Various aspects of aerodynamics and their implications on the design of the tunnels and underground stations of the magnetic levitation high-speed link in Munich (MAGLEV)

No. 59
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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. Running at a maximum velocity of 350 km/h the total journey time is reduced to about 10 min.

The vehicle of the MAGLEV project (TRANSRAPID TR09) is a magnetic levitating train which is propelled by linear motors. Conventional tracks have been replaced with a magnetic guideway which supplies the lift and thrust 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 2).

Figure 2: Artist impression of the maglev link at the airport 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 2 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 includes 3 tunnels and 2 underground dead-end stations. The tunnels are designed as double-tube, single-track tunnels (see Figure 1).

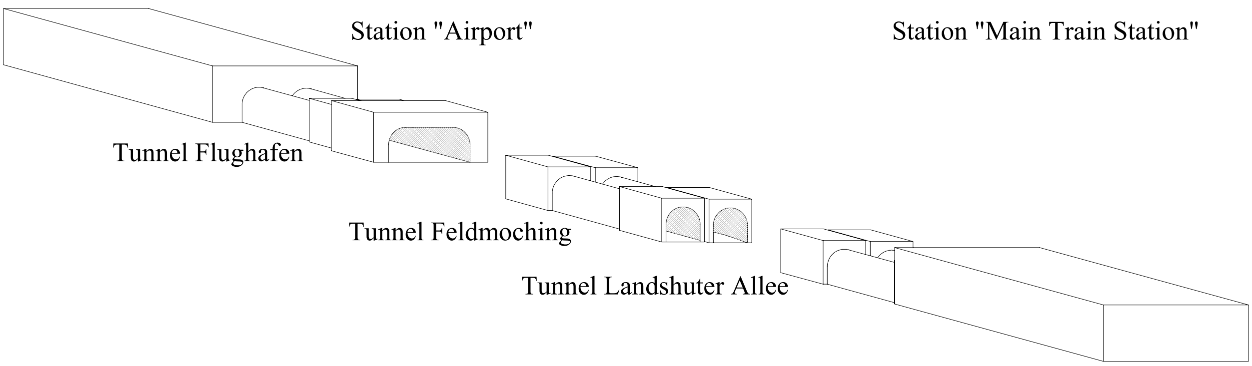


Figure 1: Sketch of the MAGLEV link in Munich

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 & cover	Bored	Cut & 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 (data represents certain planning stage – not valid anymore in all details)

For aerodynamic reasons, the velocity of the MAGLEV will be limited to 250 km/h while running in the tunnels in difference to the maximum velocity above ground of 350 km/h.

2 AERODYNAMIC ISSUES AND DESIGN OBJECTIVES

Taking the high velocity of the vehicle and the comparatively small free cross-sectional area of the tunnels into consideration there was a high risk of adverse aerodynamic effects for the passengers, vehicle and the tunnel structures 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

Further issues related to the tunnel aerodynamics were:

- air-exchange of tunnel system with environment and its effect on climate in tunnels and stations
- influence of vehicle-induced air-flows during fire incidents on smoke propagation

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 aerodynamic issues are listed in Table 2 and further explained in the chapters below.

Design objectives		Vehicle	Station	Tunnel / Portal
Health risk of passengers/staff due to pressure fluctuations	$\Delta p \leq 10$ kPa	✗	✗	✗
Pressure comfort in the vehicle and in the tunnel areas including the underground stations	Δp (Δt=1s) ≤ 0.5 kPa Δp (Δt=3s) ≤ 0.8 kPa Δp (Δt=10s) ≤ 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 $v_{mean} < 3$ 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]	✗	✗	✗
Air exchange and resulting climate	enhance air-exchange	-	✗	✗
Vehicle-induced air-flows during fire incidents	support ventilation	-	✗	✗

Table 2: Investigated aerodynamic issues

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 analysis 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 the latter criteria. The criteria for the project are presented in Table 2.

2.2 *Rolling stock pressure tightness*

The pressure comfort in the vehicle is closely linked to its sealing quality because a good sealing can attenuate the pressure changes during the tunnel journey. In general, pressure variations in a tunnel are caused by vehicles 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 vehicle. The different openings of the vehicle will cause an equalisation between the pressure outside and inside (leakage through air-conditioning, window and door sealing, 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.

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 upon a stepwise pressure change has decreased from 100 % to approx. 38 % of the initial pressure difference according to Figure 3.

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 stiffness of the vehicle, etc.

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	**Pressure tightness coefficients τ**
Unsealed train (e.g. Regional train)	$\tau < 1$ s
Minimum sealed train (e.g. Eurocity)	$1\ s < \tau < 6\ s$
Well sealed trains (e.g. ICE1, TGV)	$6\ s < \tau < 10\ s$
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 types (coarse data)

For the present study values of τ = 10 s to 20 s for the MAGLEV 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, free cross-sectional area, 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 upon reaching the exit portal (sonic boom; see Figure 4).

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 empirical Japanese acceptance criterion. The acceptance criterion is applied in a distance of 20 m and at an angle of 45 degrees from the exit portal (outside the tunnel). If the pressure fluctuation at this point is above 20 Pa there will be a high risk of non-acceptable micro-pressure waves occurring (possibly noisy).

2.5 *Air velocity*

The air velocity is relevant in respect of 2 aspects:

1. 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.

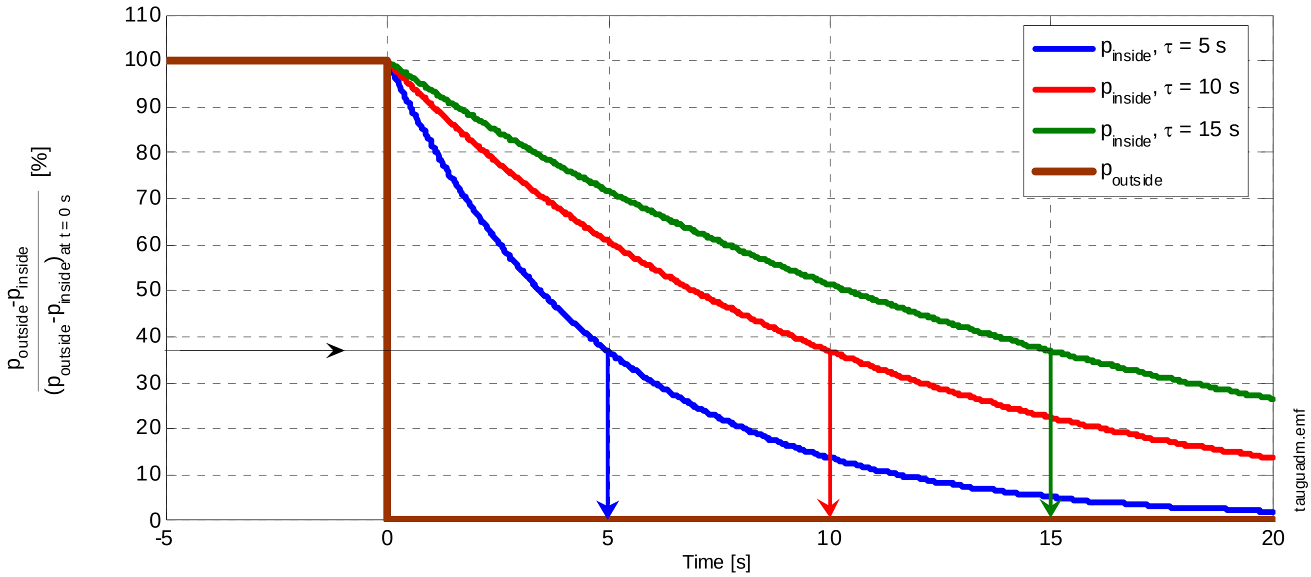


Figure 3: Pressure development in train for a sudden pressure difference to the exterior at t = 0 s

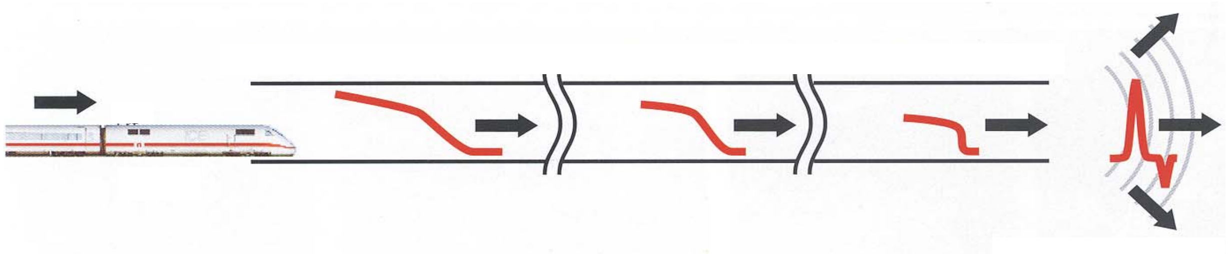


Figure 4: Development of micro-pressure waves (sonic boom; illustration of BMG/DB)

2. The wind speed acting on the installed equipment and on the tunnel structure which is 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 (DB) has written a guideline which considers these wind loads (see [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.

2.7 Climate in tunnels and stations and fire ventilation

The tunnel aerodynamics influence the climate in a tunnel system. Vehicle-induced pressure fluctuations create an air-exchange with the free environment, mainly, through portals and shafts. In the ideal case, this sufficiently removes heat, humidity and pollutants from the tunnels and underground stations. If the air-exchange needs to be enhanced further, civil measures (shafts, openings), mechanical ventilation or air-conditioning equipment is needed to create an acceptable climate.

Another aspect of tunnel aerodynamics is the air-flow during fire incidents. Moving vehicles might affect the smoke dispersion during a fire incident significantly and, thus, need to be considered for the planning of measures to alleviate fire incidents.

The aerodynamics and their impact on climate and fire in a tunnel are not further discussed herein but were mentioned for the purpose of completeness only.

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 non-acceptable conditions 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	**Free cross-sectional area [m²]**	**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 exchange: in middle of 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.

All these different measures can be more or less cost efficient to implement or they may cause some additional risks. E.g. the implementation of 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 at a first design stage (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].

It has successfully been shown that the criteria could be fulfilled by the design modifications. The effects of some of the measures are illustrated in detail in the three sections below.

	Measure	Improvement with respect to: Pressure comfort short time intervals	Pressure comfort long time intervals	Aerodynamic resistance off vehicle	Reduce micro pressure waves	Limit air flow in stations	Limit air flow in station entrances and vehicle doors	Air-exchange in the tunnel
	+ + = very efficient; + = efficient 0 = practically without effect - = unfavourable							
1	Shafts at 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.: shaft in the stations of approximate 50 m^2 (A): before stations in the tunnel (B):	0 +	0 +	+ +	0 ++	0 ++	++ ++	0 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 plat-form. 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 influence the aerodynamics and their efficiency

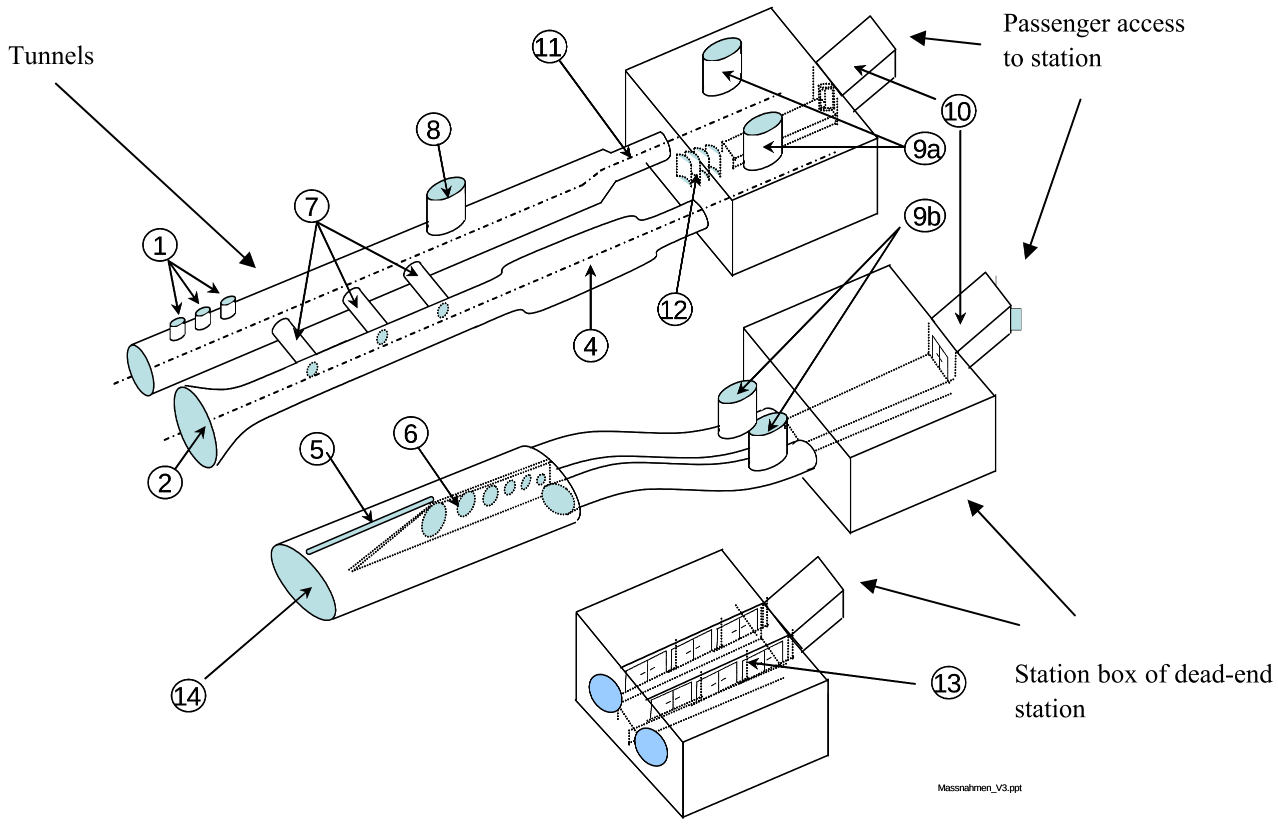


Figure 5: Illustration of the civil measures described in Table 5

		Without measures					With measures				
		Tunnel			Station		Tunnel			Station	
Results ✗ = unacceptable	**Criteria** ✓ = acceptable	Lands-huter Allee	Feldmo-ching	Flug-hafen	Main train St.	Air-port	Lands-huter Allee	Feldmo-ching	Flug-hafen	Main train St.	Air-port
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. amplitde of micro-pressure waves	Δp < 20 Pa	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓

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

4.1 Effect on the pressure comfort with and without measures

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

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.

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

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.

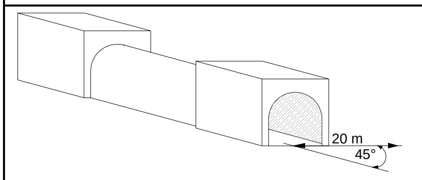
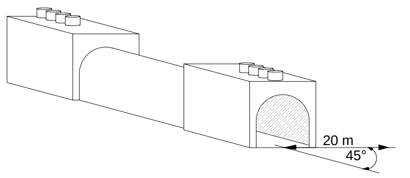
Pressure at a distance 20 m and at an angle of 45 degrees from the exit portal	
Without measures	
	South portal 35 Pa North portal 35 Pa
With measures (2 x 4 x 10 m^2 openings)	
	South portal 7.4 Pa North portal 8.7 Pa

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)

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 vehicle 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

The planning of high-speed tunnels and attached underground stations such as the MAGLEV system in Munich has to include investigations of the tunnel aerodynamics. Non-acceptable pressures, air velocities, climatic conditions, extreme traction requirements and noise might affect the safety, the comfort of people or the functionality, durability and economics of the transport system.

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

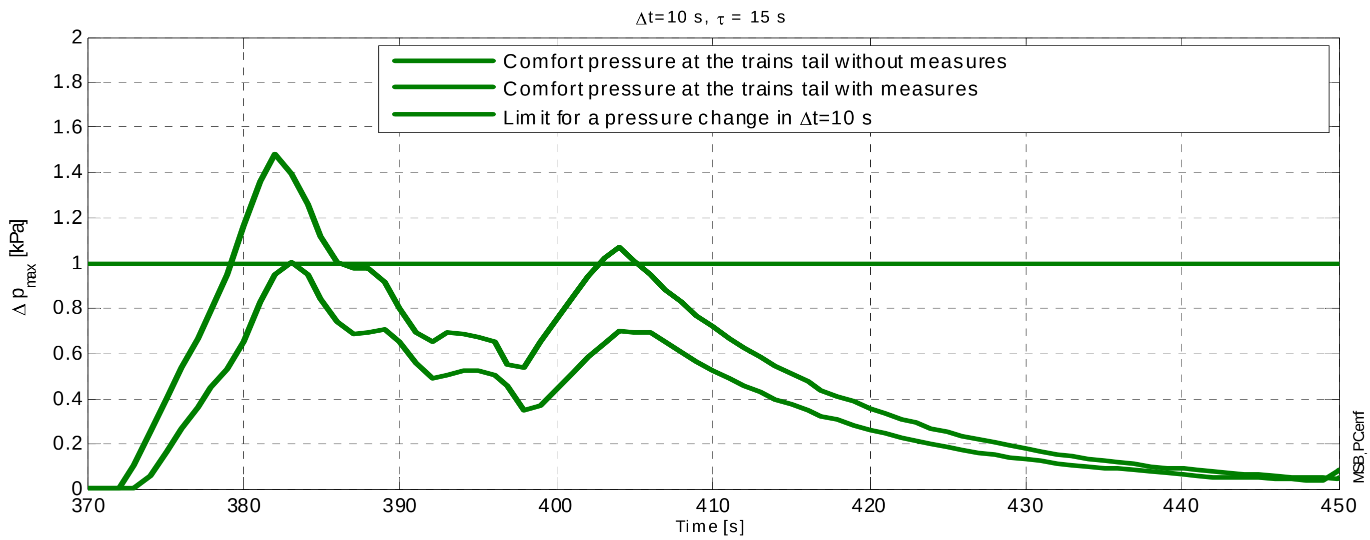


Figure 6: Example of pressure comfort in Tunnel Feldmoching without and with measures (cross section enlargement)

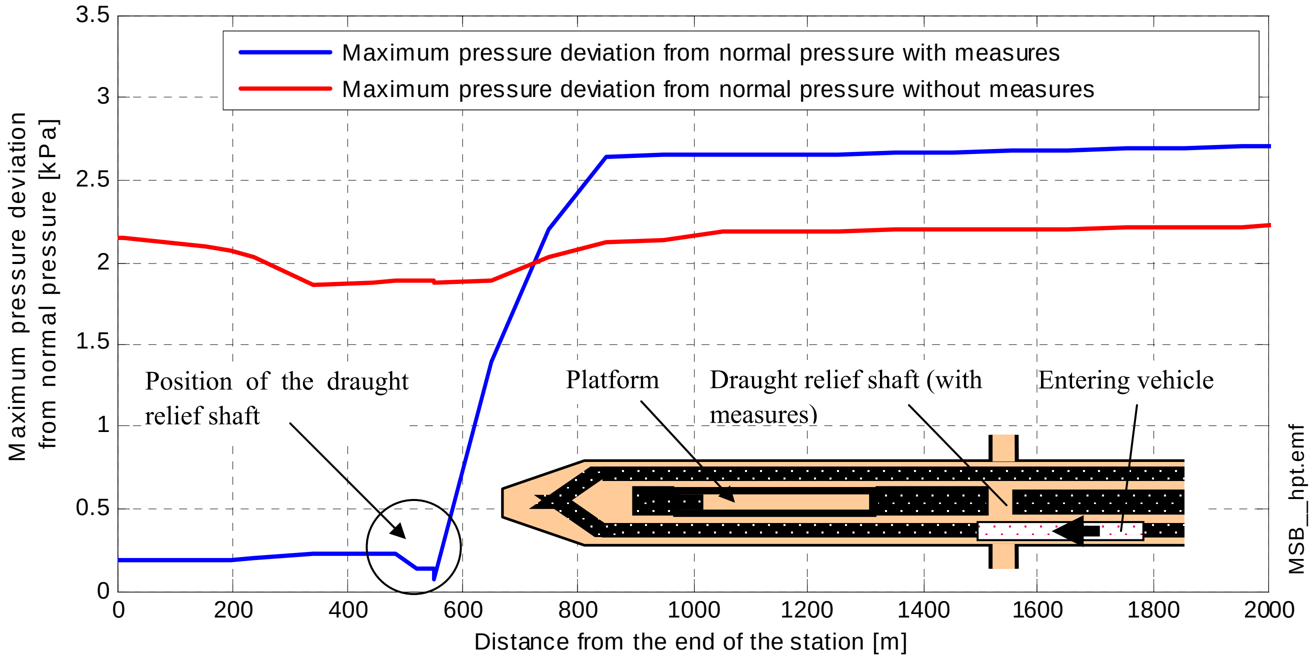


Figure 7: Result of Landshuter Allee and the attached station with and without measures

6 ACKNOWLEDGEMENTS

Grateful thanks are due to DB Magnetbahn GmbH, Munich, for giving permission to refer to their MAGLEV project. It is emphasized that all data published was used at 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