INFLUENCE OF THE TUNNEL CROSS-SECTION ON TUNNEL AERODYNAMICS

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ABSTRACT

In addition to technical aspects, financial considerations also play a role in the planning of a railway tunnel. Since the tunnel shell accounts for a significant portion of the construction costs, efforts are made to keep the excavated volume as small as possible. This often results in very small tunnel cross-sections, which, in combination with high train speeds, lead to pressure changes with high amplitudes. The loads caused by the pressure changes generally represent the design reference for the load limit of trains and the components installed in railway tunnels. It has been shown that some of the cost savings in shell construction are offset by increased expenditure on tunnel equipment. In addition, small cross-sections can cause the problem of a so-called "sonic boom", which can only be solved by additional construction work.

This article aims to highlight the connection between tunnel cross-sections and the associated aerodynamic aspects and to raise awareness of the importance of careful coordination of construction planning with regard to these aspects.

Keywords: rail tunnel, high-speed train, pressure wave, tunnel cross-section, aerodynamic burden, sonic boom

1. INTRODUCTION

When a train enters a tunnel at high speeds it induces static and dynamic pressures inside the tunnel. They affect tunnel equipment, as well as the train body. Furthermore, static pressure has effect on passenger comfort inside the train and can even cause medical injuries.

Train induced pressures are highly reliant on the tunnel cross-section. Besides geological and hydrological aspects the choice of the tunnel cross-section has significant influence on the construction costs. Hence tunnels are usually planned as small as possible with respect to the required clearance gauge and other requirements like dewatering. Aerodynamic considerations play a minor role in the planning phase of tunnel tubes. This can come back to haunt you later.

This paper aims to highlight the influence of the tunnel cross-section on various aerodynamic aspects and the associated problems. The following aerodynamic aspects are strongly depending on the tunnel cross-section:

- 10 kPa Health Criterion [1][2][4][5]
- Aerodynamic loads on tunnel structures and train body
- Pressure Comfort
- Aerodynamic Drag
- Sonic Boom

2. FUNDAMENTALS

When a train passes through a tunnel, pressure waves at nearly the speed of sound are propagated in the tunnel. Due to the superposition of waves, the pressure amplitude increases, leading to high loads on tunnel equipment and rolling stock. Besides this, the size and the direction of the impact forces change very quickly.

2.1. Static Pressure

Static pressure inside the tunnel is not directional and has impact on airtight structures like tunnel doors and the train which's coaches are sealed. Pressure transiently changes along the tunnel due to the train induced pressure wave. These fast pressure changes are overlayed by static pressure changes caused by train movement inside the tunnel. Free, non-airtight installations like traffic signs are not affected by the static pressure. Static pressure changes also can be recognised by the human ear which can be uncomfortable (pressure comfort) or even health affecting when the pressure variations are too high within a short time. **Figure 1** shows the characteristic train induced pressure wave measured near the entry portal.

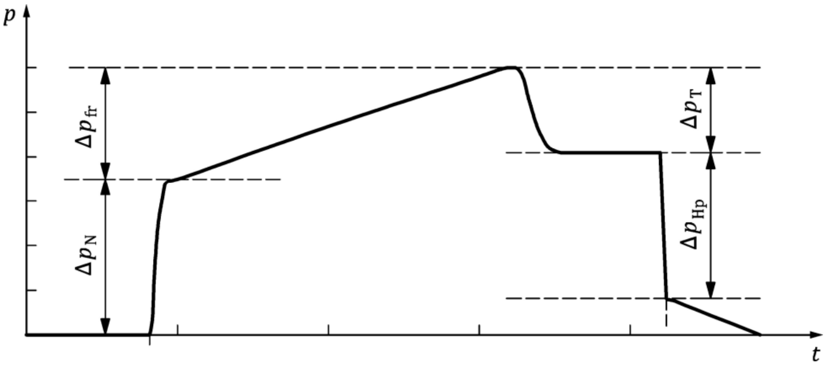

Figure 1: Pressure Wave induced by train entry (EN14067-5)

Δp_N	pressure rise due to trains nose entry
Δp_{fr}	pressure rise due to wall friction
Δp_T	pressure drop due to entry of the trains tail
Δp_{HP}	pressure drop due to train nose passing the fixed measurement position

This pressure wave travels through the tunnel at the speed of sound and is reflected by the portals. Hence pressure waves can superimpose especially in double track tunnels.

2.2. Dynamic Pressure

Dynamic pressure is directional and affects non-airtight tunnel installations (traffic signs, cables, signalling systems, etc.) that are exposed to the air currents caused by the train. The air flow in the direction of travel is caused by the piston effect, and the wake directly behind the train can exert high forces on the tunnel installations with multiple load changes.

2.3. Influencing Factors

Static as well as dynamic pressure inside rail tunnels depend on several influencing factors:

- Tunnel geometry (cross-section, length, area changes, niches, shafts etc.),
- Train geometry (cross-section, length),
- Tunnel and train wall friction,
- Train nose and tail shape.

However, the most important factor influencing the pressure level in tunnels is the blockage ratio:

$$\frac{A_{Train}}{A_{Tunnel}}$$

3. NORMATIVE TEXT AND GUIDELINES

This section lists normative texts and guidelines that deal with tunnel cross-sections and their aerodynamic aspects. Since aerodynamic aspects depend on both the railway infrastructure and the rolling stock, there are usually restrictions on the pressure inside a tunnel or inside a train rather than a minimum cross-sectional size.

3.1. TSI LOC&PAS / TSI Infrastructure:

The European Commission has passed technical specifications for the interoperability (TSI) in the trans-European high-speed and the conventional railway system and has published them in the respective gazettes of the European communities.

The TSI LOK&PAS and EN14067-5 provide reference scenarios given in Table 1. Those requirements must be met by trains to be TSI conform. The given tunnel cross-sections are not the minimum of acceptable cross-sections but gives a rough hint for the design of it.

The relevant aerodynamic properties of rolling stock are determined based on 1:1-tests and compared with the directives of TSI. The tests serve as basis for the approval and authorisation of trains and tunnels. Since 1:1-measuring of every train/tunnel combination is not possible, calculation results with validated calculation models are accepted too.

The two reference scenarios can be used to calibrate a train for 1D simulations to estimate the pressure loads inside a tunnel with a different cross-section. The reference trains lead to conservative pressure loads inside the tunnel. Modern highspeed trains usually have better aerodynamic characteristic.

Table 1: Reference cases according to TSI LOC&PAS and EN14067-5

	Reference Case		Requirements		
	V_{tr}	A_{tu}	Δp_N	$\Delta p_N+\Delta p_{Fr}$	$\Delta p_N+\Delta p_{FR}+\Delta p_T$
< 250 km/h	200 km/h	53.6 m²	≤ 1750 Pa	≤ 3000 Pa	≤ 3700 Pa
≥ 250 km/h	250 km/h	63.0 m²	≤ 1600 Pa	≤ 3000 Pa	≤ 4100 Pa

Figure 2 shows the calculated pressure wave induced by a TSI train which exactly fits the limitations shown in Table 1 (1D simulation by Gruner).

The verification is based on 1:1 -tests carried out at the reference speed or a higher speed in a tunnel with a cross-section that is as close as possible to the reference case. The transfer to the reference requirement must then be carried out using verified simulation software.

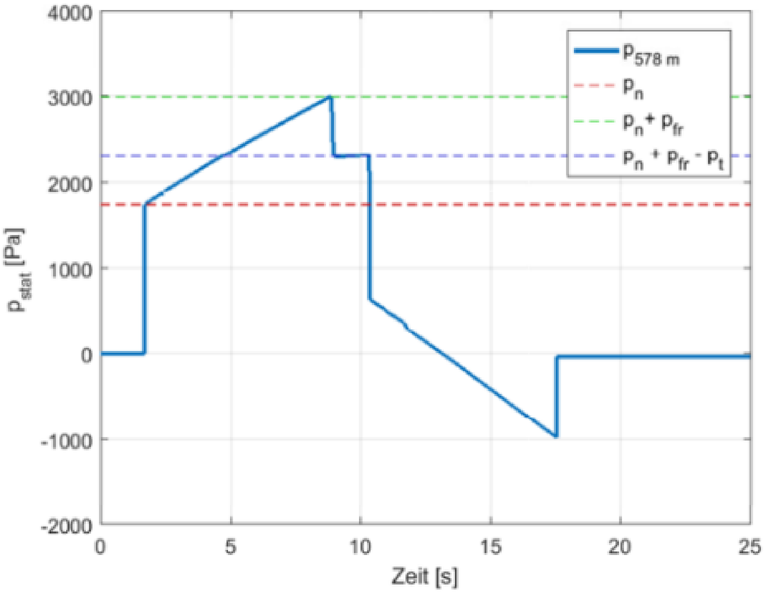

Figure 2: Reference Scenario (v_{train} < 250 km/h)

3.2. German Railway (DB)

The German Railway Service demands the following tunnel cross-sections for newly built tunnels shorter than 11 km (**Table 2**). Longer tunnels with more complex properties like air shafts, adjacent train stations or additional aerodynamically connected bores need further investigation.

Table 2: Tunnel cross-sections according to DB RIL 853 ([4])

	V_{tr}	No. Tracks	A_{tu}
High-Speed Trains	230 – 300 km/h	1	≥ 69.7 m²
	230 – 300 km/h	2	≥ 92.0 m²
Express Trains	160 – 230 km/h	1	≥ 53.7 m²
	160 – 230 km/h	2	≥ 79.2 m²

Figure 3 shows maximum pressure loads in German rail tunnels. In all cases the requirements regarding static pressure loads must be met.

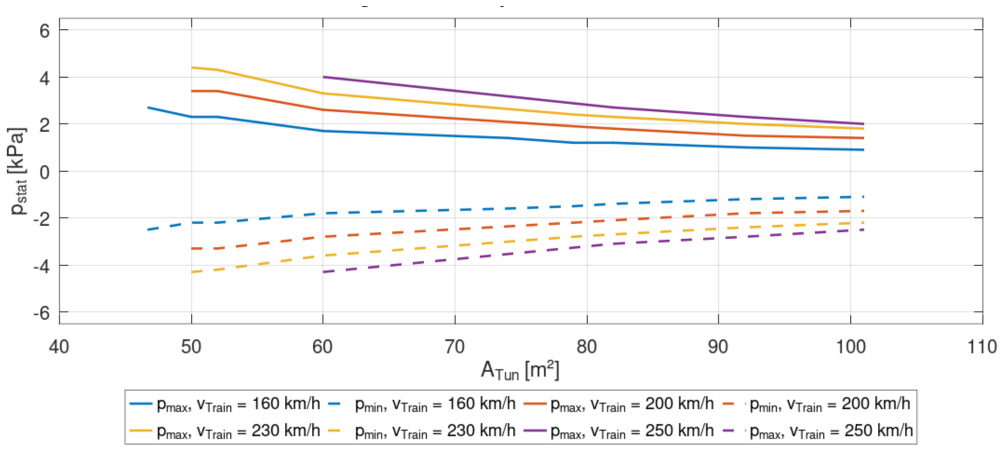

Figure 3: RIL853, Frequent pressure loads (single track)

3.3. Austrian Railway (ÖBB)

The ÖBB's actual standard cross-section for single track tunnels amounts to 54.2 m² [8]. This guideline is relatively new. Tunnels in Austria that are currently in the equipment phase, or have recently been put into operation, have smaller tunnel cross-sections. (e.g. Granitztaltunnel, Koralmtunnel, Semmering base tunnel).

4. ASSESSMENT

4.1. Static Pressure

The static pressure inside rail tunnels can be predicted by 1D simulations. For already existing tunnels pressure can be obtained by full-scale measurement.

In 2016, Gruner conducted parametric 1D simulation studies on static pressure caused by trains in tunnels. The TSI reference train (**Table 1**) was applied to simulation cases in which the parameters of train speed, tunnel cross-section, and tunnel length were varied. Pressure maxima and minima were calculated (see **Figure 4**). The figures can be used to estimate the expected static pressures as a function of the tunnel cross-section. In a further study [6], a general formula was derived with which a known characteristic pressure (e.g., maximum pressure) can be transferred to another cross-section.

Equation 1: $$\pm p_{char,tun} = p_{char,ref} * \left(\frac{A_{ref}}{A_{tun}}\right)^{\frac{3}{2}} \; [kN/m^2]$$

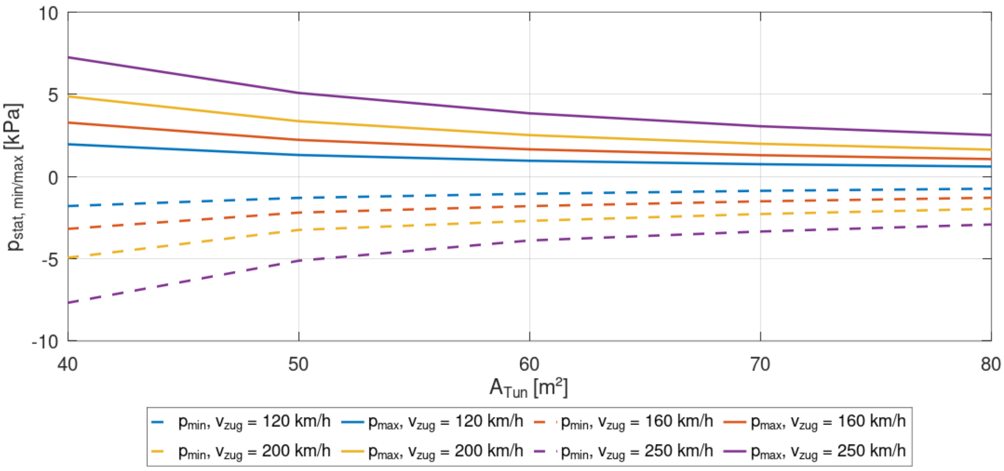

Figure 4: Static Pressure, Solo passages in long single-track tunnels

4.2. Dynamic Pressure

Dynamic pressure loads can be assessed according to RIL 853 [4]. First a dimensionless velocity is calculated using the formula below. For TSI conform tracks 0.05 must be added. Only tunnel cross-sections ranging from 32 to 101 m² are considered.

Equation 2: $$u^* = \frac{41}{A_{tun}} + 0.05 \; [-]$$

Once u* is calculated the dynamic pressure loads can be calculated.

Equation 3: $$\pm q_{std} = \pm 0.04726 * u^{*2} * v_{train}^2 \; [\text{Pa}]$$

The forces on tunnel equipment induced by dynamic pressure can be calculated as follows:

Equation 4: $$\pm F_{std} = \pm q_{std} * A_{comp} * c_{f,comp} \; [\text{N}]$$

Figure 5 shows the dynamic pressure over different tunnel cross-sections.

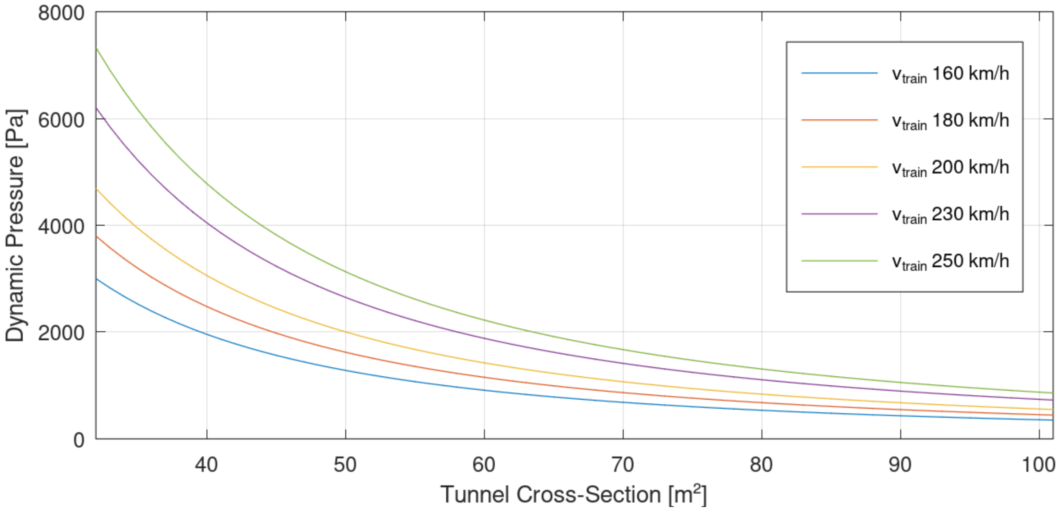

Figure 5: Characteristic dynamic pressure

5. SUBJECTS TO CONSIDER AND LIMITATIONS

5.1. The 10 kPa Criterion ("Infrastructure Reference Case")

The 10 kPa criterion refers to static pressure inside the tunnel as described in chapter 2.1. The pressure variations in tunnels during a passage of trains with a maximum speed equal or more than 200 km/h must not exceed 10 kPa. This limitation can be found in almost every normative text and guideline related to aerodynamical aspects of trains in tunnels ([1][2][3][4][5]). EN14067-5 defines the 10 kPa criterion as the maximum peak to peak pressure measured outside a train during a tunnel passage. It is a limitation for tunnel design. It can be assessed by 1D simulations using the reference train at maximum design speed described in chapter 3.1 inside the tunnel of interest. For single track tunnels a single train passage is sufficient. In doubletrack tunnels the superposition of pressure waves must be considered by variation of train entry times.

5.2. Pressure comfort

Pressure comfort refers to the pressure change per time unit inside a train passing a tunnel. It depends on the static pressure the train is exposed to and the quality of the train sealing which has a damping effect when outside pressure is transferred to the trains inside. The better the train sealing (commonly assessed using a Tau value in seconds), the more comfortable the pressure variations inside the train which the passengers are exposed to.

The Tau value is a measure for the relationship between external pressure p_e and the internal pressure p_i of a passenger coach or locomotive. The transient internal pressure can be calculated as follows:

Equation 5: $$\frac{dp_i}{dt} = \frac{1}{\tau_{dyn}} [p_e(t) - p_i(t)] \text{ [Pa/s]}$$

As train bodies are not perfectly stiff the formula can be extended by the variable k_r, (usually between 0.05 and 0.1), a measure for the stiffness of the train structure. Neglecting this parameter would lead to an overestimation of the Tau value. The extended formula is

Equation 6: $$\frac{dp_i}{dt} = \frac{k_r}{1+k_r} * \frac{dp_e(t)}{dt} + \frac{1}{\tau_{dyn}*(1+k_r)} [p_e(t) - p_i(t)]$$

Pressure comfort must be considered for all tunnels longer than 50 m [1]. It's up to the provider of the infrastructure to build tunnels in which pressure comfort can be achieved with a common pressure sealing (τ_{dyn} = 4 - 20 s). The train manufacturer must provide adequate sealing of their trains.

The ÖNORM EN 14067-5 recommends following pressure changes inside trains during tunnel passages:

Non-sealed trains (τ_{dyn} < 0.5 s)

- Double Track Tunnels: 4500 Pa within 4 seconds (critical train encounter)
- Single Track Tunnels: 3000 Pa within 4 seconds

Sealed Trains (τ_{dyn} > 0.5 s)

- 1000 Pa within 1 seconds
- 1600 Pa within 4 seconds
- 2000 Pa within 10 seconds

The values can be considered during tunnel design but aren't generally binding because the inside pressure is highly dependent on the trains using the infrastructure.

5.3. Sonic Boom

The pressure wave, which is generated when a train enters a tunnel, travels through the tunnel at the speed of sound. Most of the pressure wave is reflected into the tunnel at the exit portal. A small portion escapes at the exit portal as a micro pressure wave, which is radiated into the surrounding area. This micro pressure wave is perceived as a portal bang (sonic boom), which can have a negative impact on the immediate vicinity of the exit portal. The intensity of this phenomenon depends on the gradient of the pressure wave at the exit portal. The development of a sonic boom can be divided into 3 stages:

Entry wave

As described in chapter 2.1 the train induces a pressure wave to the tunnel. The highest temporal gradient is usually induced by nose entry (dp_N/dt, **Figure 6**).

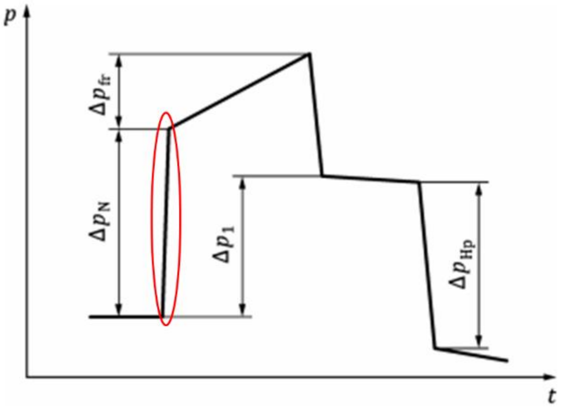

Figure 6: Entry Wave

While the gradient depends on the time the train nose needs to enter the tunnel, the magnitude Δp_N is influenced by following parameters:

- Blockage ratio (train cross-section / tunnel cross-section)
- Train speed (high speeds reduce the entry time)
- Nose length (long noses portals enhance the entry time)
- Portal shape (slanted portals enhance the entry time)

Friction has neglectable influence at this stage.

Wave steepening along the tunnel

When the pressure wave travels through the tunnel its gradient may steepen up. This is due to spatial pressure differences before and after the wave leading to differences of sonic speed. This means in some cases the pressure gradient rises along the tunnel.

Wall friction and other damping tunnel structures like shafts, niches or cross-passages reduce the amplitude of the pressure wave. **Figure 7** schematically shows the pressure wave's steepening as well as the reduction of its amplitude.

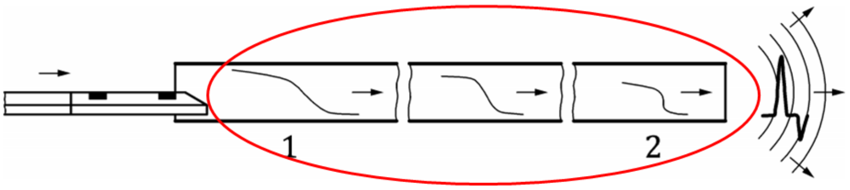

Figure 7: Pressure wave evolution along a tunnel [1] and MPW emission

Figure 8 shows the pressure gradient near the exit portal depending on the gradient near the entry portal for different tunnel lengths. The pressure gradient at the exit portal rises exponentially with gradient of the initial wave. The longer the tunnel, the more time the gradient has steepened up.

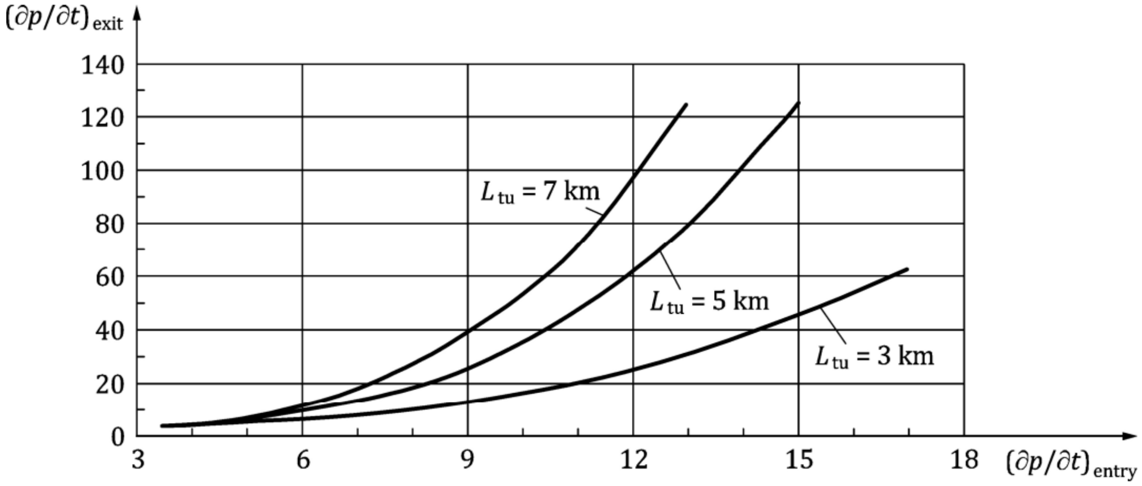

Figure 8: Wave steepening ([1])

The following factors are influencing steepening of the pressure wave:

- High blockage ratio increases the steepening effect.
- Slab tracks give advantage to a sonic boom, because they lack the damping effect of ballasted tracks (no sonic boom was reported in ballasted track tunnels).
- Wall friction and tunnel geometry (cross – passages, niches, shafts).

Micro Pressure Wave Emission

The emitted micro pressure wave (MPW) is directly proportional to the pressure gradient inside the tunnel near the exit portal. For simple portals, the MPW can be roughly estimated using Equation 7. Besides the term $(dp/dt)_{exit}$ the magnitude of the MPW depends on the tunnel cross-section (A_{tu}), the distance between the portal and the measurement position (r) and a factor **Ω** which is the spatial angle the MPW can be emitted (usually between 2 and 4). The variable c is the speed of sound.

Equation 7: $\Delta p(r,t) = \frac{2A_{tun}}{\Omega cr} * (\frac{dp}{dt})_{exit}$ [Pa]

Mitigation

As described above tunnel cross-section effects the sonic boom in two ways:

- The initial pressure gradient is higher due to higher pressure magnitudes and
- the wave's steepening effect is increased at small tunnel cross-sections.

An efficient way to mitigate sonic boom is to build a portal hood with a larger cross-section than the tunnel cross-section (Figure 10). This reduces the entry gradient. A popular example for a portal hood is the Katzenbergtunnel in Germany.

Influencing factors are:

- Hood cross-section / tunnel cross-section ratio (typically 1.5-2),
- Hood length
- Openings (area, amount, position), cf. **Figure 9**,
- Portal shape.

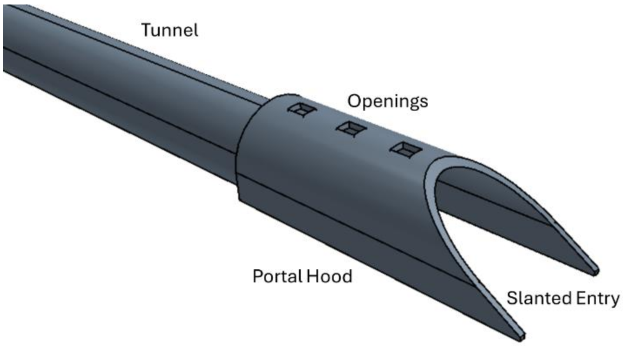

Figure 9: Portal Hood (illustriative)

Efficient portals lead to a reduction of the entry gradient of up to 50%. The performance can be assessed in advance by 3D-CFD simulation.

5.4. Aerodynamic Drag

A train is exposed to higher aerodynamic drag in a tunnel than on open track. Consequently, the train consumes more energy when passing a tunnel. The aerodynamic drag depends, besides other factors, on the tunnel cross-section as well as the tunnel length.

A common way to describe the aerodynamic drag in tunnels is the tunnel factor which is the ratio between the aerodynamic drag inside the tunnel and the open track. Typical values for the tunnel factor are between 1.0 (short tunnel, large cross-section) and 2.0 (long tunnel, small cross-section). The longer the train, the higher the tunnel factor.

6. SUMMARY AND CONCLUSION

Small tunnel cross-sections combined with high train speeds lead to pressure changes with high amplitudes. The stresses caused by these pressure changes are usually the design reference for the load limit of trains and the components installed in railway tunnels. In addition, small cross-sections can cause the problem of a so-called “sonic boom.” The mechanisms that lead to the formation of high-pressure amplitudes in tunnels were presented and the associated aerodynamic aspects were identified.

The sonic boom is a phenomenon that is often underestimated in this context. The description of the parameters influencing the supersonic boom shows that predicting it is anything but easy.

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