# TUNNEL AERODYNAMICS OF THE MAGNETIC LEVITATION HIGH-SPEED LINK IN MUNICH (MAGLEV) – CONSEQUENCES FOR PRESSURE COMFORT, MICRO-PRESSURE WAVES, TRACTION POWER AND PRESSURE LOADS

*Stig Ravn HBI Haerter Ltd. Switzerland*
*Peter Reinke HBI Haerter Ltd. Switzerland*

**ABSTRACT**

The continuing demand for fast, secure and environmentally friendly travelling prompts a need for the planning and construction of high-speed rail tunnels. However, tunnels for high-speed traffic may lead to adverse aerodynamic effects for the passengers, the rolling stock and the tunnels including their equipment. The adverse consequences of high-speed rail traffic in tunnels are often enhanced by the utilization of smaller cross sections (single track with twin tube tunnels rather than double track with single tube tunnels) and the use of slab/concrete track instead of ballast track.

By choosing adequate civil measures, the unfavourable aerodynamic conditions in the tunnel can be reduced. Taking the concept design of the magnetic levitation link in Munich (MAGLEV) as an example, the various aerodynamic implications of high-speed traffic in tunnels and underground stations are illustrated.

## 1 INTRODUCTION

The need for fast, secure and environmentally friendly travelling prompts a need for the planning and construction of high-speed public transport lines. One of these new lines planned is the magnetic levitation link in Munich running between the main rail station and the airport. The connection is about 38 km long and running at a maximum velocity of 350 km/h the total journey time is reduced to about 10 minutes. No other traffic system in Germany will be faster than the new super-speed magnetic levitation train. The vehicle (Transrapid) of the MAGLEV project in Munich is a magnetic levitating train which is propelled by linear motors. Conventional tracks have been replaced with a magnetic guideway which supplies the lift force, guidance and the power to the vehicle. Hence, no rails are in the tunnels and there is no need for a catenary or third rail system (see Figure 1).

Figure 1: An artist impression of the magnetic levitation rail link (MAGLEV) at the airport in Munich and the layout of the guideway (Illustration of BMG)

The major part of the MAGLEV line is situated above ground, but the rail link will end in two underground dead-end stations at the end of tunnels. In addition to the tunnels at the stations, one extra tunnel is situated between the stations. In all, the project comprises of 3 tunnels and 2 underground dead-end stations. The proposed tunnels are designed as double-tube, single-track tunnels. A sketch showing the entire rail link can be seen in Figure 2 below.

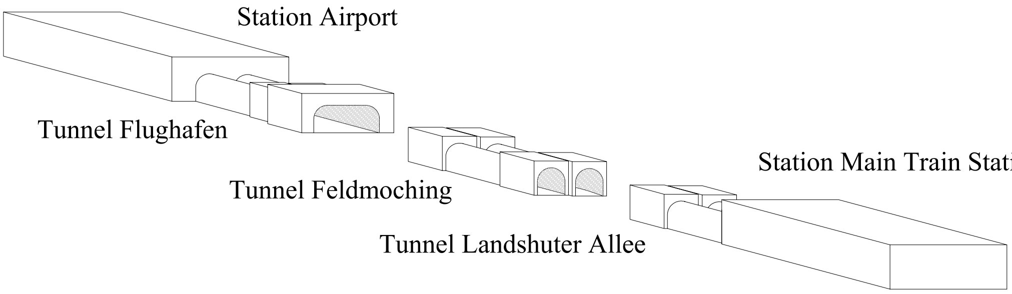



Figure 2: Sketch of the rail link (concept design without measures)

The main characteristics of the tunnels and stations are listed in Table 1.

| | **Length [m]** | | **Free cross-sectional area [m$^2$]** | |
|---|---|---|---|---|
| **Tunnel/station section** | Cut and cover | Bored | Cut and cover | Bored |
| Main train station | 311 | - | 42 | - |
| Airport station | 426 | - | 42 | - |
| Landshuter Allee | 160 | 4413 | 60 - 42 | 42 |
| Feldmoching | 360 | 2180 | 60 | 42 |
| Tunnel Flughafen | 1212 | - | 60/52 | |

Table 1: Main characteristics of the tunnels and stations for the concept design

## 2 AERODYNAMIC ISSUES AND DESIGN OBJECTIVES

Taken the high speed of the vehicle and relative small cross-section of the tunnels into consideration there was a high risk of this leading to adverse aerodynamic effects for the passengers, vehicle and the tunnels structure and equipment, in the form of:

- worsening of the pressure comfort in the rolling stock
- more severe pressure loads on the vehicle, the tunnel and its equipment
- risk of unwanted micro-pressure waves at the portals (sonic boom)
- worsening of the comfort conditions in the underground stations due to high wind velocities and fluctuating pressure waves
- increased traction power demand of the vehicle

Hence, aerodynamic investigations for the MAGLEV link in Munich were undertaken in order to cover safety and comfort issues and to determine loads and power requirements. The examined aerodynamic issues are listed in Table 2 below and further explained below.

### 2.1 Health limits and comfort related to pressure changes

Sudden pressure changes might create discomfort to train passengers and staff. The pressure comfort problem here is associated with the effect of pressure on the eardrum and can even in extreme cases inflict damage to the ears. The criteria for the pressure comfort are commonly defined by the maximum pressure change within a given time period. Several studies with pressure chambers and additional statistical enquiries in various tunnels have led to different comfort criteria. On the basis of the different criteria, the International Union of Railways (UIC) has recommended a set of pressure comfort criteria specifying the maximum acceptable pressure changes for given time intervals [1]. The criteria chosen for the MAGLEV project in Munich are partly based on these criteria. The criteria for the project are presented in Table 2.

| | | Location | | |
|---|---|---|---|---|
| **Aspect** | **Design objectives** | **Vehicle** | **Station** | **Tunnel / at Portal** |
| Health risk of passengers/staff due to high pressure fluctuations | $\Delta p \leq 10$ kPa | × | × | × |
| Pressure comfort in the vehicle and in the tunnel areas including the underground stations | $\Delta p\ (\Delta t=1s) \leq 0.5$ kPa<br>$\Delta p\ (\Delta t=3s) \leq 0.8$ kPa<br>$\Delta p\ (\Delta t=10s) \leq 1.0$ kPa | × | × | |
| Micro-pressure waves at the external portals and interior portals within the underground stations | $\Delta p < 20$ Pa | | × | × |
| Air velocity related to comfort | $v_{max} < 5$ m/s<br>$v_{mean} < 3$ m/s | | × | |
| Air velocity related to loads - Forces on objects | $F_{structure} > F_{wind}$ [N] | | | × |
| Aerodynamic resistance for the traction requirements of the vehicles - Forces on vehicle | $F_{available} > F_{necessary}$ [N] | × | | × |
| Examination of the loads on the rolling stock and the tunnel structures including the underground stations | $P_{structure} > P_{possible}$ [Pa] | × | × | × |

Table 2: Investigated aerodynamic issues

### 2.2 Rolling stock pressure tightness - sealing quality

The pressure comfort in the train is closely linked to its sealing quality as a good sealing can attenuate the pressure changes during the train ride. In general, pressure variations in a tunnel are caused by trains passing the tunnel. Major pressure waves are generated at portals or at changes of the free cross-sectional area within the tunnel. The pressure variations develop outside the train. The different openings of the train will cause an equalisation between the pressure outside and inside (leakage through air-conditioning, window and door sealings, sealing between two coaches, etc.). The speed of the pressure equalisation is determined by the size of the openings. Large openings will cause a faster pressure equalisation than small ones which may lead to discomfort or not depending on the pressure variation within a certain time interval.

The pressure tightness coefficient τ is used to specify the sealing quality of rolling stock. It describes the time in which a difference between the internal and the external pressure has decreased from 100 % to approx. 38 % of the initial pressure difference according Figure 3.

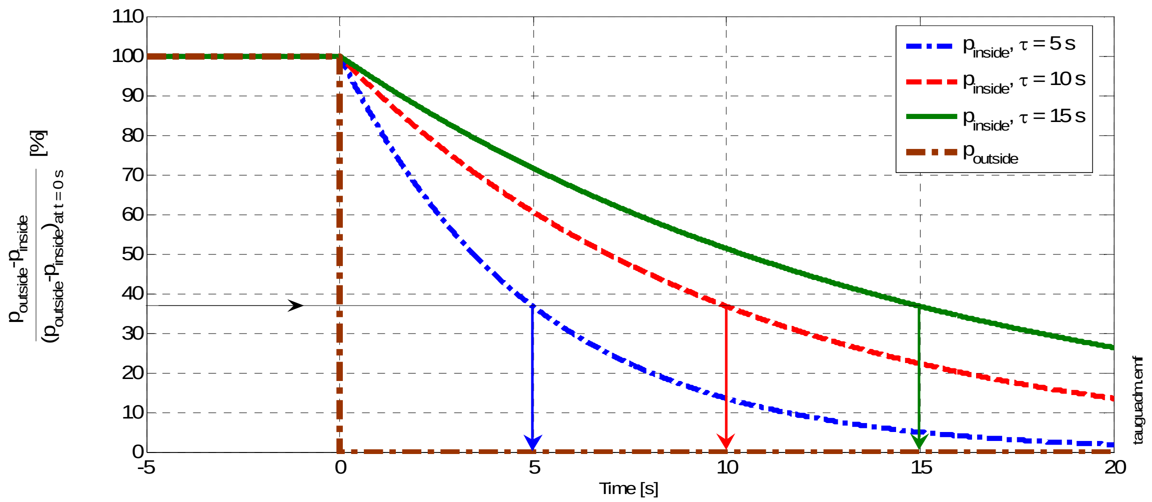



Figure 3: Pressure development in train for a sudden pressure difference to the exterior at t = 0 s

It should be noted that specifying the sealing quality of a vehicle by a single time constant such as τ is a significant simplification. τ-values of the coaches might vary significantly depending on the location, the pressure gradient, the time and the condition of the coach. The impact of different pressure tightness coefficients on the decreasing pressure difference between the exterior and the interior of the train is shown in Figure 3. Typical pressure tightness coefficients are listed in Table 3.

| **Train type** | **Typical pressure tightness coefficients τ** |
|---|---|
| Unsealed train (e.g. Regional train) | $\tau < 1$ s |
| Minimum sealed train (e.g. Eurocity) | $1 \text{ s} < \tau < 6$ s |
| Well sealed trains (e.g. ICE1, TGV) | $6 \text{ s} < \tau < 10$ s |
| Excellently sealed trains (e.g. ICE3, Transrapid) | $\tau > 10$ s |
| Assumption for the maximum structural load on a vehicle | $\tau = \infty$ s |

Table 3: Comparison of typical pressure tightness coefficients of different train type

For the present study values of $\tau = 15$ s were taken into account.

### 2.3 Pressure loads

The magnitude of the pressure fluctuations in a tunnel is, among other factors, a result of the speed, the cross-section, the length, the shape and the roughness of the train and the length, roughness and the civil construction type of the tunnel and the portals. The traversing pressure waves and pressure changes along a moving train will affect the:

– tunnel equipment and installations
– forces acting on the train surfaces (windows, doors, climate system etc.)
– possibly the function of the drainage system
– pressure comfort for the train passengers and staff
– functionality of the ventilation/cooling systems of the cross-passages
– forces acting on cross-passage doors and cabinets

### 2.4 Micro-pressure waves

The initial pressure wave generated by trains at the entrance portal steepens as the wave propagates through the tunnel. With unfavourable tunnel and train design the pressure wave, propagating at the speed of sound, might detonate with a loud sound when reaching the exit portal (sonic boom; see Figure 4).

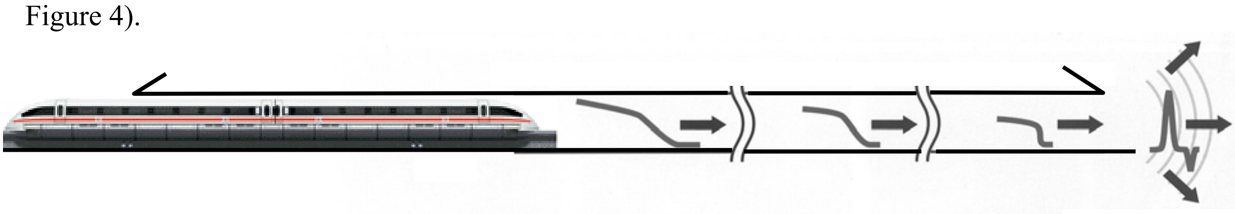


Figure 4: Development of micro-pressure waves (sonic boom; illustration of BMG/DB)

In general, the probability of creating non-acceptable pressure fluctuations at the exit portal increases with smaller cross-sections at the entrance portal (high blockage ratio) and with change from ballast to slab track. As the velocity of the train increases linearly at the portal entry, the amplitude of the pressure wave increases in a quadratic and the gradient of the pressure wave in a cubic manner. The risk of micro-pressure waves occurring was assessed using an empiric Japanese acceptance criterion. The acceptance criterion is applied in a distance 20 m and at an angle of 45 degrees from the exit portal (outside the tunnel). If the pressure there is above 20 Pa there will be a high risk of micro pressure occurring.

### 2.5 Air velocity

The air velocity can be evaluated in two parts. The first part is the influence of high air velocity on the platform or through doorways which can be experienced as uncomfortable for the passengers. Experiments have shown that the wind speed should be kept below a maximum of 5 m/s and below a velocity of 3 m/s on average. The second part is the wind speed acting on the installed equipment and on the tunnel structure which characterised by very high velocities occurring in the annulus between the train and tunnel. The latter is not discussed in this paper but German Rail has written a guideline which considers these wind loads [2] for further information.

### 2.6 Traction power requirements

The traction power requirements for the rolling stock are determined by the:

- aerodynamic drag (nose and tail loss and skin friction drag)
- rolling resistance
- potential energy (elevation in the system)
- kinetic energy (acceleration or deceleration)

The sum of these forces needs to be compared with the available traction power of the vehicle in order to determine if the desired speed can be achieved.

## 3 CIVIL MEASURES TO IMPPROVE AERODYNAMIC CONDITIONS

The outcome of the calculations for the first concept design (see Table 6) showed that due to the relative high blockage-ratio and the high speed of the train, certain problems occurred such as:

- too high pressure fluctuations affecting the passengers comfort
- too high air velocities in the platform areas affecting the passengers comfort
- high risk of non-acceptable micro-pressure waves at the external portals and interior portals within the underground stations affecting the passengers and portal neighbours comfort

The above examples of unfavourable impacts of the aerodynamics can be reduced by small or large alterations of the civil design of the tunnels. An indication of the measures and their effect is given in the following section.

### 3.1 Shafts or openings

Shafts in a tunnel system might have different functions as shown in Table 4.

| Function | Cross section [$m^2$] | Location |
|---|---|---|
| Pressure comfort improvements | 10 | >> 100 m from the portal |
| Draught relief to lower air velocities | >> 50 | close to the station |
| Micro-pressure wave reduction | 10 | close to the portal |
| Climate improvements | 30 | against re-circulation: near station or portal; for enhanced air ex-change: in the middle of the tunnels |
| Smoke removal/ventilation | 20 | at the station and in the tunnel |
| Escape route | e.g. 8 | at tunnels and stations |

Table 4: Principal functions of shafts in a tunnel system

### 3.2 Portal design

By altering the design of the tunnel entrance it is possible to lower (or worsen) the initial pressure wave. One way is to attenuate the wave by shaping the portal as a trumpet. Another approach is an open gap along the tunnel structure and perforated walls at the beginning of the entrance to the tunnel tube. This would lower the effect of the pressure wave generated as the train enters the tunnel, and have an effect on the pressure loads, pressure comfort and on micro-pressure waves.

### 3.3 Enlarged tunnel cross section

The enlargement of the tunnel cross section will mitigate several aerodynamic effects. However, this is one of the most cost sensitive measures. The various possible measures are summarized in Table 5 and illustrated in Figure 5 together with an assessment of the impact of the different aerodynamic issues.

| | **Improvement with respect to: (+ + = very efficient + = efficient 0 = practically without effect - = unfavourable)** / **Measure** | **Pressure comfort short time intervals** | **Pressure comfort long time intervals** | **Aerodynamic resistance** | **Micro pressure waves** | **Air flow in stations** | **Air flow in station entrances** | **Air-exchange in the tunnel** |
|---|---|---|---|---|---|---|---|---|
| 1 | Shafts at the portals of a total of approximate 30 m$^2$ distributed along first 100 tunnel meters | 0 | 0 | 0 | ++ | 0 | 0 | 0 |
| 2 | Trumpet-shaped portal expansion of approximate 100 m$^2$ to 40 m$^2$ along 100 to 200 m starting from portal | + | 0 | 0 | ++ | 0 | 0 | 0 |
| 3 | Measures 1 and 2 in the first 500 tunnel meters | + | ++ | 0 | ++ | 0 | 0 | 0 |
| 4 | Enlargement of the free tunnel cross section along the entire tunnel length e.g. from 42 m$^2$ to 52 m$^2$ | ++ | ++ | ++ | ++ | ++ | ++ | - |
| 5 | 100 m long and 0.3 m broad gap along the first 100 tunnel meters outward | + | 0 | 0 | ++ | 0 | 0 | 0 |
| 6 | Gallery or perforated partition walls along the first 100 tunnel meters; gradual decrease of the opening area between tubes | + | 0 | 0 | ++ | 0 | 0 | - |
| 7 | Opening and/or additional installation of open cross sections of >> 10 m$^2$ e.g. every 300 m | + | ++ | ++ | ++ | ++ | ++ | - |
| 8 | 1 shaft/tube (air relief shaft) of 50 m$^2$ in the centre of the tunnel | ++ | ++ | ++ | + | ++ | ++ | - |
| 9 | Shafts/tubes (air relief shaft), i.e.:<br>shaft in the stations of approximate 50 m$^2$ (A):<br>before stations in the tunnel (B): | <br>0<br>+ | <br>0<br>+ | <br>+<br>+ | <br>0<br>++ | <br>0<br>++ | <br>++<br>++ | <br>0<br>0 |
| 10 | Air-lock entrances; revolving doors at the station platform | 0 | 0 | - | 0 | 0 | ++ | - |
| 11 | Reduction of the free cross section in front of the entrance into the station – maybe in combination with shafts in the tunnel or with open cross passages | - | 0 | - | 0 | + | + | 0 |
| 12 | Open platform and large distance between the end of the single-railed tunnels and the platform. The open distance between the platform and the tube would be equipped with air turning vanes directing the air from one tube to the other tube | 0 | 0 | 0 | 0 | ++ | + | 0 |
| 13 | Aerodynamic decoupling of platform and tunnel by platform screen doors | 0 | 0 | - | 0 | ++ | + | 0 |
| 14 | 1 double-track tunnel instead of 2 single-track tubes | ++ / - | ++ / - | ++ | ++ | ++ | ++ | - |

Table 5: Possible measures to improve the aerodynamics

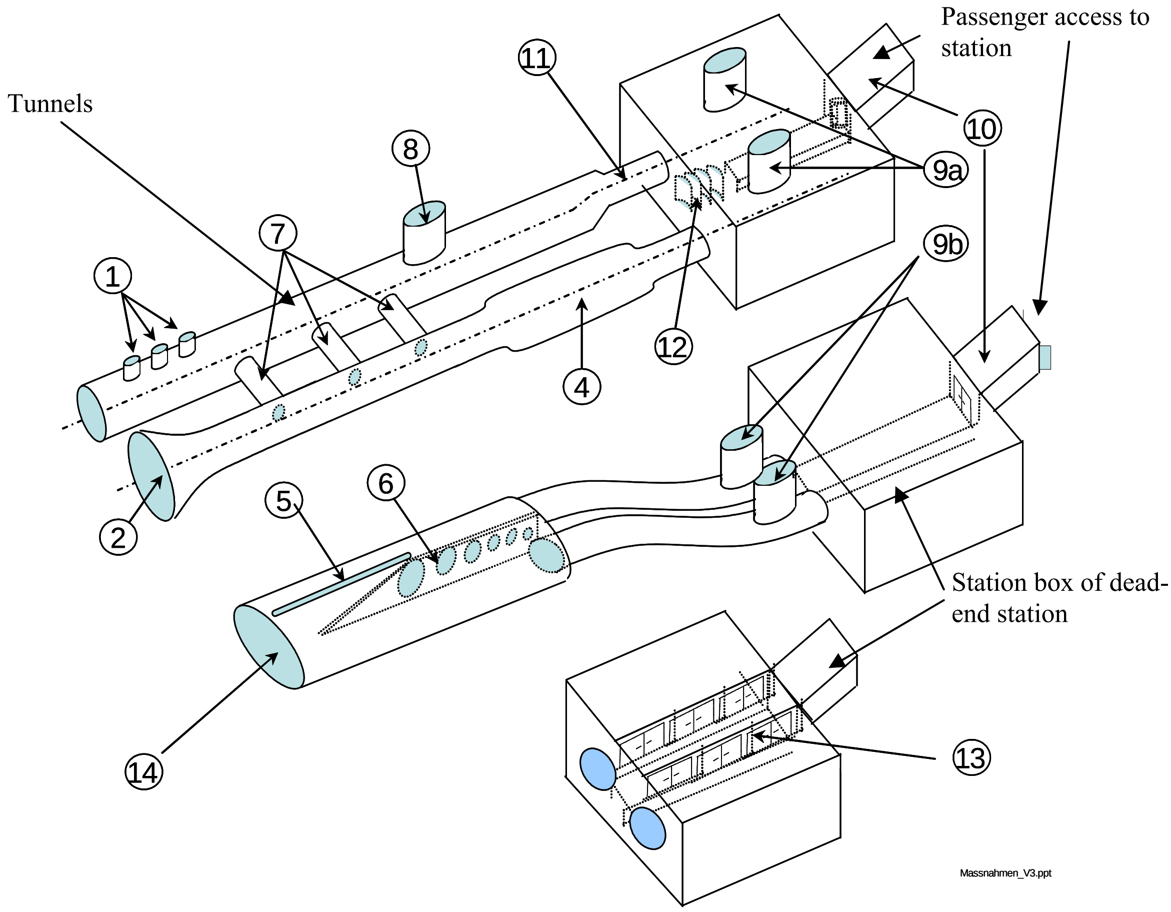



Figure 5: Illustration of the civil measures described in Table 5

All these different measures can be more or less cost efficient to implement or they may cause some additional risks. E.g. the implementation with additional open cross passages (No. 7) can prove to be a problem in the event of fire as smoke can migrate from one tunnel tube to the other. Other examples could be that implementing a single-bore, double-track tunnel could improve the aerodynamic situation for a single moving train but could worsen the aerodynamics with another passing train in the other direction.

In order to fulfil the aerodynamic criteria the following measures were applied (see Figure 5):

- No. 1: shafts at the portal of approximate 40 $m^2$ distributed over the first 100 tunnel meter
- No. 4: enlargement of the complete bored tunnel sections from e.g. 42 $m^2$ to e.g. 52 $m^2$
- No. 9a: shafts (draught relief shafts), i.e. shafts in stations of 50 $m^2$
- No. 10: air-lock entrances from the outside to the platform
- No. 13: (glass -) platform screen doors between platform and the tunnel

## 4 AERODYNAMIC RESULTS

The results of the aerodynamic calculations for the concept design with and without measures are presented in the Table 6 below. The calculations are based mainly on results form the 1D simulation program Thermotun [3].

| ✓ = acceptable<br>✗ = unacceptable<br>**Results** | **Criteria** | **Without measures** | | | | | **With measures** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Tunnel** | | | **Station** | | **Tunnel** | | | **Station** | |
| | | Landshuter Allee | Feldmoching | Flughafen | Main train St. | Airport St. | Landshuter Allee | Feldmoching | Flughafen | Main train St. | Airport St. |
| Health criteria | Δp ≤ 20 kPa | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Pressure criteria short term | Δp (Δt=1s) ≤ 0.5 kPa | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Pressure criteria middle term | Δp (Δt=3s) ≤ 0.8 kPa | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Pressure criteria long term | Δp (Δt=10s) ≤ 1.0 kPa | ✓ | ✗ | ✗ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Max. amplitude of micro-pressure waves | Δp < 20 Pa | ✗ | ✗ | ✓ | ✗ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |

Table 6: Results of the aerodynamic calculations for the design without and with measures

It has successfully been shown that the all the criteria could be fulfilled. The effects of some of the measure are illustrated in detail in the three sections below.

### 4.1 Effect on the pressure comfort with and without measures

Figure 6 shows the effect on the pressure comfort with a cross-section enlargement (Figure 5 No. 4) for the Tunnel Feldmoching.

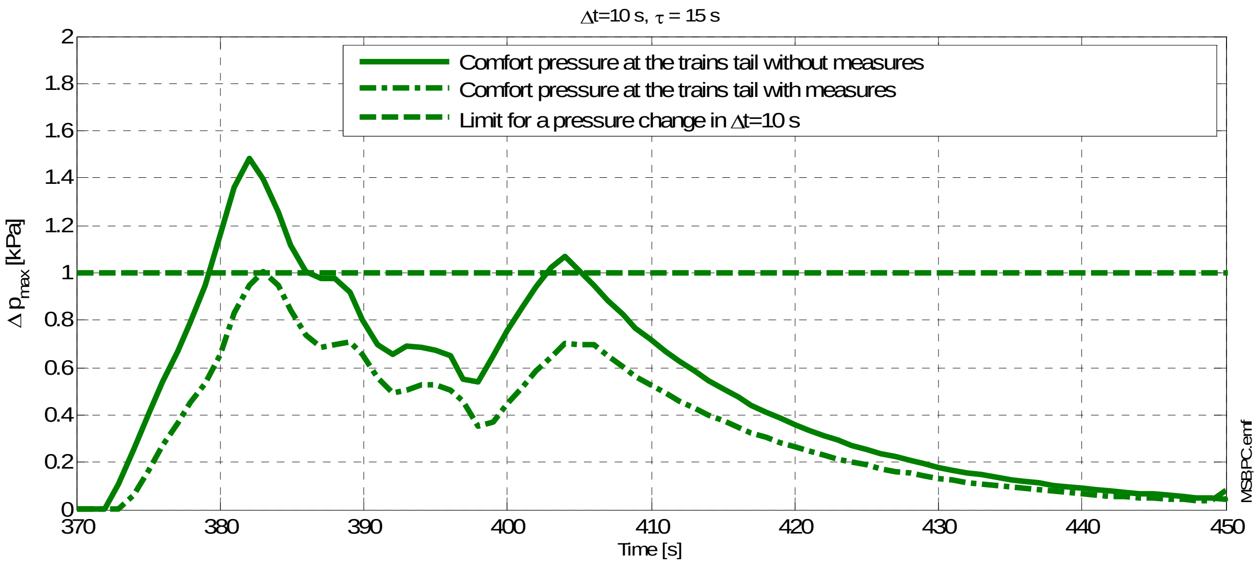



Figure 6: Example of pressure comfort in Tunnel Feldmoching without and with measures (cross section enlargement)

By increasing the free cross-sectional area of the tunnel, the overall aerodynamic load will be lowered. In addition, this means that pressure fluctuations within certain time intervals will be smaller, hence improving the comfort for the passengers. In addition, the aerodynamic impact on the installed equipment, tunnel structure as well as on the rolling stock will be reduced. Furthermore, the lower aerodynamic draught will also reduce the traction power required for the vehicle.

### 4.2 Effect of the micro-pressure waves with and without measures

The results of applying the pressure relief shafts / openings at the portals at tunnel Feldmoching on the amplitude of the micro-pressure waves are shown in the Table 7 below.

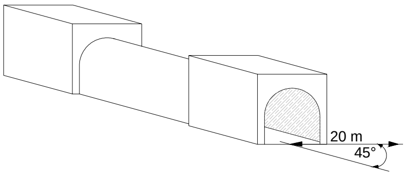
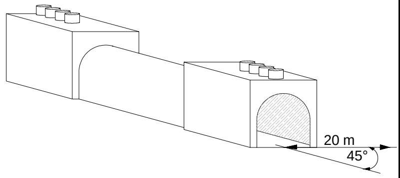
| **Pressure at a distance 20 m and at an angle of 45 degrees from the exit portal** | |
|---|---|
| Without measures   | With measures (2 x 4 x 10 $m^2$ openings)   |
| South portal 35 Pa | South portal 7.4 Pa |
| North portal 35 Pa | North portal 8.7 Pa |

Table 7: Micro-pressure waves at portals of tunnel Feldmoching with and without measures (shaft/openings at portal hood; criterion checked outside 20 m away from portal at 45° - angel)

It is evident that the use of the four pressure relief openings at the portals reduces the amplitude of the micro-pressure waves significantly.

### 4.3 Effect on the pressure at the station box with and without measures

Figure 7 illustrates the effect of installing pressure relief shafts along the first 100 tunnel meters and by placing a draught relief shaft just in front of the station box (No. 9a, 4 and 1) on the tunnel Landshuter Allee and the Main Train Station.

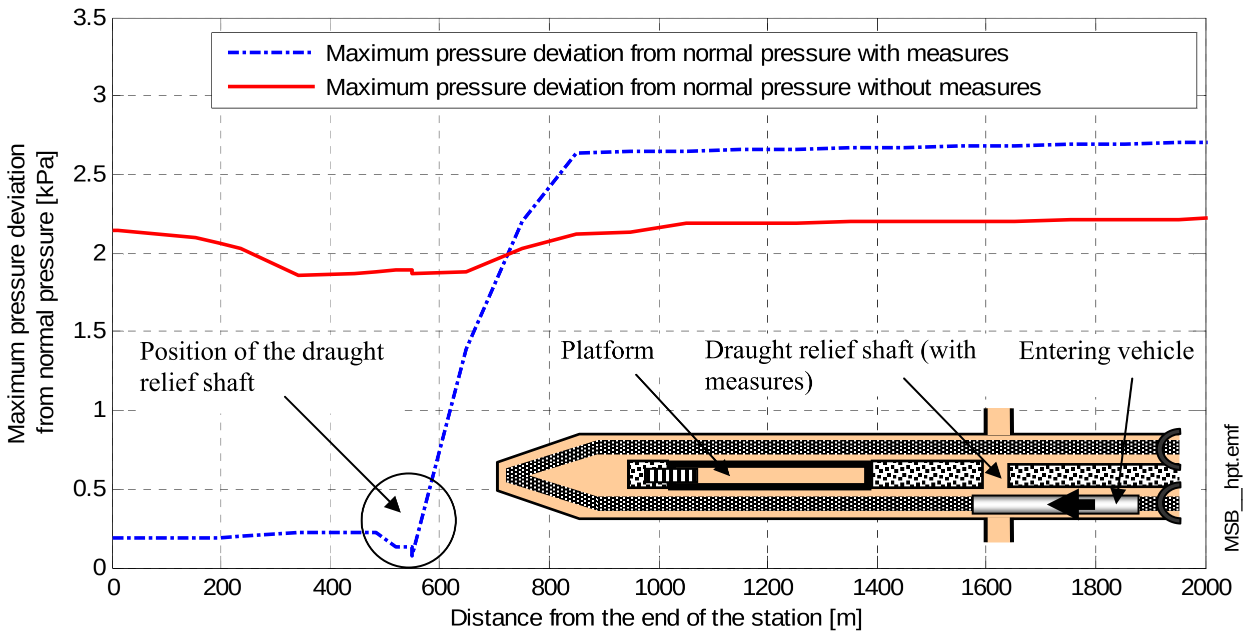



Figure 7: Result of Landshuter Allee and the Train Station with and without measures

Due to the draught relief shafts just in front of the station, the platform will be aerodynamically decoupled from the tunnel section. This will result in a reflection of the initial pressure wave generated by the train as it enters the tunnel at the shaft and thus having almost no impact on the platform region. The lower pressure in the station box will reduce the effect of high air velocities on the platform and other accesses. The shafts at the beginning of the tunnel entry reduce the risk of micro-pressure waves occurring.

## 5 CONCLUSIONS

When planning high-speed tunnels, it is very important to include investigations of the aerodynamics. If problems (with pressure, air velocity, comfort, noise from micro-pressure waves (sonic boom), extreme traction requirements and highly fluctuating pressure waves affecting the vehicle, the installed equipment and tunnel structure) are uncovered after the opening of the project, the cost for the mitigation of some of these problems could run very high.

It should be pointed out, that all the aerodynamic aspects mentioned in this paper are not MAGLEV specific, i.e. the same issues apply for all high-speed rail traffic. However, certain aspects are enforced by MAGLEV project such as:

- Higher inclinations possible, strong acceleration and deceleration possible leading to stronger pressure fluctuations
- Slab-track which can enhance the possibility of micro pressure waves
- Smaller free cross-sections possible because of the absence of a catenary system leading to increased traction power requirements, stress on the installed equipment and tunnel structure due to higher pressure fluctuations

It has shown that non-acceptable aerodynamic conditions can be eliminated by reasonable measures. Theses proposed measures insure comfort and safety for the passengers and staff and do also reduce the running cost by lowering the aerodynamic traction requirements.

## 6 ACKNOWLEDGEMENTS

Grateful thanks are due to Bayerische Magnetbahnvorbereitungsgesellschaft (BMG), Munich, for giving permission to refer to their MAGLEV project. It is emphasized that all data published refers to an intermediate design stage of the project and might not be relevant and/or correct anymore.

## 7 REFERENCES

[1] UIC, "Arrangements to ensure the technical compatibility of high speed trains", UIC leaflet 660, 2nd edition, 2002

[2] Deutsche Bahn, "Eisenbahntunnel planen, bauen und instand halten", Regelwerk D853, August 2003

[3] Thermotun, Version 5.2, 2004, Prof. Alan Vardy, UK