Aerodynamic Aspects of Maglev Systems

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ABSTRACT: Aerodynamics is one of the key system issues when designing a maglev system or a high-speed railway system. There are several aerodynamic aspects that rule both into rolling stock and infrastructure design. On the basis of experience from the German high-speed railway system, this paper presents the most prominent aerodynamic topics which will affect the system design of the maglev system planned in Germany.

1 INTRODUCTION

From the system point of view, the aerodynamics of a maglev and a high-speed railway system do not differ in principle. In both cases there are trains running on ground, either in open air or in tunnels. In both cases the interaction of trains and infrastructure implies aerodynamic system issues, e.g. that of train-induced aerodynamic loads.

Thus, differences in aerodynamic issues of maglev and high-speed railway systems are to some extend rather linked to differences in the practical setting and design of these systems than to the principle difference of maglev and vehicle/rail technology.

When comparing the aerodynamics of the existing German high-speed railway system to those of the German maglev project, which shall link Munich airport with Munich city centre (e.g. Wellner 2005, Fried 2005), there are various differences.

This paper aims to give a brief overview of aerodynamic questions of the German high-speed railway system and to relate them to the German maglev project. The paper indicates for what aerodynamic topics the long-term operation of German high-speed railway system provides significant experience and where the German maglev project will enter new aerodynamic terrain. Thus, this paper might support ongoing aerodynamic studies linked to the German maglev project.

2 HIGH-SPEED RAIL IN GERMANY

In Germany, high-speed railway operation started in 1991, when the high-speed lines Hanover-Wuerzburg and Mannheim-Stuttgart were opened and ICE service was started. The first German high-speed train, the ICE 1, was designed for 280 km/h as well as the two lines. Both lines show a substantial share of tunnels and high bridges and both lines had been dedicated to mixed traffic. As beside ICE trains and IC trains there are also cargo trains running on these lines, the slope of these lines is limited to 12 ‰. The maximum operational speed in tunnels is currently restricted to 250 km/h due to potential tunnel passings of high-speed and cargo trains.

In 1998, DB set the high-speed line Hanover-Berlin into service. This line is designed for 250 km/h and also implies mixed traffic. Different to the first two high-speed lines, this line is free of any tunnels.

In 2002, the high-speed line Cologne-Frankfurt was opened. This line shows very steep gradients (up to 40 ‰) and is dedicated to high-speed railway operation only. So far, the only high-speed train running on that line is ICE 3 (electrical multiple units (EMU) with distributed traction). Here, operational speed is the maximum line speed of 300 km/h. The Cologne-Frankfurt line is also specific with respect to the track: this is the first German line with slab track. Similar to the lines Hanover-Wuerzburg and Mannheim-Stuttgart the line crosses the German midland mountains in north to south direction. Due to the high line gradients it shows a smaller share in tunnels.

In 2002 and 2004, two more high-speed lines with ballasted track were opened. The Cologne-Düren and the Rastatt-Offenburg line are both existing lines without any tunnels which were upgraded for 250 km/h. There is mixed traffic on both lines.

In May 2006, the new high-speed line Nuremberg-Ingolstadt was opened. As the Cologne-Frankfurt line this line was built with slab track and with a maximum line speed of 300 km/h. Different to Cologne-Frankfurt, the line is designed for mixed traffic; beside high-speed trains there will be regional and potentially also cargo trains on the line. The Nuremberg-Ingolstadt line implies only some tunnels, but two of considerable length (> 7 km).

A summary of all the German high speed-lines in service is given in Table 1.

What is common to all so-far existing German high-speed lines is the principle tunnel design. So far, all high-speed line tunnels were built as a single tube with double track. The cross section is 92 m^2 for 300 km/h (lines Cologne-Frankfurt, Nuremberg-Ingolstadt) and 82 m^2 for speeds up to 280 km/h (lines Hanover-Wuerzburg, Mannheim-Stuttgart).

Table 1: Existing High-speed Lines in Germany.

High-speed line	Length in km	Start of operation	Maximum line speed in km/h
Hanover-Wuerzburg	327	1991	280
Mannheim-Stuttgart	99	1991	280
Hanover-Berlin	257	1998	250
Cologne-Frankfurt*	177	2002	300
Cologne-Düren	40	2002	250
Rastatt-Offenburg	45	2004	250
Nuremberg-Ingolstadt*	89	2006	300

* with slab track.

3 AERODYNAMIC ISSUES OF THE GERMAN HIGH-SPEED RAILWAY SYSTEM

3.1 General

From the system point of view, aerodynamical topics which affect and define the interface between rolling stock, infrastructure and operation are of paramount importance. This paper will concentrate on these aerodynamic issues.

In general, railway aerodynamics consists of two fields: aerodynamics of open air and tunnel aerodynamics. Especially in case of mixed traffic, tunnel aerodynamics plays a most prominent role in high speed railway aerodynamics.

3.2 Aerodynamics in open air

One of the most classical aerodynamic issues of high-speed rail is that of train-induced aerodynamic loading. When a train passes another train or an object as a noise barrier a pressure pulse is generated on the side of the other train or on the noise barrier primarily by the train nose and secondarily be the train tail (e.g. CEN 2003a, CEN 2005). For trains, which consist of several coupled train units, also the coupling position will generate a significant pressure pulse on the passed wall. The train-induced dynamic pressure loads strongly depend on the train speed, on the nose shape of that train and on the distance between train and wall.

In case of train-induced pressure changes on infrastructure components (e.g. noise barriers) there shall not be a profound problem in dimensioning according to the known maximum line speed. However, for non-concrete barriers there might easily result a fatigue problem if the dynamic character of the pressure load is not taken into account properly.

At least in the case of mixed traffic, the probably more complex issue is the one of train-induced aerodynamic loading on other trains. Cargo, regional or intercity rolling stock which is supposed to enter new high-speed lines, had not necessarily been designed to withstand pressure variation induced by fast running high-speed trains. Thus, even for high-speed line sections, which are free of any tunnel, high-speed train-induced aerodynamic loads on other rolling stock might have to be considered.

The issue of train-induced slipstream effects on track-side workers is a significant one. Safety of track-side workers requires the declaration of appropriate hazard zones and safe areas, and thus, affects e.g. the minimum spacing of noise barriers to the center of track.

The issue of train-induced aerodynamic loads (slipstream effects) on passengers at the platform is not governed by high-speed rail operation since common maximum passing speed is limited by German regulations to 200 km/h (exception: on the Hamburg-Berlin line platform passings with 230 km/h are permitted due to special measures).

Trains also induce aerodynamic loads on the track. At higher speed train-induced (pressure) loads on track absorbers, on installed signaling devices etc. had to be studied. In the last years the subject of ballast projection gained significant importance. In various European countries, test runs on (new) high-speed lines with ballasted track (max. line speed 300 km/h and above) led to some specific ballast projection incidents. Although several railway operators and train manufactures started intense research activities and although various train-side or track-side countermeasures are under testing, the phenomenon is not yet completely understood.

From the system point of view, another very prominent aerodynamic issue is cross wind safety. With the introduction of light-weight vehicles while train speed was still increasing, studying the cross wind stability of high-speed trains and the cross wind exposure of high-speed lines became a standard task of railway aerodynamics. These studies – which directly feed the analysis and assessment of cross wind safety – are quite complex and demanding. In Germany, a new comprehensive regulation to tackle the cross wind issue was set into force recently (DB Netz AG 2006).

Among the aerodynamic system issues, aerodynamic resistance might be the most prominent one. Resistance to motion, and hence aerodynamic resistance, directly interacts with the necessary installation of power, with time schedules and with energy consumption. Thus, aerodynamic resistance and its experimental testing play a big role in the specification, the design and the acceptance of high speed trains.

3.3 "Classical" tunnel aerodynamics

One peculiarity of tunnel aerodynamics is that most of its aspects are linked to each other. Thus, tunnel aerodynamics is a perfect representative of the linked characteristics of the railway "system". When running through a tunnel the flow and pressure field around the train is strongly affected by the tunnel design (CEN 2003b, CEN 2006). Aerodynamic resistance and passing effects might be much stronger in a tunnel than in open air. In addition, tunnel aerodynamics involves also pressure waves, which propagate through the tunnel with the speed of sound, and which in superposition with the pressure variations due to train passing(s) form a complex pressure wave pattern within in the tunnel. Pressure variations in the tunnel result in aerodynamic loading on the train(s) and on tunnel installations. The pressure variations which penetrate into the train may cause aural discomfort of passengers.

In a simplified approach, the amplitudes of the various pressure variations basically depend on the blockage ratio (ratio of train cross-section to tunnel cross-section), on the train speed and on the geometry of the train nose. The way the pressure changes form the resulting pattern of pressure variation in the tunnel primarily depends strongly on tunnel length, train length, the existence and the geometry of portals, shafts and niches and the relative entry time between two trains.

Within DB, the cross-section of tunnels is standardized in a guideline (DB Netz AG 2002). Following the current version, new double-track tunnels for train speeds above 230 km/h shall be built with a cross section of 92 m^2. The actual cross section of existing double-track high-speed tunnels is that of 82 m^2 for lines with maximum line speed of 280 km/h and 92 m^2 for those with maximum line speed of 300 km/h. In combination with an aerodynamically relevant train cross-section of about 10.4 m^2 for ICE 3 or 11 m^2 for ICE 1 / 2, currently realized blockage profiles are in the range of about 0.11 to 0.13.

To improve fire safety, future tunnels on German high-speed lines have to be built twin-bored and single track when they exceed a length of 500 m and when they are dedicated not only to passenger but also to cargo train operation. In the present version of the guideline (DB Netz AG 2002), for speeds from 230 km/h to 300 km/h the standard cross-sectional area for single-track tunnels is about 60 m^2.

Table 2 and 3 provide an overview of blockage rations of existing and future German high-speed line tunnels.

Table 2: Blockage ratios in existing German high-speed line tunnels with double-track on the basis of DB Netz AG (2002).

Line speed in km/h	Tunnel size in m^2	Train type	Aerodyn. train size in m^2	Resulting blockage ratio
250 (280)	82	ICE 1	11.0	0.13
250 (280)	82	ICE 3	10.4	0.13
250 (280)	82	TSI-train*	12.0	0.15
300	92	ICE 1	11.0	0.12
300	92	ICE 3	10.4	0.11
300	92	TSI-train*	12.0	0.13

* Train with max. cross-section still conform to Technical Specifications for Interoperability of Rolling Stock (EC 2002a).

Table 3: Blockage ratios in future German high-speed line tunnels with single-track on the basis of DB Netz AG (2002).

Line speed in km/h	Tunnel size in m^2	Train type	Aerodyn. train size in m^2	Resulting blockage ratio
230 to 300	60	ICE 1	11.0	0.18
230 to 300	60	ICE 3	10.4	0.17
230 to 300	60	TSI-train*	12.0	0.20

* Train with max. cross-section still conform to Technical Specifications for Interoperability of Rolling Stock (EC 2002a).

The cross section of actual German double-track tunnels (cf. to Table 2) had been originally chosen in order to meet with ICE trains the so-called "10 kPa health criterion". This criterion was proposed by ERRI (1998), accepted by UIC (e.g. UIC 2005) and finally adopted by EC (2002b) for the European Technical Specifications for Interoperability (TSI) in order to ensure passenger health with respect to pressure variations within the train in an extreme (emergency) case.

According to this criterion, the peak-to-peak pressure variations within the train must not exceed 10 kPa during the whole tunnel passage even in the case of a so-called "critical passing" of two trains and, simultaneously, a complete failure of the pressure sealing system. The expression "critical passing" describes the very incident when two opposing trains enter the tunnel within the specific time interval leading to the worst pressure wave superposition.

Although the 10 kPa health criterion is well-accepted and established in numerous European railway regulations, it seems not to be appropriate from the technical point of view. First, the threshold value of 10 kPa seems to be too small; and secondly, the simultaneous incident of a critical passing (critical relative entry time of two trains has to be met within fractions of a second) and a complete failure of the pressure sealing system (e.g. broken window) is a non adequate scenario. In Japan, the 10 kPa criterion is neither accepted nor fulfilled for Shinkansen lines.

One reason for the European-wide introduction and "popularity" of the 10 kPa criterion might have been that it provides a clear and – due to the link to passenger health – a hard criterion for dimensioning double-track tunnels. It is quite fair to say, that the 10 kPa criterion actually led to an in-principle aerodynamically balanced sizing of double track tunnels.

If double-track tunnels on 300 km/h lines show a cross-sectional area of about 90 to 100 m^2

- aerodynamic loads on the structure of passenger trains and tunnel installations remain in a reasonable, manageable range,
- aerodynamic resistance does not exceed that of open air tremendously,
- decent pressure comfort can be achieved just by proper sealing of coaches and by cut-off valves for the HVAC system,
- and the phenomenon of micro-pressure wave is avoided at least for ballasted track tunnels.

For the special (German) case of cargo train operation on high-speed lines, there remains the problem of aerodynamic loading on cargo trains when being passed by high-speed trains in a tunnel. Here, the aimed solution is to technically exclude passings of high-speed trains and cargo trains within a tunnel by a corresponding functionality of the train control system.

The well-chosen and balanced the cross section of so far German high-speed (double-track) tunnels might have been, the new quest to build new tunnels generally single-track will cause a system change in terms of tunnel dimensioning. For single track-tunnels the 10 kPa criterion plays no big role since the critical passing of two trains is excluded. Thus, the only "hard" criterion disappears and tunnel dimensioning becomes a new compromise between various "negotiable" requirements.

As stated before, the cross-sectional area of future high speed singe-track tunnels in Germany will be 60 m^2 according to the corresponding DB guideline. Thus, the typical blockage ratio will be 0.17 to 0.18 (also cf. to Table 3). The cross-sectional area of 60 m^2 will further result in increasing tunnel factors for the aerodynamic resistance. The maximum pressure loads on trains and on tunnel installations are smaller than those in a 92 m^2 tunnel in case of near-critical passings. However, the "ordinary" pressure load level, which is experienced during every single tunnel run, increases considerably. In addition, in single track tunnels the maximum air speeds – which also cause aerodynamic loading e.g. on signal plates or antennas – will increase. All in all, these are manageable challenges.

What with respect to so-far system design actually really makes a difference, is the issue of pressure comfort in long tunnels. In long future tunnels with 60 m^2, the requirements on pressure tightness of rolling stock will have to increase quite tremendously in order to ensure the same pressure comfort as in today's high-speed trains of DB. Pressure variations experienced by passengers within a sealed high-speed train are not really effected by the crossing situation within the tunnel (because the time scale of the pressure variation linked to the passing is much smaller than the time constant τ for the pressure tightness). In consequence, pressure comfort in double-track tunnels just "benefits" from the bigger cross-sectional area and is much easier to achieve than in single-track tunnels.

Or in other words: In single-track tunnels pressure comfort becomes more expensive and, thus, the pressure comfort target has to be carefully derived. Hence, DB is still very interested and active in the subject of pressure comfort and pressure comfort criteria (e.g. Berlitz 2003).

3.4 Micro-pressure waves

Beside the "classical" disciplines of tunnel aerodynamics, recently also the micro-pressure wave phenomenon, also known as "sonic boom", gained very practical relevance in Germany.

The basic mechanism is that the gradient of the entry pressure wave generated by the train increases while the wave is propagating (with the speed of sound) through the tunnel. The pressure wave – which might actually result in a shock wave – then reaches the end portal and leads to the transmission of a micro-pressure wave. An illustration is given in Figure 1.

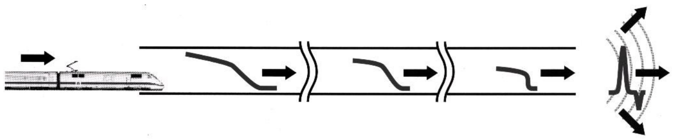

Figure 1: Illustration of development of micro-pressure waves.

The key of the micro-pressure wave phenomenon is the steepening of the pressure wave. This steeping process happens, when

- the entry pressure gradient is that high, that the speed of sound differs significantly within the wave front
- and dispersion and friction effects that usually counteract this phenomenon are sufficiently small.

In railways, the phenomenon of micro-pressure waves was first observed in Japan in 1975 and became – due to long tunnels with cross sections of only 64 m^2 in combination with slab track and with high train speed – a standard aspect of JR tunnel aerodynamics (e.g. Ozawa et al. 1991). In Europe, sonic boom effects did not occur under operational conditions. The main reasons are the bigger cross-section of European high-speed tunnels (entry pressure gradient reduced) and the use of ballasted track (dispersion and friction increased).

The first European high-speed lines with slab track had been built in Germany. The longest tunnel of the 300 km/h-line Cologne-Frankfurt, which was built with slab track and opened in 2002 (also cf. to Table 1), is the Schulwald tunnel with a length of ca. 4500 m and a cross-sectional area of 92 m^2. At this tunnel an audible micro-pressure only occurs artificially, when two test trains enter that tunnel in a parallel run (Herb et al. 2003).

Also the May 2006 opened Nuremberg-Ingolstadt high-speed line was designed for 300 km/h and implies various 92 m^2 double-track tunnels. This line was originally planned to be built with ballasted track; then a change to slab track was decided which, however, did not lead to changes in the design of the already built tunnels. In December 2005, when high-speed tests on the new line started, sonic boom incidents occurred at the portals of the 7700 m long Euerwang tunnel and of the 7260 m long Irlahüll tunnel. There are no residential areas closed to any of these portals, but there are public routes and hiking paths in the direct portal vicinity.

Although there are no applicable German regulations for the sonic boom and although other acoustic regulation had been complied with, DB decided to take measures to reduce the micro-pressure wave emissions at these 4 tunnel portals. As target values had been defined:

- Even directly at the portal, the C-weighted peak level $L_{c,peak}$ of the micro-pressure wave has to be equal or lower than 135 dB(C) which is the lowest threshold within EC (2003),
- On the public areas, the impulse corrected (cf. to ISO 2003), C-weighted sound exposure level $L_{RE} = L_{CE} + \Delta L$ of the micro-pressure wave has to be equal or lower than the C-weighted sound exposure level of the train passing event.

On the basis of this assessment, DB installed in spring 2006 acoustical track absorbers in the tunnels Euerwang and Irlahüll. These absorbers act like artificial ballast and lead via dispersion and friction to a significant inhibition of the pressure wave steepening process. Remaining micro-pressure wave emissions now comply with the given objectives, and commercial operation on the line was started in May 2006 as planned and scheduled. A more detailed report about the micro-pressure wave incidents at the Nuremberg-Ingolstadt line, the efficiency of the countermeasures taken and the acoustic and aerodynamic assessment of the remaining micro-pressure wave emissions is in preparation and will be published soon (Tielkes et al. 2007, Degen et al. 2007).

Even, when the subject of micro-pressure waves was well known for a long time and was anticipated to become of very practical relevance for future single-track tunnels in Germany, the micro-pressure wave incidents on the Nuremberg-Ingolstadt line had a new experience in many respects.

For Germany, of paramount importance is that the so-far abstract phenomenon of sonic boom became very tangible and, thus, an intense discussion about its assessment and (legal) appraisal started. This discussion will surely have an impact on ongoing single-track tunnel construction projects.

The responsibility and the challenge for the very near future will be to achieve a sound German regulation to assess micro-pressure wave emissions and to define reliable and economic countermeasures for upcoming single-track tunnel construction projects. Hereby, the aspect of micro-pressure waves shall not affect the sizing of the tunnel cross section as long as other measures are efficiently applicable.

4 AERODYNAMIC ASPECTS OF THE GERMAN MAGLEV SYSTEM

4.1 General

As mentioned before, aerodynamics of high-speed railway systems and maglev systems do not differ too much from the system point of view. The classical aerodynamic interface issues between vehicles and infrastructure are similar for both system and can be dealt with with the same methodological approaches. Mostly, specific aspects of the maglev system – e.g. aerodynamic interaction between vehicle and guideway – had been early addressed and extensively investigated also by full-scale tests.

4.2 Aerodynamics in open air

In open air, aerodynamics of maglev systems include the interaction between vehicle and guideway and in other respects issues that are basically known from high-speed railway system. In principle these are aerodynamic loads on other trains and on infrastructure components, the effects of natural winds and the subject of aerodynamic resistance.

Concerning aerodynamic loading on other trains and on objects as noise barriers, at a very early stage studies on the basis of railway experience had been done (e.g. Peters 1983). Even more important: there had been numerous tests carried out at the TVE test facility in Lathen. Predicted values for the aerodynamic loads had been also confirmed by tests in Shanghai (Löser 2004).

Generally, the same counts for aerodynamic interaction between vehicle and guideway, for cross wind effects and for aerodynamic resistance. These issues are supposed to be well investigated by wind tunnel and by full-scale tests and are addressed within the first draft of the upcoming design guidelines for German maglev systems (EBA 2006).

The TR 09 train of the maglev project in Munich will slightly differ (also in terms of height) from the TR 08 train and the Shanghai train. Thus, aerodynamic studies concerning aerodynamic loading, cross wind effects and aerodynamic resistance have to be updated and some wind tunnel and full-scale tests have to be redone.

4.3 "Classical" tunnel aerodynamics

In terms of physics, there is no difference between tunnel aerodynamics of the German maglev system and those of the German high-speed railway system.

The aerodynamic parameters for tunnels of the Munich maglev project (Reinke & Ravn 2005) differ substantially from those of so-far existing tunnels of the German high-speed railway system: The tunnels of the Munich maglev project will be built single-track. As stated in section 3.3, existing high-speed railway tunnels in German are double-track ones and imply blockage rations of about 0.11 to 0.13. Whereas according to (DB Netz AG 2002) for future single-track tunnels of the German high-speed railway system the blockage ratio will be about 0.17 to 0.18 (from 230 km/h up to 300 km/h), the three tunnels of the Munich maglev project will imply a blockage ration of about 0.24 (up to 250 km/h).

Thus, for the Munich maglev project, the subject of tunnel aerodynamics is of very special importance:

- different to aerodynamics in open air, there are so-far neither long-term test data from the TVE test facility in Lathen nor experiences from the Shanghai project available;
- for the German high-speed railway system, there is up to now no corresponding operational experience with single-track tunnels.

Consequently, the subject of tunnel aerodynamics – even when the physics are well known – does require careful attention.

As pointed out in section 3.3 the most prominent aspects when dimensioning the general cross-section of single-track tunnels are aerodynamic loads, pressure comfort and aerodynamic resistance (The aspect of micro-pressure waves shall not influence the regulation of tunnel cross-section as long as other measures as portal hoods are efficiently applicable).

For the Munich maglev project quite comprehensive tunnel aerodynamic studies were carried out (Reinke & Ravn 2005). The decided cross section of 52 m^2 for the 250 km/h tunnel assures that for the specified pressure tightness of the TR 09 train, the chosen pressure comfort criterion ($|\Delta p| \leq 0.5$ kPa within 1 s; $|\Delta p| \leq 0.8$ kPa within 3 s and $|\Delta p| \leq 1.0$ kPa within 10 s) are met. The decided tunnel design also accounts for other requirements concerning aerodynamic loads and aerodynamic resistance.

While from the system point of view the Munich maglev project is apparently well-balanced, continuous attention has to be turned to the train's conformity with the train specifications. With respect to classical tunnel aerodynamics, the actual pressure tightness, its interrelation with the HVAC system and the actual aerodynamic resistance of the TR 09 train seem all-important.

In the draft of the upcoming design guidelines for German maglev systems (EBA 2006) the maximum pressure variation on the train is set to $|\Delta p|_{max}$ = 5500 Pa. For a train running through a single-track tunnel (no pressure waves of other trains within this tunnel; no shafts) the maximum pressure variation $|\Delta p|_{max}$ is not strongly depending on the tunnel length as illustrated in Figure 2. When in each case the tunnel length is chosen as "critical", $|\Delta p|_{max}$ can be computed with respect to train speed and tunnel cross section. Figure 3 gives an overview.

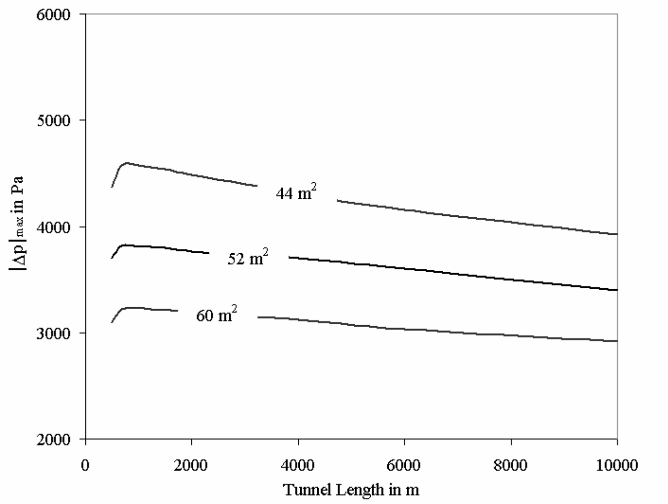

Figure 2: Maximum pressure variation $|\Delta p|_{max}$ acting on a 12.4 m^2-train in a tunnel with respect to tunnel length and tunnel cross-section (single-track tunnel, no pressure waves of other trains, no shafts, train length 100m, train speed 250 km/h).

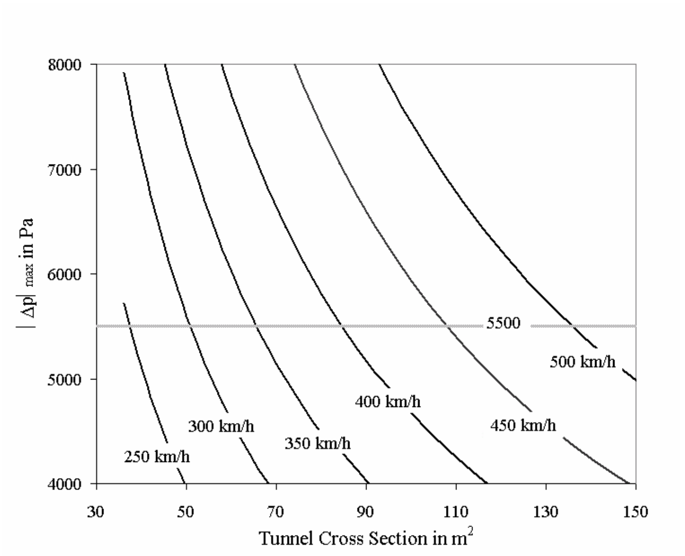

Figure 3: Maximum pressure variation $|\Delta p|_{max}$ acting on a 12.4 m^2-train in a tunnel with respect to tunnel cross-section and train speed (single-track tunnel, no pressure waves of other trains, no shafts, train length 100m, "critical" tunnel length).

For maximum pressures of $|\Delta p|_{max}$ = 5500 Pa, which are in the range of German railway experience (corresponds to doors, windows etc.), the minimum tunnel cross-section with respect to train speed can be derived. If then a pressure comfort criteria is set, the required pressure tightness can be derived. Figure 3 shows that especially for very high speeds a fixing of the maximum pressure variation to $|\Delta p|_{max}$ = 5500 Pa according to EBA (2006) will lead to very big cross sections for single-track tunnels

Tables 4 displays some corresponding reference values for the required pressure tightness of the maglev train if the pressure comfort criterion is chosen to be $|\Delta p| \leq 0.5$ kPa within 1 s; $|\Delta p| \leq 0.8$ kPa within 3 s and $|\Delta p| \leq 1.0$ kPa within 10 s according to Glöckle (1994). This three-stage criterion, often referred to as the "DB pressure comfort criterion", does not imply a requirement for longer time intervals. On the other hand UIC (2002) proposed a four-stage criterion with an additional requirement of $|\Delta p| \leq 2.0$ kPa within 60 s. As already stated in section 3.3 the chapter of pressure comfort criteria is not yet closed. At DB, upcoming long, single-track tunnels initiated further studies on pressure comfort.

Table 4: Reference values for the required pressure tightness ("dynamic τ-value") to comply with the so-called "DB pressure comfort criterion" (Glöckle 1994). Results refer to single-track tunnel, no pressure waves of other trains, no shafts, maglev train with cross-section of 12.4 m^2, train length 100m.

Train speed in km/h	Tunnel size in m^2	τ_{dyn} in sec depending on l_{tun} = 1000m	2000m	4000m	6000m
250	38	23	27	24	26
300	51	24	27	22	25
350	66	24	26	23	25
400	85	22	26	23	25
450	108	21	26	23	24

Although the discussion on pressure comfort criteria still goes on, it might be supposed that a modern pressure comfort criterion will imply also a requirement for a time-interval significantly larger than 10 s. Thus, the pressure comfort criterion adopted for Table 4 is not the most ambitious one in discussion. Nevertheless, Table 4 points out that for the pressure tightness values bigger than τ_{dyn} = 20 s are required. By standard measures (sealing, cut-off valves for the HVAC), these values can hardly be achieved without effecting other issues (e.g. closing time of doors). In consequence, for the Munich maglev project a tunnel cross-section of 52 m^2 was decided. This value actually corresponds to a $|\Delta p|_{max}$ of about 3800 Pa, which will then lead to required τ_{dyn} –values of about 15 s.

If for train speeds of 300 / 350 / 400 / 450 km/h the same approach were chosen, the required cross section would be about 72 / 95 / 123 / 156 m^2, respectively. It is quite obvious, that for a maglev project with substantial tunnel share, these cross sections are inefficient. Thus, potential German maglev projects of the future, which take full advantage of the maglev design speed and which show a substantial single-track tunnel share, will require an active system to control the train internal pressure (e.g. Suzuki 1997). That means, that in this case pressure comfort will become less important with respect to tunnel dimensioning. For new maglev projects, the best compromise between the requirements of aerodynamic resistance and aerodynamic loading will most probably lead to smaller tunnel cross-sections than those associated with $|\Delta p|_{max}$ = 5500 Pa.

In consequence, the requirement within the draft of the upcoming design guidelines for German maglev systems (EBA 2006), requesting the maximum pressure variation on the train to be generally $|\Delta p|_{max}$ = 5500 Pa, seems to be inappropriate from the system point of view. Apparently, this way the efforts on vehicle and infrastructure side are not generally balanced with a view to minimum system costs.

The author recommends to cancel the design requirement of $|\Delta p|_{max}$ = 5500 Pa within (EBA 2006) and to initiate further (system) studies on single-track tunnel aerodynamics at very high speeds.

In addition, the proposition of double-track maglev tunnels might be re-assessed (in consideration of other needs). At least in individual cases, there might be actually the opportunity to technically exclude tunnel passings by the train control system without affecting timetable and train operation. From the aerodynamic position, this would produce relief with respect to various issues.

4.4 *Micro-pressure waves*

As well as for “classical” tunnel aerodynamics, the methods to assess micro-pressure waves radiating from maglev tunnel exits are the same as for high-speed railway. And as well as for “classical” tunnel aerodynamics, it has to be noted that the investigation of maglev micro-pressure waves

- can neither correspond to long-term test data from the TVE test facility in Lathen nor to experiences from the Shanghai project;
- was not directly supported by German railway experience since up to now there were neither sonic boom incidents nor single-track high-speed tunnels in operation.

Nevertheless, the topic of micro-pressure waves has been subject not only of Japanese but also of endurable European research (e.g. Schulte-Werning et al. 2002). Dating back several years, the topic of micro-pressure waves had become a standard issue within the planning process of new German high-speed lines. Thus, also for the Munich maglev project, sound investigations of the micro-pressure wave issue had been carried out and corresponding and efficient countermeasures had been disclosed (Reinke & Ravn 2005).

The intention of this paper is to point out the new experience made with the Nuremberg – Ingolstadt high-speed railway line. The micro-pressure wave incident at that line and its successful elimination did not only result in full-scale data for the various stages of the overall mechanism of micro-pressure wave generation (cf. also to Figure 1) but also in a serious and very practical discussion how to assess the emitted micro-pressure wave according to German standards. Although a tentative threshold was agreed for the Nuremberg – Ingolstadt line, the discussion on a well-defined and univocal assessment of micro-pressure wave emissions will continue and will also make an impact on ongoing development projects. Thus, for the Munich project it is recommended to safeguard the so-far design by further studies which incorporate the new experiences.

The objective for future projects shall be to reduce micro-pressure waves to a level where their (acoustic) effects are basically imperceptible. In consequence, the phenomenon of micro-pressure waves shall be rather considered as an aerodynamic than as an acoustic topic. The ambition for the near future must be to fix a German limit, expressed in terms of aerodynamic parameters and agreed by authorities, experts and operators, which is as pragmatic and active as the Japanese one.

Within the framework of further development of the German maglev system and against the background of projected increase of tunnel speeds, research on economic and efficient countermeasures – infrastructure and vehicle ones – shall be intensified.

5 SUMMARY AND CONCLUSIONS

Aerodynamics of high-speed railway systems and maglev systems do not differ in terms of physical principles and analysis methods. However, there might be substantial differences in terms of system layout which also lead to different focuses in the field of aerodynamics.

Referring to the situation in Germany, a very important factor is the quest for single-track tunnels in order to support fire safety. So far, existing German high-speed railway tunnels had been built as double-track tunnels. While single-track tunnels for high-speed railway (≥ 250 km/h) are under planning or under construction, also the Munich maglev project implies single track tunnels. Whereas physics and methods of calculation are well-known, the so far non-existing practical experience shall be acknowledged. In principle, single-track tunnels of future maglev projects will feature even higher speeds than Munich maglev tunnels and German railway tunnels, and thus, will face further challenges.

From the system perspective a proper design of a maglev system with single-track tunnels involves a balanced and optimized compromise between general and superior requirements – in this case especially the limitation of required tunnel cross section due to various reasons – and the various (competing) technical requirements, namely

- the limitation of train-induced aerodynamic loads acting on the train and on the infrastructure,
- the affirmation of an appropriate pressure comfort to passengers,
- the global avoidance of bothering micro-pressure wave emissions,
- the limitation of aerodynamic resistance.

For the Munich maglev project, corresponding studies had been carried out and system parameters had been decided. Now, it has to be ensured that deduced train specifications, especially regarding pressure tightness, its interrelation with the HVAC system and the actual aerodynamic resistance of the train seem will be matched. With respect to the topic of micro-pressure waves, the experiences recently made at the Nuremberg-Ingolstadt line need to be accounted for.

Within the framework of further development of the German maglev system and against the background of projected increase of tunnel speeds it is recommended to intensify / to initiate

- studies on perceived pressure comfort and on a active system to control the train’s inner pressure;

- studies on increase of the endurable pressure loads;
- investigations on economic and efficient sonic boom countermeasures, both on the infrastructure and on the vehicle side.

Further, the concept and feasibility of double-track tunnels might be re-considered with respect to future projects.

The objective shall be the best derivation of an appropriate set of system parameters for future high speed maglev operation in tunnels.

It should be mentioned and appreciated, that also high speed railway will benefit remarkably from progressive maglev activities in the field of (tunnel) aerodynamics.

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