Swissmetro: Safety aspects related to the low pressure environment.

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Abstract.

Due to both the high travel speed and tunnel length planned in the future Swissmetro system, reducing aerodynamic constraints and excavation costs is of utmost importance. The solution chosen is to maintain a low pressure atmosphere in the tunnel. The low pressure, which will likely range between 10 kPa and 25 kPa, may be a source of health hazards for the passengers. The potential adverse effecs may be direct, in case of an accidental decompression, or indirect in case of fire or vehicle stoppage inside the tunnel. A hazard analysis has been carried out during the Swissmetro main study in order to assess the effects of the low pressure. A review of the data available in other fields, such as aviation and diving medicine, as well as numeric simulation have been performed during this study. The results are briefly discussed in this paper.

Introduction

Reducing aerodynamic constraints is a major concern in rail tunnels. Because of the limited free space available, several undesirable aerodynamic effects occur in underground structures: aerodynamic drag, unsteady pressure waves (in front of the vehicles), and aerodynamic unsteady transverse forces (at the vehicle tail). The usual way to reduce these effects is to oversize significantly the tunnel diameter. Although, this counterbalancing measure is unfortunately expensive due to the large excavation work induced.

Due to both the high travel speed (about 400 km/h) and tunnel length (about 300 km) it is of utmost interest to keep aerodynamic constraints and excavation costs at "low" levels in the future Swissmetro system (an underground MAGLEV train planned for interurban linking in Switzerland). The solution chosen for the Swissmetro is to maintain a low pressure atmosphere in the tunnel in order to reduce aerodynamic drag while keeping a low tunnel diameter.

A wide range of tunnel pressures has been studied during the project's main study. The final pressure level in the tunnel will likely range between 10 kPa and 25 kPa. At such levels, excavation costs and aerodynamic undesired effects may be significantly reduced. On the other hand, the requirement of a low pressure environment has major consequences on Swissmetro design and characteristics. When considering their physical environment, the Swissmetro vehicles are comparable to planes rather than trains. As a matter of facts, the pressure levels considered are similar to those encountered by planes flying at 34'000- 52'000 ft.

Direct effects of the low pressure environment

The low pressure environment is a cause of an obvious hazard. In case of air-tightness failure, the vehicle pressure may drop suddenly and cause health damage to passengers. Until now, risk of public exposure to a sudden decompression have been limited to civil aviation and, at a lesser extent, to diving activities. The large experience acquainted in these two fields concerning accidental decompression and hypobaric environment exposure effects must be considered in the Swissmetro project. As a matter of facts, disregarding the system considered, the physiological effects and threshold values are the same. Although, it must be stressed that the preventive measures adequate in an underground structure may differs significantly from the one adequate in an underwater or aerial environment. Four potential effects are associated with decompression or low pressure environments:

Hypoxia

Hypoxia is a generic term used to depict the effects of an oxygen lack. In hypobaric environment, where hypoxia is due to the low oxygen partial pressure PO_2, its effects increase with the decreasing ambient pressure. At pressures below 0.66 atm, the oxygen lack become progressively incapacitating, clouding judgement and altering muscular coordination. Loss of consciousness may occurs, more or less quickly, below 0.5 atm. Hypoxic effects are or prime concern in safety because in case of a severe oxygen deprivation, which last more than 3 minutes, irreversible health damage may occurs. For this reason, aviations' safety rules against hypoxia include an emergency descent to a safe altitude level within a maximum time laps of 2 min. 30.

Barotraumas

In case of an ambient pressure decrease, the gases present into the body cavities get expanded, conformingly to the well-known Boyle-Mariotte's law. For enclosed cavities or cavities without sufficient openings, the internal pressure may become significantly higher than the external one, leading to a mechanical stress on the body's tissues. The damages or pains resulting from this relative "overpressure" are called barotraumas. Basically, any body cavity is potentially concerned by barotraumatic effects: intestinal tract, sinuses (if obstructed), lungs, teeth (because of holes in fillings), inner ear. Barotraumas may become significant for pressure drop ratios of about 2, although their extent is largely dependent on the decompression kinetics and individual physiological parameters. In a general manner, barotraumas may cause severe pain (incapacitating) or damage. In that regard, the pulmonary barotraumas are of special interest.

In case of an explosive or a rapid decompression, the glottis orifice may not be sufficient to evacuate the lungs' gases. Being flexible, the lungs may somehow compensate the overpressure by expanding themselves to reach the double of their normal volume. Beyond this point, the increase of the intrapulmonary pressure may cause irreversible damage (aeroembolism).

- When the glottis is **closed** during the decompression, it is generally assumed that pulmonary damages may occur at pressure ratios higher than 2.3 (Violette's criteria).

  Equ. 1 $$\varepsilon = \left(P_{b0} / P_{b1} \right)^{0.9}$$ (ε : lungs' expansion factor)

- When the glottis is **open**, the decompression effects will depends on the its kinetics. It is assumed that pulmonary damage may occurs only if:
  - the gas leakage ratio (the orifice area to the cavity volume ratio) is higher than 1/200 m^{-1}
  - the ratio between initial and final pressure is higher than 2,3.

Ebulism

The water vapor pressure at 37°C is of about 6.3 kPa. Therefore, when the body's environment drop below this pressure level, the blood may boils, with short term fatal consequences. Ebulism may be encountered only in extreme decompression situations. As the pressure range being studied in the Swissmetro project is higher than the Ebulism level, this effect cannot occurs.

Decompression sickness

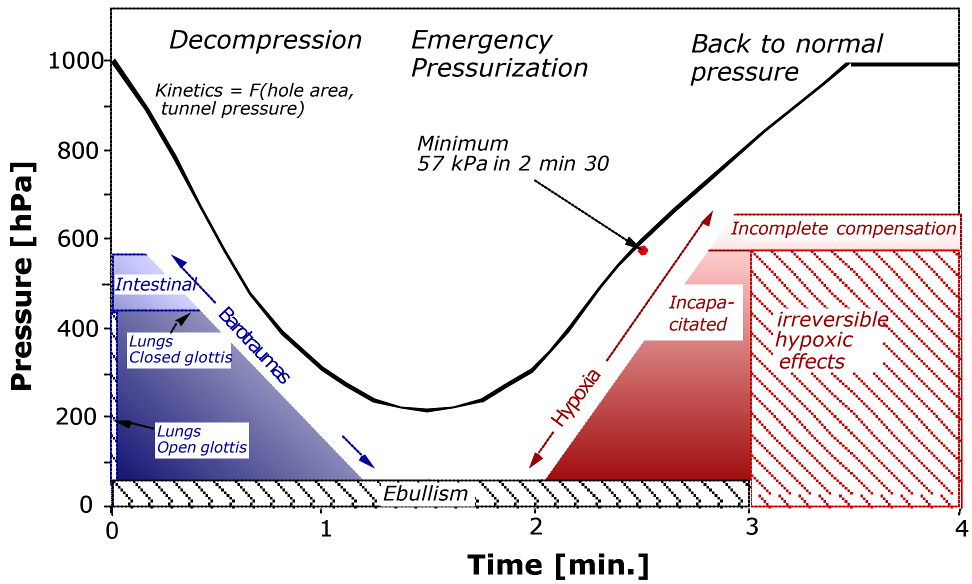
The so named DeCompression Sickness (DCS) embrace all the symptoms associated with the effects of an ambient pressure drop on the gases dissolved into the body's fluids. While the external pressure decrease, the quantity of dissolved gases (mainly nitrogen) will progressively be reduced to reach equilibrium. This process is quite slow and may take, for instance, about two hours for fat tissues. Thus, in case of a quick decompression, for which the pressure drop exceed 10 Pa/s, the denitrogenation cannot be completed and the body's fluids are over-saturated. The situation becomes problematic when the inner nitrogen pressure exceed the total ambient pressure. At this point, called the Haldane's critical over-saturation limit $\overline{R}$, nitrogen bubbles may appear into the body fluids.

Equ. 2 $$\overline{R} = P_{N_2} / P_b = 1{,}58$$ ***[-]***

Although DCS may have severe consequences. It must be stressed that its symptoms are delayed from several minutes to several hours after the decompression exposure. For this reason, DCS is only marginally relevant in hypobaric environments such as the Swissmetro tunnel. As a matter of facts, in case of an accidental decompression, immediate measures must be initiated in order to counter hypoxic effects.

The physiological effects related to the low pressure environment vs are summarized in Figure 1. (hypothetical decompression curve)

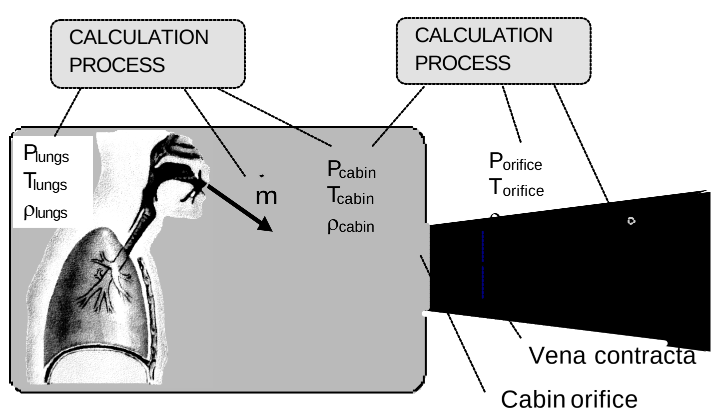
Figure 1. Low pressure physiological effects



Simulating decompression

The physiological effects related to hypobaric environment and decompression exposure are well known, being supported by a large number of human and animal experimentations. It appears that these effects are dependant on the decompression parameters and kinetics (pressure drop rate, initial to final pressure ratio, final pressure level). In the Swissmetro, the decompression conditions may differs from the situations encountered in the field of aviation or diving. Simulations have therefore been carried out in order to evaluate the health hazard associated with decompression cases in this enclosed and underground space. The modelling tool is also intended, at a further stage of the project development, to evaluate the efficiency and to make the dimensioning of the possible counter measures.

Figure 2. Schematic view of the decompression model



The model used in this study is based on classical fluid mechanics' theory. The decompression is described as a gas leakage, flowing trough three compartments: the passengers' lungs, the vehicle's cabin and the tunnel. The model used allows calculation of pressure kinetics inside both vehicle's cabin and passengers' lungs. A schematic view of the model is presented in Figure 2. Numerical simulation has been implemented using *Ithink (version 5.0)*, a flow processing software. The parameters and the numerical values considered during simulation are summarised in Table 1.

Table 1. Parameters used for decompression simulation

Type	**Parameter**	**Default value**	**Minimal value**	**Maximal value**
infrastructure	tunnel volume	300'000 m^3	580 m^3 (1)	1'200'000 m^3 (2)
vehicle	vehicle volume	300 m^3	200 m^3	1500 m^3
	numb. of passengers	200	200	800
	orifice area	0.1 m^2	0.01 m^2	5 m^2
	vehicle pressure	100 kPa	-	-
aerodynamic	tunnel pressure	10 kPa	1 kPa	100 kPa
physiology	lung volume	5 dm^3	0.1 dm^3 (3)	6 dm^3 (3)
	orifice area	1 cm^2	-	-

(1) with vehicle airbags
(2) without vehicle airbags or any tunnel partition
(3) ranging from new-born to adult (ending inspiration)

Simulation results

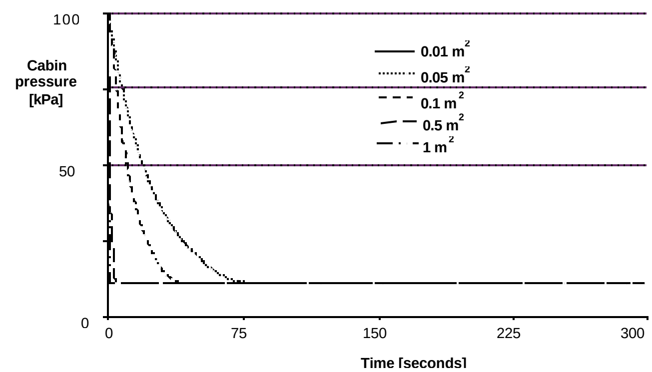
Orifice area

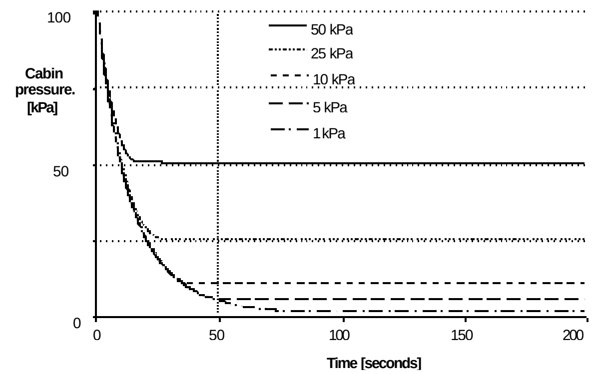
As previously reported in both experimental and theoretical studies, the leaking orifice area has a major impact on decompression kinetics. As shown in Figure 3 (a), decompression kinetics for a wide range of orifice areas has been calculated. As a matter of fact, disregarding their likelihood, a large number of scenarios ranging from a single crack or a leaking joint to the sudden loss of a door must be considered.

From the viewpoint of hypoxia, the decompressions will lead to similar situations, if more or less quickly. However, considering barotraumas, variation of the orifice area may lead to significantly different results. The potential health damages increase dramatically beyond 1 m^2. These results are consistent with the current aviation standards, which give a maximum of 1/200 m^{-1} for the leaking coefficient. Considering Swissmetro defaults parameters, this limit is exceeded only for orifices larger than 1.5 m^2. Further simulations have shown that the pulmonary overpressure exceeds the physiological limit of pulmonary barotraumas, for orifice areas of about 5 m^2.

Tunnel pressure

A wide range of tunnel pressure has been considered during the Swissmetro study. Decompression scenarios for pressure levels ranging from 1 kPa to 50 kPa, have been computed. As shown in Figure 3 (a), a change of the tunnel pressure may affect both barotraumas and hypoxia effects. The range of pressure levels planned in the tunnel is below the compensated hypoxic level (about 57 kPa).





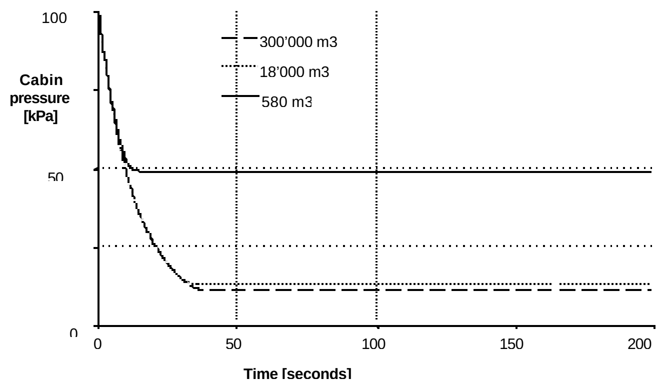


Figure 3: Decompression simulation results

(a) Decompression kinetics for several orifices areas
(b) decompression kinetics for several tunnel pressure levels
(c) decompression kinetics for several volumes of low-pressure compartment

Tunnel volume

To maintain a low-pressure level the Swissmetro tunnel will be an enclosed space, although of considerable volume. In order to allow regular traffic, the tunnel section between two stations (length of 40 to 60 km) will not be partitioned. The cabin volume of about 300 m^3 is then negligible considering the 1'200'000 m^3-surrounding tunnel. Therefore, during regular operating conditions, the situation will be similar to a vehicle travelling in an open space low-pressure environment.

In case of emergency however, reducing the free space surrounding the vehicle may mitigate the adverse effects of decompression. Until now, two solutions have been considered to reduce the surrounding space; partitioning the tunnel with emergency airtight doors, or isolating the vehicle with, for instance, inflatable joints. An example of simulated decompression with and without mitigating measures are shown in Figure 3 (c).

Implications for the Swissmetro project

Open glottis pulmonary barotraumas effects are highly dependent on the orifice area. Thus, similarly to aviation, the leakage coefficient will be maintained below 1/200 m^{-1}. It must be emphasised that Swissmetro vehicles will have a reduced number of built-in orifices, as windows are not planned in the current design.

Other barotraumas as well as hypoxic effects following decompression are mainly related to the tunnel pressure level. As this parameter has a dramatic impact on safety, costs and aerodynamics, it must be carefully optimised.

The pressure levels currently considered, ranging between 10 kPa to 25 kPa, may lead to acute hypoxic situations. Therefore, similar to the current aviation practice, an emergency pressurisation procedure (within 2 min. 30) is planned. In Swissmetro tunnels, an emergency pressurisation may be achieved using intermediate shafts to provide a local air supply or using a pressurised area in the tunnel (pipe, service tunnel) to provide a continuous air supply. As a local air supply generates a pressure wave, which may cause mechanical damage and adverse health effects, the first solution has been discarded.

Decompression sickness is not considered as a major public hazard in the Swissmetro system. Indeed, the decompression scenarios simulated point out a prevalence of hypoxic and barotraumatic effects. Moreover, considering the emergency pressurisation system planned, the exposure time to a hypobaric environment will be below the delay observed before DCS symptoms. Marginal cases of occupational exposures resulting in DCS may however occur.

Partitioning the tunnel in order to mitigate decompression is of little use because of the large volumes involved. A significant change in decompression kinetics may however be achieved by isolating the vehicle. In this latter case, the volume of the surrounding low-pressure compartment is in the same range as the cabin's volume and the final pressure reached is dramatically increased. The technical feasibility of this solution must be investigated further.

Confinement

Confinement, understood as a "limited" available space, is a common problem encountered in may underground infrastructures. However, in the Swissmetro system a confinement in the sense of an "enclosed space" will also be present. As a matter of facts, one side-effect of the hypobaric environment is the need of a partitioning between the tunnel and the areas occupied by people (stations, vehicle). Hence, maintaining a normal pressure inside the vehicle imply that the cabin atmosphere will be separated, at last partially, from the tunnel one. Basically two solutions can be considered: (a) pressurising and conditioning the tunnel air or (b) recycling and conditioning the cabin inner air. The first solution is the one used successfully onboard planes. In tunnel the air quality is however lower than in altitude, thus the air conditioning required may be more complex (filtering, cleaning,..). The second solution is not used in public transportation systems although it has been applied in other fields such as in submarines or in underground protected areas (mines).

The values used are presented in Table 1. A sensitivity analysis has been performjed for the main model parameters. The oxygen consumption and the cabin's volume are two of the key parameters of the model. As a matter of facts, their effects on both the carbon dioxide production and concentration are important. Moreover, the oxygen consumption ranges in a large scale (one to four ratio).

Table 2. Parameters used for IAQ simulations

type	parameter	Default value[(1)]	minimum	maximum
Technical design	Air cabin's volume per passenger	1500 l	1000 l	2000 l
Physiological	Oxygen consumption	$2.2\ 10^{-2}$ mol/min.	$1.3\ 10^{-2}$ mol/min. min. adult at rest	$4.4\ 10^{-2}$ mol/min. man, maximum for a light physical activity
	weight	60 kg	40 kg	100 kg

The simulation results obtained while varying these two parameters are presented in Figure 5. A total loss of air supply after 20 minutes of normal functioning has been considered. The results obtained are expressed in terms of carbon dioxide concentration and pulmonary ventilation rate. These two values are used as indicators of potential health effects.

It takes only a few minutes to reach significant pollutants levels. It is indeed generally assumed that a 1500 ppm level of carbon dioxide is the upper limit for a good air quality. Although this concentration is based on comfort (odours) and not on toxicological considerations. The carbon dioxide threshold limit (short-term limit) of 3%, which is an indicator of adverse health effects, is only reached after about two hours. Although it must be stressed that the estimated pulmonary ventilation rate is increased significantly after about one hour.

As expected, the cabin's volume may affects significantly its "habitability" in terms of IAQ. But individual parameters, such as the oxygen consumption level, may have predominant effects. Oxygen consumption is of particular interest in this regard because it may vary significantly with stress.