CFD STUDY OF TEMPERATURE AND SMOKE DISTRIBUTION IN A RAILWAY TUNNEL WITH NATURAL VENTILATION SYSTEM

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ABSTRACT
A study of safety in a railway tunnel with natural ventilation system is presented. The study investigates conditions within the tunnel near a burning train. An emergency scenario is defined and criteria for the assessment of the safety of the escaping passengers are discussed. Two different approaches were employed in a coupled manner: 1-D analysis using the code SPRINT, developed by HBI, and 3-D CFD analysis using the commercial code FLUENT. It is concluded that the 1-D approach is in most cases sufficient for an overall safety assessment whereas 3-D CFD is more appropriate for gaining additional insight in regions of particular interest in complex tunnel geometry.

1 INTRODUCTION

In case of emergency in railways tunnels it is usually not recommended to stop the train before the exit. Modern railway tunnels should nevertheless provide the highest possible level of the safety for the passengers in case of an incident that forces a train to stop within the tunnel. The understanding of the behavior of smoke and temperature arising from a fire on a burning train is of essential importance for the design of the tunnel's safety features as, for example, rescue areas, cross passages and the ventilation system.

The probably most reliable approach to check the functionality of a ventilation system would be to perform full-scale fire tests prior to opening the tunnel for operation. However, these tests are very expensive and often do not consider the flow motion in the tunnel that was induced by the entering train before it came to halt. Therefore, the transferability of the results to real conditions and the prediction of the escape conditions of the passengers might be difficult. Moreover, a parametric study (fire position, train speed etc.) is impossible.

Numerical (CFD) three-dimensional simulations provide an excellent mean for gaining a better insight in the neighborhood of the fire and prediction of the escape conditions for the passengers. Moreover, CFD provides the results in a format that can easily be post-processed to create animation for the training of people who have to deal with the fire in case of emergency (fire fighting forces, conductors etc.) Nevertheless, CFD simulations are still time-consuming. Their practicability for parametric studies and design is therefore limited.

For this reason, the overall design of the ventilation system is mostly carried out using one-dimensional methods, which allow to vary the key design parameters in a very straightforward way in order to devise the optimal solution using an acceptable amount of resources. In a further step, this solution can be verified in regions of particular interest using CFD or full scale experiments.

The Purpose of this paper is to compare the predictions of a one-dimensional simulation of the time-dependent smoke and temperature distribution near a burning train with the results obtained from a three-dimensional CFD simulation.

2 BASICS

The emergency scenario assumes a burning train that enters a tunnel. The train is forced to stop in the tunnel. No active ventilation exists in the tunnel. Instead the smoke is extracted by natural convection through the vents in the tunnel roof.

2.1 EMERGENCY SCAENARIO AND TUNNEL GEOMETRY

Figure 1 shows a sketch of the tunnel with the position of the incident train. The following assumptions are made for the emergency scenario.

- The train stops near the middle of the tunnel in such a way that the fire is located midway between two vents.
- No trains enter or leave the tunnel after halt of the train.

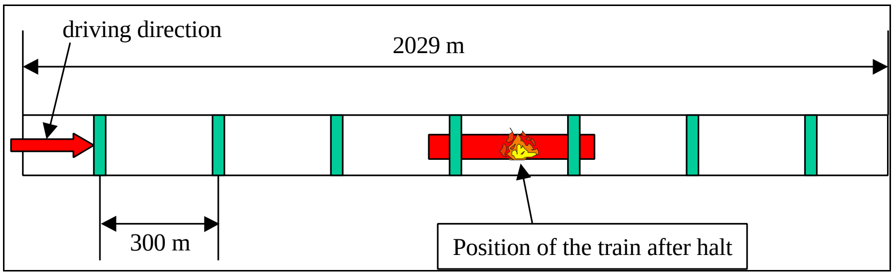


Figure 1 Geometry of the tunnel and position of the train after halt in the tunnel

Tunnel geometry:

- Length : 2029 m
- Cross Section : approximately square shape 6.7 x 6.7 m^2

Geometry of the vents

- Spacing: equally spaced at 300 m distance
- Cross Section: 6.7 x 2.4 m^2
- Height: 2.4 m

2.2 TRAIN SPECIFICATIONS

The technical specifications for the train are as follows:

- Train length: 400 m
- Train height and width: 3.89 x 2.95 m^2
- Max. deceleration: 1.1 m/s^2

3 NUMERICAL SIMULATIONS

3.1 APPROACH

The following approach was employed for the numerical simulations:

1. Estimation of the critical velocity.
2. One-dimensional transient analysis of the smoke and temperature propagation in the whole tunnel.
3. Three-dimensional transient analysis of the smoke and temperature propagation near the train.

3.2 PREDICTION OF CRITICAL VELOCITY

The critical velocity, i.e. the minimum longitudinal air velocity required to prevent backlayering, is calculated using the semi-empirical “Kennedy”-formula [1]. For this study, the critical velocity was estimated to 2.2 m/s.

3.3 ONE-DIMENSIONAL ANALYSIS OF THE SMOKE AND TEMPERATURE PROPAGATION

For the given scenario, the smoke propagation is driven by the airflow induced by the entering train as long as the air velocity in the tunnel exceeds the critical velocity. Afterwards, more complex smoke-propagation patterns are observed. The resulting flowfield, smoke propagation and temperature distribution are simulated with the code SPRINT, developed by HBI. SPRINT [2] calculates the velocity and temperature distribution of an incompressible flow in a tunnel by means of a one-dimensional time-dependent model, based on the governing equations describing the conservation of mass, axial momentum and energy, as well as additional relations for smoke propagation. The fire is modeled as a source of heat and smoke. Temperature and speed of the upper and lower layers are calculated. This information, generally missing in one-dimensional models, is necessary in order to predict the smoke propagation correctly, which is a result of both passive convection and gravity-driven propagation. Ambient temperature is assumed for the lower layer that covers 50% of the tunnel height. Heat transfer from the upper to the lower layer is neglected. Advective energy transport occurs therefore only in the upper part of the tunnel, where higher temperatures are observed. Convective and radiative heat transfer to the wall is also limited to the upper layer. SPRINT was validated against the results from the Memorial Tunnel Fire Ventilation Test Program with good results [2].

3.4 THREE-DIMENSIONAL ANALYSIS OF THE SMOKE AND TEMPERATURE DEVELOPMENT NEAR THE TRAIN

The three-dimensional simulations were carried out using the CFD code FLUENT, release 5.5. The grid was generated using GAMBIT, FLUENT Inc.'s standard preprocessor. The system of equations for mass, momentum and energy were solved simultaneously. Turbulence was modeled by means of the k-ε model. The density of the gas mixture was calculated according to the ideal-gas laws.

4 COMPUTATIONAL SETUP

4.1 1-D ANALYSIS

The computational domain for the 1-D analysis is shown in Figure 1. The whole tunnel is modeled. The train enters the tunnel and stops at the position indicated in the figure. The air velocities induced by the train as well as the smoke production of the entering train are considered for the analysis.

4.2 3-D ANALYSIS

4.2.1 COMPUTATIONAL DOMAIN

The computational domain for the CFD analysis is illustrated schematically in Figure 2.

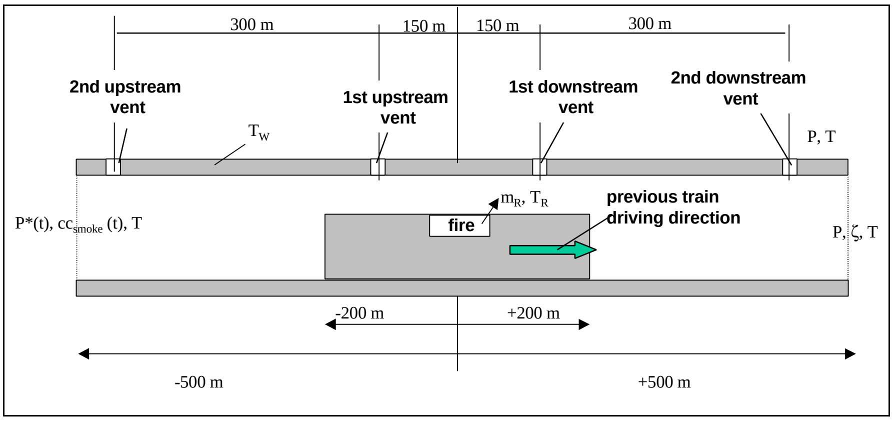


Figure 2 Computational Domain for CFD simulation

4.2.2 FIRE MODEL

The fire intensity is constant, with the following characteristics.

- Convective heat-release rate: 30 MW,
- Smoke-production rate: 43 kg/s at 1000 K,
- Smoke concentration at the source: 4.2%,
- Fire length: 25 m (one wagon).

Radiation is not explicitly accounted for in this investigation. It is assumed that the flames leave the wagon through the open upper side.

4.2.3 BOUNDARY CONDITIONS

The following boundary conditions were imposed.

- Solid walls: T = 300 K.
- Main outlet: Pressure outlet with additional loss coefficient set as obtained from the 1-D simulation.
- Vent outlets: Pressure outlet.
- Inlet: Pressure inlet with additional definition of the entrance smoke concentration obtained from the 1-D analysis.
- Fire: as specified in Chapter 4.2.2.

4.2.4 GEOMTRY AND GRID

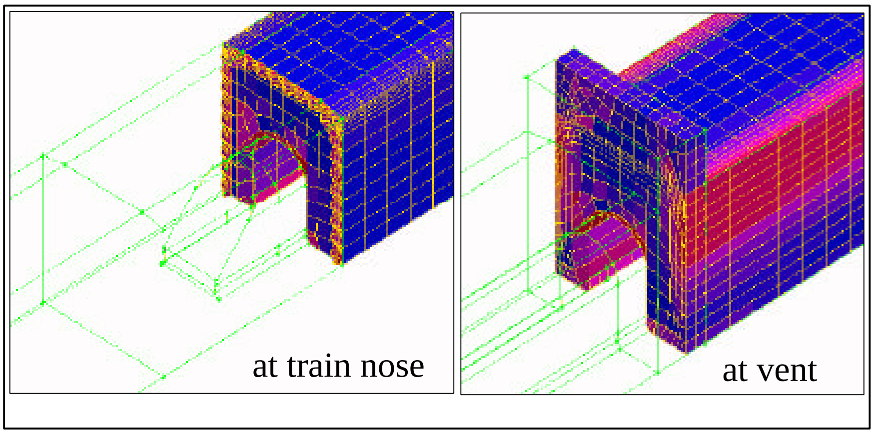


Figure 3 Details of mesh

A state-of-the-art hybrid meshing technique was used to efficiently mesh the geometry. The grid consists of 180’000 cells with variable shape: hexahedral, pyramidal and tetrahedral. Grid refinement was used in important areas near the tunnel walls. Details are shown in Figure 3

5 EVALUATION CRITERIA FOR PASSENGER SAFETY

5.1 EXPOSURE TO CO

A relationship between the concentration of CO and the time to incapacitation (loss of consciousness) is given in [5]. The following correlation was used to calculate the time to incapacitation for an “average” person at a high level of activity.

$$t = \frac{30}{8.2925 * 10^{-4} * (10^4 * X_{CO})^{1.036}} \qquad \text{[min]} \qquad (1)$$

X_{co} represents the volume concentration [%] of CO in air.

5.2 EXPOSURE TO HEAT

[5] proposes the following correlation for the relationship between the exposure of a human to heat (convective and radiation) and the time to incapacitation (loss of consciousness):

$$t = e^{(5.1849 - 0.0273 * T)} \qquad \text{[min]} \qquad (2)$$

T represents the air temperature in °C. Note that this correlation is only valid under conditions of low speed (<30 m/min) air movement in the tunnel.

5.3 VISIBILITY

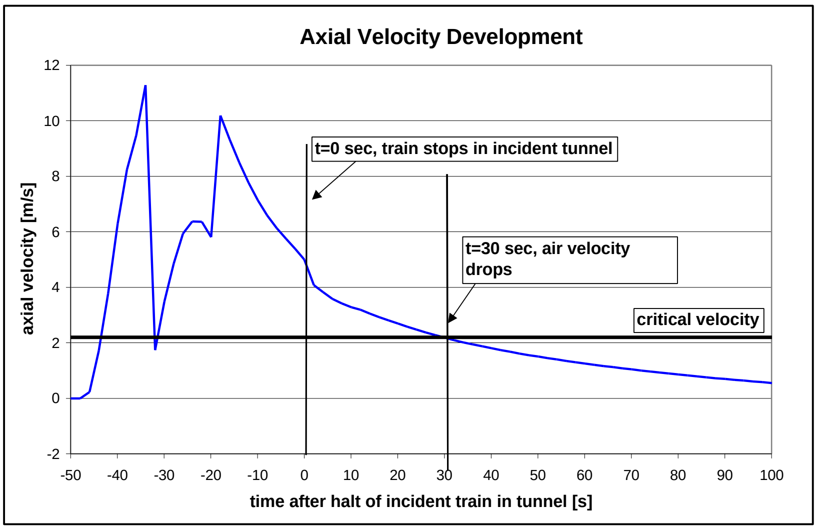
The visibility is estimated based on the mass optical density D_m as proposed in [6], A value of D_m=0.25 m^2/g and light reflecting signs were assumed.

6 RESULTS

6.1 ONE-DIMENSIONAL ANALYSIS

The goal of the 1-D analysis is to provide an overview about the development of temperature, visibility, and time to incapacitation inside the tunnel.

6.1.1 AXIAL VELOCITY UPSTREAM OF THE FIRE



The development of the axial velocity upstream of the fire is shown in Figure 4. The entering train induces air velocity with a peak level of approximately 10 m/s in the tunnel. After halt of the train, the velocity decreases quickly. The velocity drops below the predicted critical velocity (2.2 m/s see Chapter 3.2) after about 30 sec

Figure 4 Transient axial velocity upstream of the fire

6.1.2 TEMPERATURE

Figure 5 shows the temperature development at 5 different time steps. The average between the temperatures of the hot smoke layer and the cool layer of tunnel air underneath is represented. The positions of the vents at +/- 150 m distance from the fire are clearly visible. Downstream of the fire approximately stable conditions occur. In the region between fire and downstream vent, high temperatures occur that endanger the escaping passengers. The performance of the downstream vent increases as the axial velocity decreases. Nevertheless, the vent cannot completely prevent the propagation of hot air in the region downstream of the train. Backlayering occurs upstream of the fire. Hot air is transported towards the upstream vent creating unfavorable conditions for the escaping passengers.

The front of hot air reaches the position of the upstream vent (at + 150 m) about 250 sec after halt of the train.

Similar to the downstream vent also the upstream vent cannot completely prevent the transport of hot air in the region behind its position.

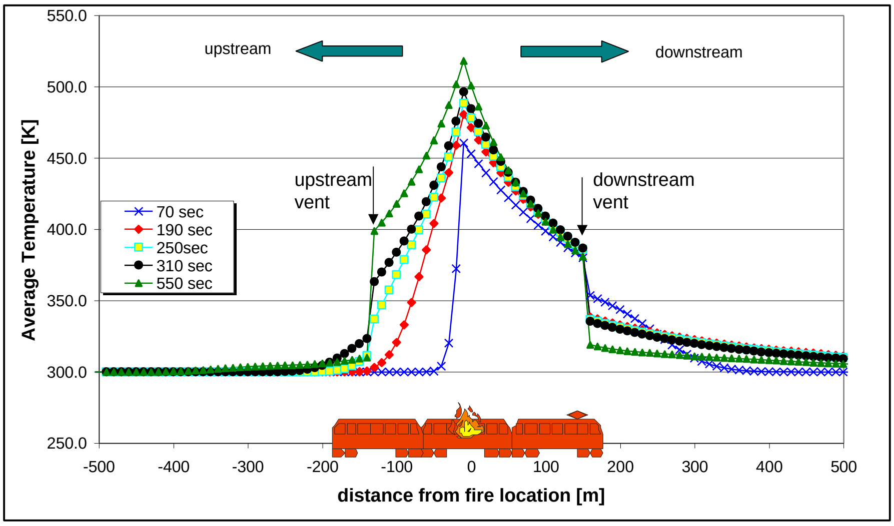


Figure 5 Temperature development

6.1.3 VISIBILITY AND TIME TO INCAPACITATION

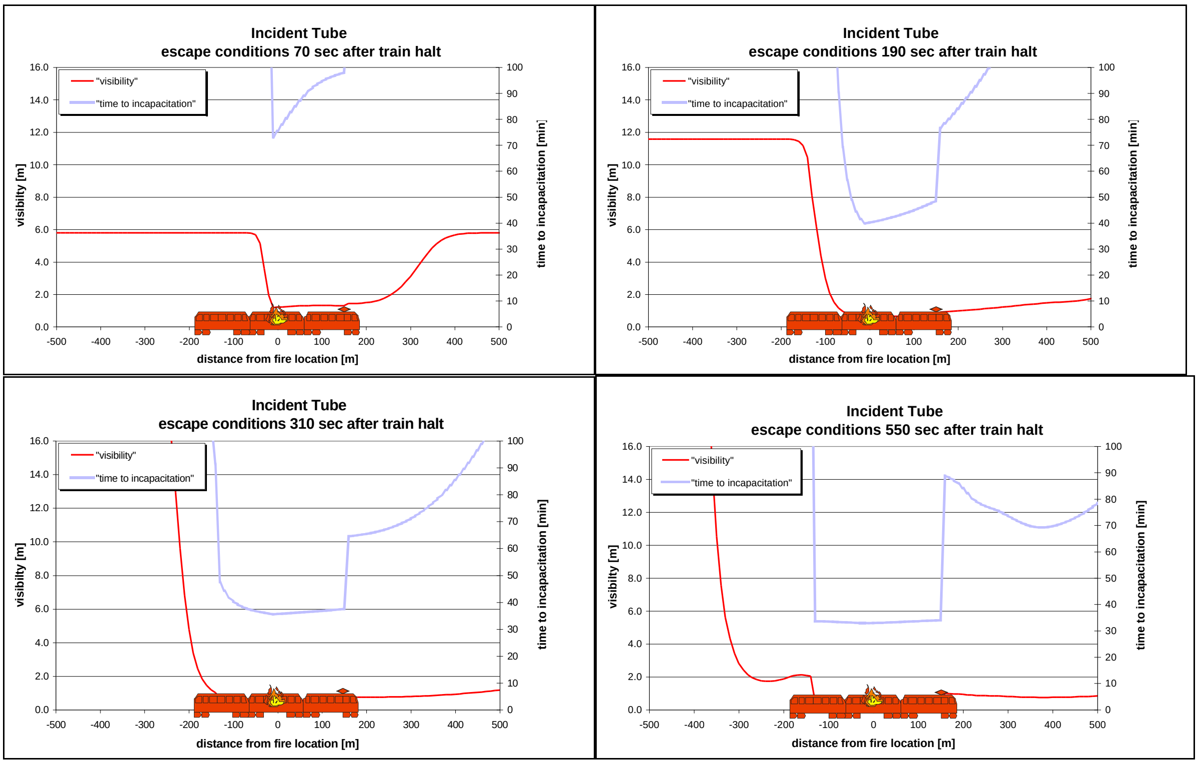


Figure 6 Visibility and time to incapacitation at 70, 190, 310, 550 sec after halt of the train

Figure 6 shows the development of the visibility (Chapter 5.3) and the estimated time until incapacitation (Chapter 5.1). The smoke production of the fire leads to strongly reduced visibility near the train. In particular downstream of the fire, conditions occur that are not favorable for the passengers. Near the train, the visibility reduces quickly upstream of the fire as the smoke propagates towards the vent. The smoke that remained from the entering train in the tunnel causes reduced visibility upstream of the train. Afterwards, fresh air is transported into this region, leading to improved visibility. No danger of the passengers is expected from the concentration of CO, as the estimated time to incapacitation is sufficiently long to allow the passengers to escape.

6.2 THREE-DIMENSIONAL ANALYSIS

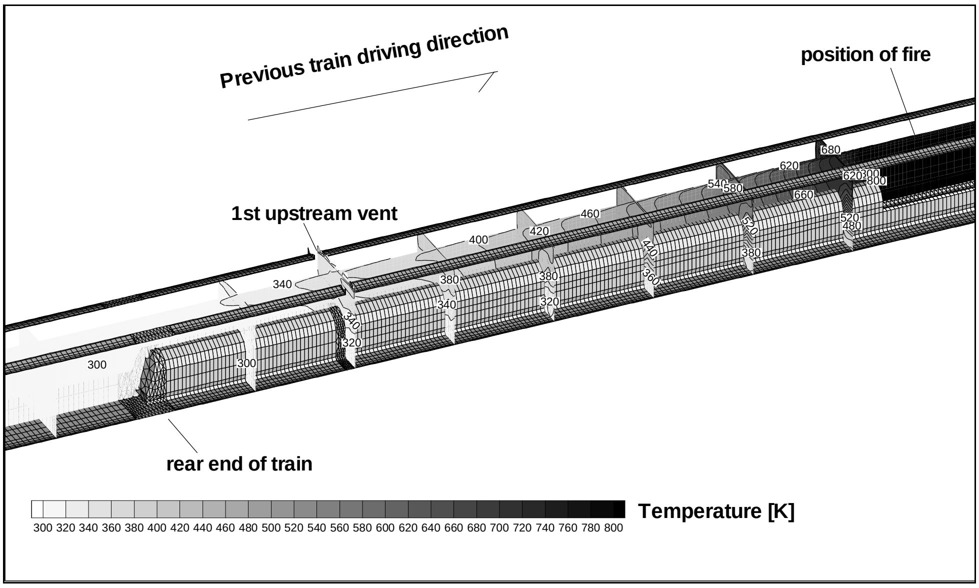


Figure 7 Temperature distribution near the train upstream of the fire at 280 sec after halt of the train

6.2.1 3-D TEMPERATURE DISTRIBUTION

Figure 7 shows as an example the temperature distribution upstream of the fire 280 sec after halt of the train. The figure reveals the huge amount of information that can be obtained from 3-D CFD simulation. Thermal stratification develops upstream of the fire leading to lower temperatures and improved escape conditions towards the tunnel bottom. The layer of hot smoke has reached the position of the upstream vent. The performance of the vent is not sufficient to prevent smoke from propagating further towards the rear end of the train. Note the good agreement with the 1-D predictions (Chapter 6.1.2).

To simplify the discussion of the results, the temperature and visibility distributions as presented in the following chapters were extracted from a section plane located at the emergency stairway at a distance of 0.75 m from the tunnel wall. This section plane is representative for the assessment of the escape conditions for the passengers.

6.2.2 TRANSIENT TEMPERATURE DEVELOPMENT

The transient temperature development at the emergency walkway is shown in Figure 8. The propagation of the zone of hot air in downstream direction is clearly visible. Thermal stratification develops downstream of the fire. After about 180 sec, the layer of hot air starts to decrease which leads to degradation of the escape conditions in this region. The performance of the downstream vent increases as the axial velocity in the tunnel decreases. This causes decreasing temperatures downstream of the train after about 180 sec.

Upstream of the fire, the figure indicates backlayering starting after 30 sec. Consequently, the layer of hot air starts propagating in upstream direction. Similar to the downstream region, thermal stratification develops also upstream of the fire leading to relatively low temperature in the lower part of the tunnel. Steady state conditions are reached after about 540 sec.

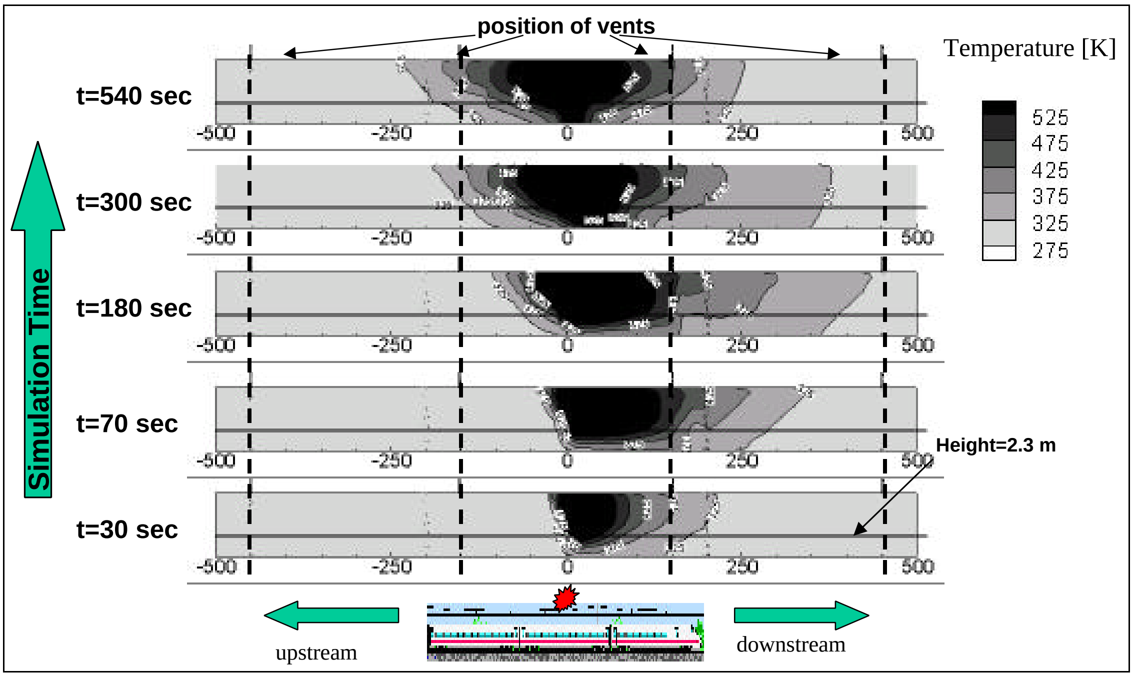


Figure 8 Transient development of the temperature in a section plane parallel to the train at a distance of 0.75 from the tunnel wall (representative for the situation on the emergency walkway - highest shown temperature is 525 K)

6.2.3 TRANSIENT VISIBILITY DEVELOPMENT

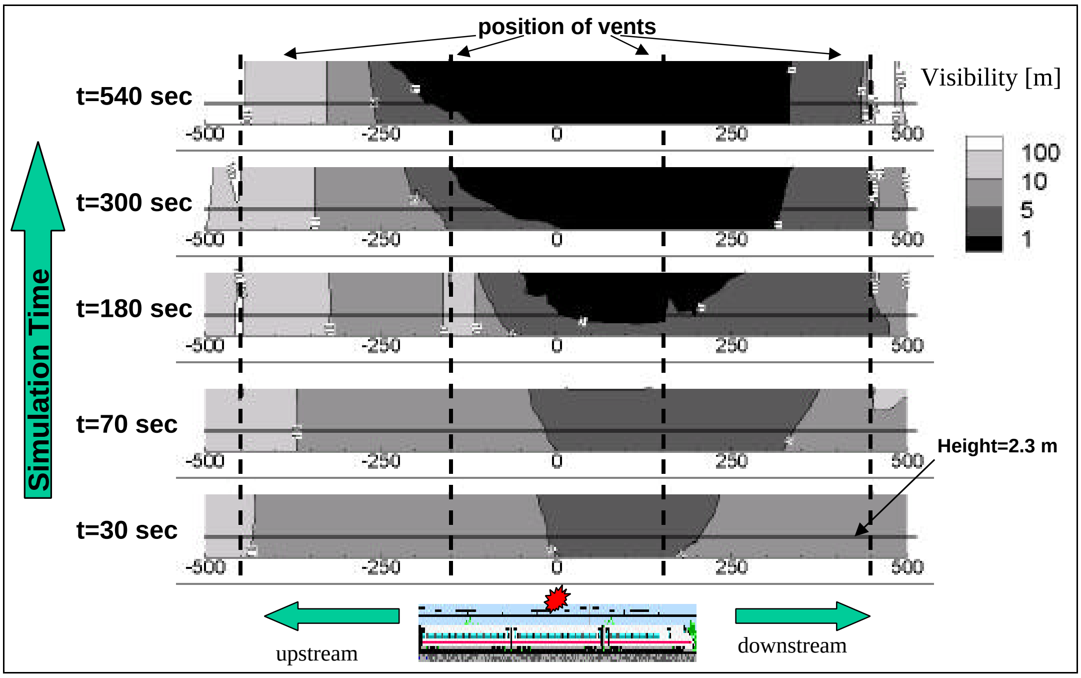


Figure 9 Transient development of the visibility in a section plane parallel to the train at a distance of 0.75 from the tunnel wall (representative for the situation on the emergency walkway)

The transient development of visibility at the emergency walkway is shown in Figure 9. The figure reveals the strongly reduced visibility near the train. Note also the reduction of visibility upstream of the train caused by the smoke that remains in the tunnels from the entering train. Similar to the temperature, 'visibility' stratification develops and leads to better visibility conditions in the lower part of the tunnel. Nevertheless, the reduction of visibility below 5 m on the emergency walkway can represent an increased risk for the life of the passengers.

6.2.4 TIME TO INCAPACITATION

The results obtained by the CFD simulation are compatible with the results of the 1-D analysis.

7 SAFETY ASSESSMENT

The discussion of the safety in the tunnel will be based on the four regions A, B_{up}, B_{down}, and C as defined in Figure 10.

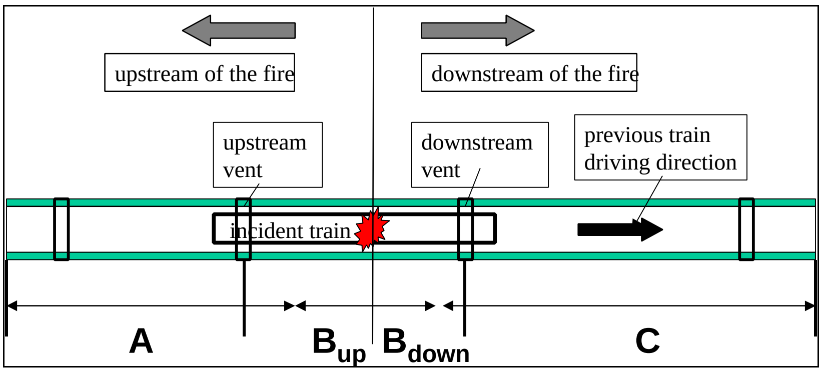


Figure 10 Definition of regions for the safety assessment

Given normal head or body height, the following limiting values are set for the attempt to escape.

- Time to incapacitation 1.8 m height: > 20 min
- Temperature at 1.8 m height: < 100 °C (=exposure time > 10 min from equation 3)
- Range of vision at 1.8 m height: > 5 m

Table 1 summarizes the results of the 1-D and 3-D analysis with respect to tunnel safety. A very similar picture is obtained from the two approaches. Only in the region B_{down}, differences occur during a very limited period of time. This is because the 1-D cross section mean temperature estimates the temperature at body height too high when thermal stratification occurs.

In particular between the fire and the vents life threatening conditions for the escaping passengers can occur. With further distance from the fire, the conditions improve. However, the strongly reduced visibility downstream of the vent (region C) can lead to risk for the life of the passengers. The concentration of CO in the air and the hereof resulting period of time to incapacitation is not expected to create additional risk for the passengers.

Region A			
t [sec]	Time Limit 3D / 1D analysis	Temperature Limit 3D / 1D analysis	Visibility Limit 3D / 1D analysis
30	fulfilled / fulfilled	fulfilled / fulfilled	fulfilled / fulfilled
70	fulfilled / fulfilled	fulfilled / fulfilled	fulfilled / fulfilled
180	fulfilled / fulfilled	fulfilled / fulfilled	fulfilled / fulfilled
300	fulfilled / fulfilled	fulfilled / fulfilled	fulfilled / fulfilled
540	fulfilled / fulfilled	fulfilled / fulfilled	**violated / violated**
Region B_{up}			
t [sec]	Time Limit 3D / 1D analysis	Temperature Limit 3D / 1D analysis	Visibility Limit 3D / 1D analysis
30	fulfilled / fulfilled	fulfilled / fulfilled	fulfilled / fulfilled
70	fulfilled / fulfilled	fulfilled / fulfilled	fulfilled / fulfilled
180	fulfilled / fulfilled	fulfilled / **violated**	**violated / violated**
300	fulfilled / fulfilled	**violated / violated**	**violated / violated**
540	fulfilled / fulfilled	**violated / violated**	**violated / violated**
Region B_{down}			
t [sec]	Time Limit 3D / 1D analysis	Temperature Limit 3D / 1D analysis	Visibility Limit 3D / 1D analysis
30	fulfilled / fulfilled	fulfilled /	fulfilled /
70	fulfilled / fulfilled	**violated / violated**	**violated / violated**
180	fulfilled / fulfilled	**violated / violated**	**violated / violated**
300	fulfilled / fulfilled	**violated / violated**	**violated / violated**
540	fulfilled / fulfilled	**violated / violated**	**violated / violated**
Region C			
t [sec]	Time Limit 3D / 1D analysis	Temperature Limit 3D / 1D analysis	Visibility Limit 3D / 1D analysis
30	fulfilled / fulfilled	fulfilled / fulfilled	**violated / violated**
70	fulfilled / fulfilled	fulfilled / fulfilled	**violated / violated**
180	fulfilled / fulfilled	fulfilled / fulfilled	**violated / violated**
300	fulfilled / fulfilled	fulfilled / fulfilled	**violated / violated**
540	fulfilled / fulfilled	fulfilled / fulfilled	**violated / violated**

Table 1 Assessment of safety for the escaping passengers as obtained from the 3-D and 1-D analysis (fulfilled: safety granted, violated : safety not granted)

8 1-D VERSUS 3-D APPROACH

The 1-D and 3-D approaches lead to a very similar safety assessment for the conditions of this particular study. This is attributed to the relatively simple geometry which was investigated. More detailed data is obtained from the 3-D CFD. In particular at the vents and near the fire, three-dimensional flow structures develop that violate the assumptions of the 1-D analysis. However, for the safety assessment this regions are of minor importance. The escape conditions for the passengers are determined by the conditions in the lower part of the tunnel near the walls. A detailed analysis of the CFD data in this region shows that the conditions predicted by the 1-D approach represent very well the escape conditions for the passengers. The prediction of thermal stratification, which in general is excluded from the 1-D approach, can help to improve the conditions for the passengers. The CFD study

showed that thermal stratification develops, which leads to a different safety assessment for a very limited period of time in the region B_{down} near the train. However, the combination of all evaluation criteria (temperature, visibility and time to incapacitation) for passenger safety can counter-balance for this limitation of the 1-D analysis as long as the 1-D assumptions for the global flow conditions are fulfilled.
In consideration of its cost, the use of 3-D models should therefore be mostly restricted to more complex configurations, where the approximations used by 1-D models are not allowable anymore. This is for instance the case for the investigation of smoke propagation into cross passages or smoke extraction from rescue areas. For a simple geometry the use of 1-D methods in most cases will be more efficient.

9 CONCLUSIONS

A study of tunnel safety in a tunnel with a natural ventilation system was presented. The study investigated the conditions near the burning train after its halt. An emergency scenario was defined and criteria for the assessment of the safety of the escaping passengers were presented. Two different approaches were used:

- 1-D approach using the program SPRINT, an HBI internal development,
- 3-D approach using the commercial CFD program FLUENT.

The following conclusions can be drawn from the study:

- The study gives a detailed picture of the safety of the escaping passengers. Temperature, visibility, time-to-incapacitation were derived from the simulations and used for the safety assessment.
- The high temperature levels and the significantly reduced visibility lead to an increased risk for the escaping passengers close to the fire. The concentration of CO in the air and the resulting period of time to incapacitation are not expected to create additional risk for the passengers.
- A very similar safety assessment is obtained based on both investigation methods, although the 3-D CFD simulation illustrates the development of thermal stratification near the fire, which is not possible using the 1-D approach.
- The study showed that SPRINT is a reliable design tool as long as the one-dimensional assumptions are valid for the investigated geometry. In this case, the 1-D approach leads to correct predictions of the relevant air-quality parameters in the tunnel and the escape conditions of the passengers.
- For a more complex tunnel geometry, including for example cross-passages or rescues areas, however, 3-D CFD should be employed because it will lead to more comprehensive and reliable results. Moreover, in particular for a complex flow condition, regions of high risk will be revealed by the 3-D CFD that could be overlooked by a 1-D analysis.

10 REFERENCES

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