENCES

- [1] M. Bettelini, “Transient One-Dimensional Simulation for Optimum Road-Tunnel Ventilation”, ITA-AITES World Tunnel Congress, Sept. 19-25, 2008, Agra, India.
- [2] Fire Dynamics Simulator (FDS), <https://pages.nist.gov/fds-smv/>
- [3] F. Guetg, J. Amberg, M. Bettelini, “Prevention of portal recirculation for the Riedberg tunnel”, 19th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels, Brighton, UK, 18th-30th September 2022.