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A SYNOPSIS OF AERODYNAMIC AND AEROACOUSTIC RESEARCH FOR MODERN HIGH-SPEED TRAINS

Burkhard Schulte-Werning

Deutsche Bahn AG
Forschungs- und Technologie-Zentrum
Voelckerstr. 5, 80939 Muenchen, Germany
e-mail: burkhard.schulte-werning@bku.db.de

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Abstract. *The aerodynamic requirements for a modern high-speed train of the next generation follow three lines of optimisation. Firstly lower energy consumption as a result of reduced aerodynamic drag, secondly lower noise emission by optimised "streamlining" of the train shape and of the pantograph design and thirdly improved interaction with the infrastructure and the meteorological environment. The needs for increased sustainability and smooth operation conditions complete this catalogue.*

In the last few years, basic research work has been performed in several projects initiated by European railway undertakings to enable the aerodynamic improvement of future train sets. Examples that can be named are the aerodynamics projects TRANSAERO and RAPIDE in the BriteEuram framework and the acoustics project K2 in the bilateral French-German DEUFRAKO framework. Furthermore, the three European high-speed operators FS, SNCF and DB launched a project focussing on the drag and noise reduction effect of bogie fairings fitted to trains with a cruising speed far beyond 200 km/h.

This article describes the numerous research activities and the results currently available in connection with the lines of optimisation outlined above.

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1 INTRODUCTION

In the last few decades, mobility in Europe, based on automobiles for individual traffic and lorries for freight traffic, has grown more and more; yearly growth rates of more than 10% have often been reported by statistics. Even with a fully developed construction programme for motorways and similar high-performance roads, these growth rates cumulated over the years cannot easily be handled in an environment-friendly way. The European Commission has therefore given distinct political signals to get more passengers onto the railways.

This policy represents a clear challenge in the next few decades for European railway companies: the considerable increase in mobility in a Europe with falling borders will cause a doubling of the traffic volume within the next 10 to 20 years. Since an efficient trans-European transportation net-work is indispensable to handle the mobility increase and the road network has reached its socio-ecological limits, the railway network will be strengthened. As part of it, an attractive high-speed network plays a key role in the strengthening concept. In parallel, the high standard of safety has to be kept while interoperability across the former national borders, which now transform into technical interfaces between different railway sub-networks, has to be ensured.

Figure 1 shows the planned high-speed railway network in Europe, to be operated by trains with cruising speeds beyond 200 km/h. As the design of the national railway systems show some distinct variability, the rules for interoperability have to be carefully investigated.

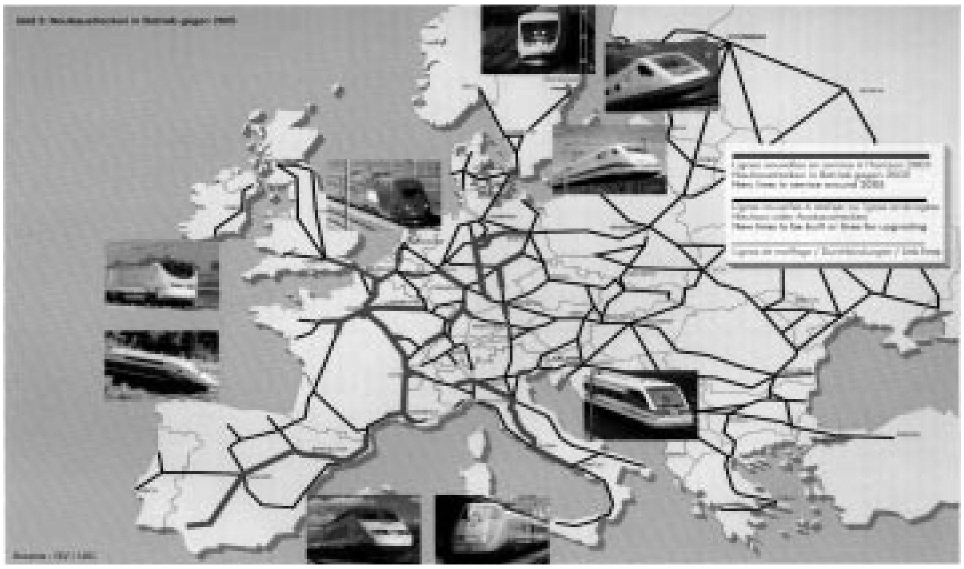

Figure 1: Trans-European high-speed railway network to be operated within the next years [Source: UIC]

2 AERODYNAMIC AND AERO-ACOUSTIC EFFECTS OF SUBSTANCE

Railway companies operating trains at high speeds meet complex problems due to aerodynamic effects. These effects can be grouped into three basic categories following the interests of the railway operator:

I Lower energy consumption as a result of reduced aerodynamic drag and lighter vehicles

II Lower noise emission by optimised "streamlining" of the train contour and especially of the pantograph shape

III Improved interaction with the meteorological environment such as impact of side-wind gusts on high-speed trains,

IV Improved interaction with the infrastructure like:

- Forces generated during train-passing and related fatigue of train structures,
- Generation of micro-pressure waves at the exit portals of tunnels, creating environmental problems in the form of an audible bang, the so-called "Sonic Boom",
- Pressure wave generation in tunnels, creating discomfort for passengers and crew on the train,
- Tail coach oscillations induced by periodic vortex separation.

Since technical solutions developed with respect to the specific boundary conditions of the national railway system alone might be poorly compatible with the national rules in other countries, the nowadays research undertaken to shed light on the stated problems shows a clear international approach.

2.1 Less energy consumption by reduced aerodynamic drag

Currently European high-speed trains such as the ICE, TGV and ETR 500 achieve scheduled speeds of 280 km/h. Several TGV routes are operated at 300 km/h even today and the forthcoming commissioning of the ICE 3 route will allow this commercial speed on the new Cologne-Frankfurt route. Hence the trend towards higher speeds in rail traffic is continuing undiminished. Future generations of high-speed lines may be operated with maximum speeds of up to 350 km/h [22]. This further refinement of rail-traffic can only be effected economically if issues of environmental acceptability are taken sufficiently into account.

The increase in speed from 280 km/h to 350 km/h outlined above would, for example, lead to a 60% rise in operational energy costs on account of drag given the present state of high-speed train technology. As the acceleration capability of the train also has to be increased, the traction force will not be concentrated in a locomotive anymore but will be distributed along the train length via electrical multiple units (EMU). This allows both for a less overall weight of the train and an end car with passenger seats, thus increasing the transport capacity of the train.

The considerable reduction in drag and noise, compared with loco-hauled trains, brought about by streamlined exterior styling, an aerodynamically smooth skin along the whole train, suitably designed inter-coach gangways and the flush arrangement of doors, windows and boarding steps has already been set out in [9]. The potential for reducing drag has already been successfully tapped, e.g. on the ICE in conjunction with underfloor fairings. This treatment has simultaneously reduced the amount of aerodynamic noise emission of the train.

A further means of reducing drag involves bogie fairings mounted flush with the external contour of the train to produce a favourable airflow. Studies conducted in the thirties as well as recently on the Japanese Shinkansen 300X research train identify the potential saving relative to a reference configuration without such fairings as being approx. 10 % [9, 15].

Calculated on the basis of the operating costs for present-day European HST routes, bogie fairings would allow typical savings of between 5 and 10 million EURO to be effected in annual energy outlay for the various HST fleets.

For a systematic assessment and precise quantification of this potential for reducing drag and noise emissions of high-speed trains HST of European design under domestic operating conditions, the railway undertakings DB (Germany), FS (Italy) and SNCF (France) decided to investigate the aerodynamic impact of such bogie fairings in a joint research venture in cooperation with the BREDA train manufacturer. The ETR 500 mid-train coach was investigated in the wind tunnel (Figure 2), substantially confirming the potential of more than - 10% aerodynamic drag for a complete train set and will be investigated under full-scale conditions on the "Direttissima" high-speed line in Italy in autumn 2000 [19].

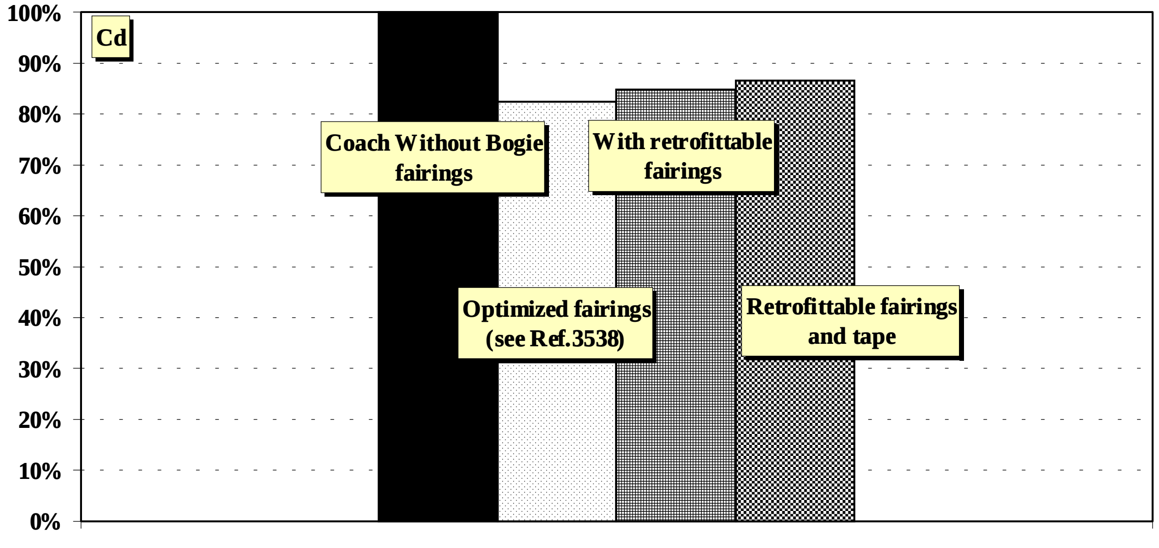

Figure 2: Effect of various types of bogie fairings for a ETR 500 mid-train coach [19]

2.2 Lower noise emission by optimised "streamlining"

Above 300 km/h, aero-acoustic sources become dominant over the rolling noise generated also. It is calculated that passing noise levels are likely to be 6 dB(A) higher. Furthermore, environmental regulations for rail operations are likely to become more rather than less stringent in future, necessitating wide-ranging endeavours in the field of research and development to help rail-borne transport hold its own against the motorcar and the aeroplane.

Additionally, bogie fairings lead to a reduction in locally generated aerodynamic noise resulting from the high level of turbulence in the bogie area, a fact that will have a favourable impact on noise emissions for the vehicle as a whole. If the skirting descends far enough down and is additionally lined with sound-damping material on the inside, partial damping of the noise caused by wheel/rail contact can also be expected. In total, a noise reduction of 3 dB(A) is aimed for [19].

Basically, the demand for low-resistance and low-noise vehicles goes hand in hand with the demand for an overall aerodynamically optimised vehicle. From the fact that the separation and flow noises make a substantial contribution to noise creation, it follows that areas with flow separation on the vehicle must be avoided as far as possible, thus reducing the aerodynamic drag of the train at the same time as well.

The pantograph is a structural element with a particular type of construction consisting, in its present-day forms, of a filigree, geometrically heterogeneous frame with rigid and movable joints. The tandem components of such rigid/movable-joint frame structures and their flow interactions lead to great time fluctuations of the aerodynamic forces. This then results in corresponding fluctuations of the contact-force between the pantograph contact-strip and the contact wire, leading to considerable wear caused both by arcing effects and by surface friction.

The small-scale separation structures behind a rigid/movable-joint frame structure also lead to relatively broadband noise radiation. On account of the exposed position of the pantograph high above the train, noise creation cannot however be reduced simply by means of passive noise-protection measures such as conventional noise barriers.

On the contrary, this specific characteristic of the noise effect of the pantograph leads to the situation that the effectiveness of existing noise barriers based on a sound source in the wheel/rail area and assumed in the project-approval procedure is often no longer achieved when higher speeds are involved. This means of course that the substantial investment costs also become increasingly questionable.

In relation to rolling noise, the typical screening effect of a 2 m high noise barrier is 10 dB. With rising speed, the relative portion of the pantograph in the overall noise increases however. Since what is concerned here is predominantly a so-called dipole sound source, the radiated sound output of aerodynamic sound sources increases by approximately the sixth power of the running speed; that of the rolling noise, on the other hand, by only the third power. That means that the portion of train noise that is no longer screened off by the noise barrier increases as well. For very high speeds (independent of train length and number of pantographs), the portion of the pantograph noise can even be predominant. In this case, the screening effect of the noise barrier would be reduced to well below 10 dB [20].

On account of the above-mentioned sound-creation characteristics of a pantograph, which even today lead to a reduction in the effectiveness of noise barriers, future pantograph generations will have to radiate distinctly lower sound levels. This will safeguard the effectiveness of existing noise-protection installations and thus their substantial investment costs.

As part of the DEUFRAKO framework (a cooperation between the Ministry for city planning, Housing and Transport of the Republic of France and the Ministry for Research and Technology of the Federal Republic of Germany) investigations in the project K2 "Noise Sources of Guided High-Speed Transport" showed the maximum noise reduction potential of the conventional pantograph structure, e.g. by selective trip wiring of the rods in wind-tunnel tests (figure 3), to be 7 dB(A) less than the currently used pantograph [5].

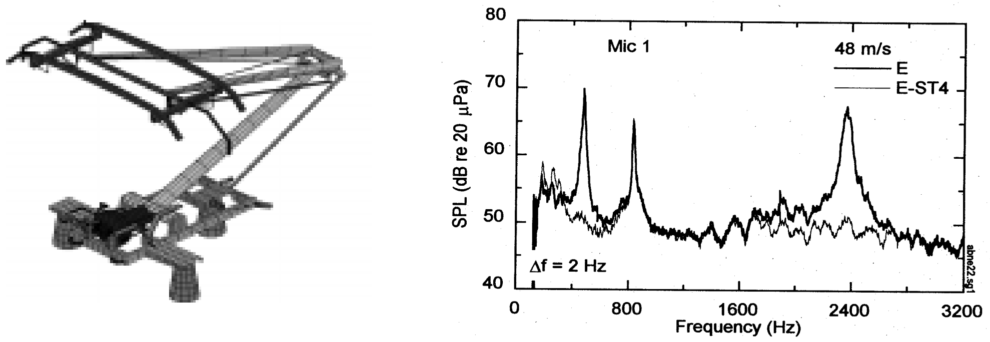

Figure 3: Reduction of the pantograph noise by aerodynamic optimisation: Tonal peak reduced by selective trip wiring of the framework rods [5].

Any greater noise reductions can only be achieved by employing new concepts. In a project of DB with the railway manufacturer Adtranz, the aero-acoustical optimisation was done by means of a semi-empirical simulation tool developed by DB which basis is a huge data set of the Strouhal number, the turbulent correlation length and the insteady lift force coefficient for basic geometrical configurations. By simulating a rod framework the local noise emission was calculated and minimised in a step by step manner [10].

The result is shown in figure 4, a forerunner configuration was tested in the wind-tunnel of the Japanese Railway Technical Research Institute RTRI at Maibara and showed up to 15 dB(A) less noise production, depending on the velocity. Moreover the contact force variation between the panto-head an the catenary is reduced by active control thus reducing the wear and consequently the maintenance efforts later on [1, 2, 3, 4, 7, 11].

Figure 4: Aero-acoustically optimised pantograph out of ADtranz-DB collaboration.

2.3 Improved interaction with the meteorological environment

When using non-powered, light-bodied vehicles placed in first position of the high-spped train, strong wind gusts may under extreme conditions lead to wind load conditions, where the vehicle dynamics has to be investigated with care. Measures have to be taken for safe and economical operation. In principle, these are structural counter-measures like increase in the vehicle mass, operational restrictions and track-side constructional measures e.g. wind-breaking devices.

Of course, each counter-measure has its specific merits, but one of the most effective means was regarded to be walls and fences near the track. Because of the high costs for equipping the tracks, clear knowledge of the actual effectiveness of such shelters is needed. CFD calculations, model-scale tests and full-scale tests (as a reference case) were performed on the reaction of a leading vehicle to strong side wind and a parametric study was undertaken for the optimisation of the wind fence design.

This effect was investigated within the Brite/Euram-project TRANSAERO (Transient Aerodynamics for Railway System Optimisation) running from 1996 to 1999, where DB, FS and SNCF joint their research forces with 9 other academic institutions in Europe [12, 14, 17].

As the scenario for all investigations, the DB IR driving trailer running on a 8m high embankment was chosen. The geometry of the train and the embankment as well as the natural atmospheric boundary layer were simulated in the model-scale tests and the CFD calculations corresponding to the conditions found on the real test site. At the track-side, the sheltering effect of a 2 m high (relative to the rail top level) noise barrier and a 2 m high wind fence with 50% porosity was measured.

In the full-scale tests, the vehicle was equipped with a 6m long nose boom, which, at its head, carried a 2D-ultrasonic anemometer and probes for the measurement of the ambient conditions. Several locally fixed anemometers were placed near the track and upstream of the embankment as a reference. Furthermore, the vehicle was equipped with load-measuring wheel-sets (vertical and lateral forces) and sensors for accelerations and deviations of the bogies and vehicle body. All signals were recorded simultaneously.

For the investigation in the model-scale tests with a vehicle moving in a turbulent boundary layer flow over fixed ground, the "standard" wind tunnel equipment did not seem to be sufficient because of the limitations of these facilities in simulating the train/ground interaction and the turbulent atmospheric boundary layer. To overcome these restrictions, a moving model rig was integrated in a large boundary layer wind tunnel. The scale 1:50 model is catapulted at a speed of 10m/s perpendicular to the mean flow across the test section of the wind tunnel, where the natural turbulent wind profile is simulated with roughness elements. Several test series were performed under different yaw angles and wind fence geometry like porosity and height.

For the numerical investigation of the problem, two RANS-CFD codes with different capabilities concerning grid generation and solver algorithms were chosen, both using an RNG-k-ε-turbulence model [13].

Several parametric variations of the test set up were computed, varying the scale (Re Number) of the problem, the height and porosity of the wind fence and the position of the train on the embankment (track near the fence or on the downstream track). In some cases, a slit of one meter was left open between the bottom of the fence and the ground, corresponding to the elevation of the track over the top of the embankment.

A solid barrier extending 2m over track level reduces the rolling moment of a leading vehicle to at least 30% on both track sides. On the "near wall" track the rolling moment Cmx is nearly zero (see Figure 5). These results obtained by the CFD parametric study are in good agreement with model- and full-scale investigations. A higher wall is usually not necessary. A 2m high fence with 50% porosity reduces the rolling moment to approximately 50% on both track sides.

All three methods gave good results on the whole. Specific limitations due to the modelling (Re-number effects, simulation of porous media, representation of vehicle/ground interaction, capability of simulating highly separated flow) have to be respected, of course.

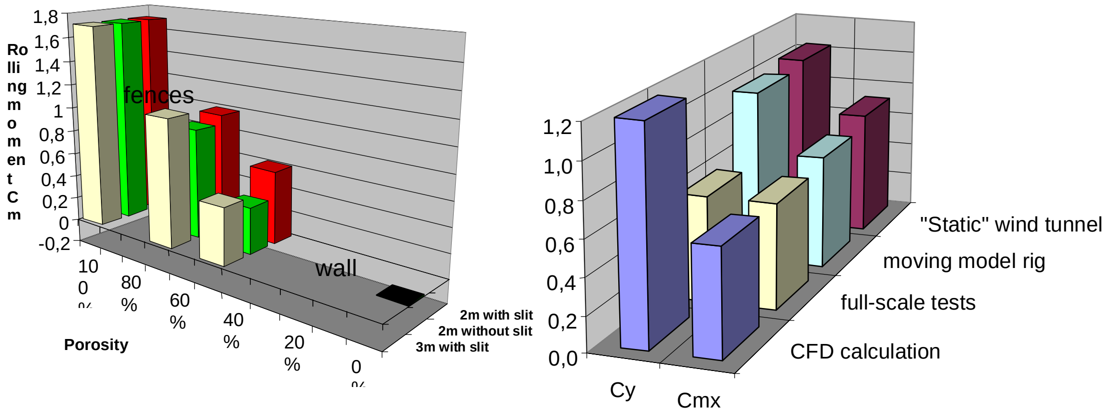

Figure 4: Effect of wind barriers on the rolling moment Cmx on the near wall track (left), and comparison of different tools in side force Cy and rolling moment Cmx for the open embankment case (right) [14]

2.4 Improved interaction with the infrastructure conditions

When **two trains are passing** each other, high unsteady forces moving along the surface of the vehicles lead to fatigue or even, in the long term mode, to failure of structures, both on high-speed trains and on freight wagons (Figure 6).

Figure 6: Typical train passing situation of interoperable high-speed trains (Source: SNCF)

These effects are mainly dependent on the track spacing, the length and the shape of the train's head, the (relative) train speed and the location of the train passing. In tunnels, the effects can be significantly higher than in open air. Because of the ever increasing train speeds and the growth of the effects with the square of the velocity, these questions become more and more relevant in interoperable high-speed traffic.

Also in the TRANSAERO framework [14, 17], a series of full-scale tests was carried out on the Italian "Diretissima" high-speed line between Rome and Florence with passings of two FS ETR500 trains and ETR500 / freight trains in open air and in the Terranuova Le Ville tunnel. The train speed was up to 280km/h, the tunnel diameter 69m² with a track spacing of 4.2m. These tests formed the data basis for the validation of the model-scale tests and numerical simulations.

Various parametric studies have been performed on laboratory level, altering the nose shape (ETR500, TGV-A, ICE1), the nose length on basis of the ETR500 (3.0, 1.0, 0.3 times the standard nose length), the train speed and the track spacing (3.4m, 4.2m and 4.5m) for both passings in open air and in tunnels. The calculations were performed with two approaches, one using the 3D-panel method, "START" code with about 4,700 panels per train.

The model-scale tests used the moving model rig of AEAT, where a scale 1:25 model train is shot along a 150m long model track at speeds of up to 280km/h. Pressures were measured for a shortened moving model ETR500 train (3.7m long) on a stationary model (ETR500 and freight train). The first 750 m of the Terranuova Le Ville tunnel including the basic surroundings at the tunnel portals were modelled, leaving space for the moving model fired past the stationary model.

Figure 7 shows the effects of track spacing "e"and nose length on the amplitude of the head pressure pulse in a passing situation. It can be seen that at a given nose length the track spacing e is an important parameter with $\Delta cp \sim 1/e^2$. The nose length has a great influence on the loads of passing trains as well.

Also the shape of the different European high speed trains (TGV-A, ICE1, ETR500) showed a significant influence on the loads on windows and structures of the opposite train.

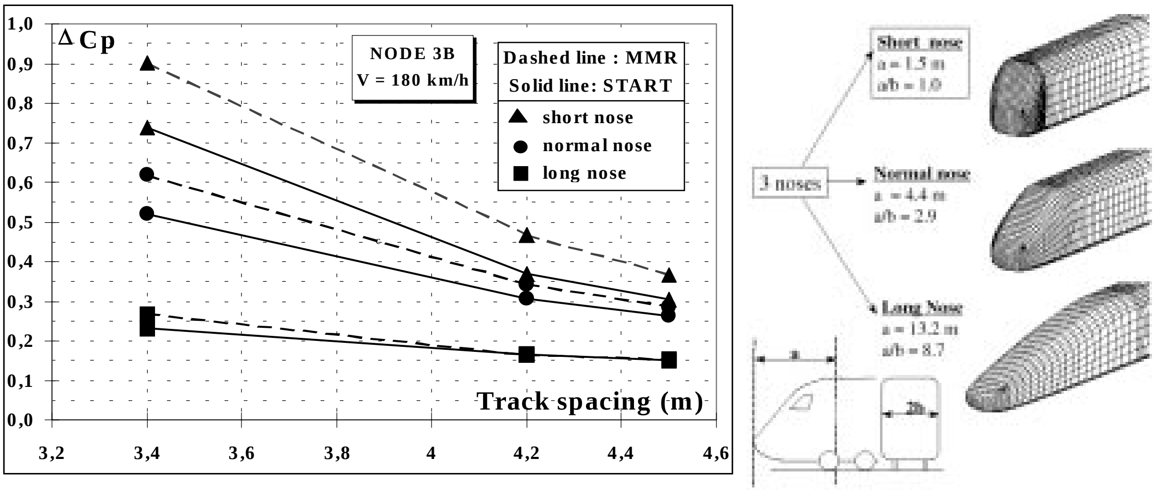

Figure 7: Effect of nose length and track spacing on pressure differences in passing situations. Results of CFD (Start) and Moving Model Rig (MMR) [17]

Pressure wave effects in tunnels can, in general, be divided into three phenomena: Pressure wave generation when the train enters the tunnel, propagation of the pressure wave on its way through the tunnel and pressure wave radiation, where the non-reflected part of the pressure wave is emitted into the surrounding environment. In very smooth and long tunnels, this emission acts as an audible "sonic boom" sound effect, which may bother people near the track.

Within the TRANSAERO project the aim was to follow the pressure wave from the generation over the transmission in the tunnel to the discharge at the tunnel exit [14,17].

The sonic boom effect was created in a full scale test to establish a validation data basis and to develop constructional counter-measures at the tunnel portals, e.g. hoods and chambers, and to validate numerical tools for the pressure transfer in the train. This was by far not an easy task, because most of the suitable tunnels in Europe are equipped with standard ballast tracks and consequently show a too high damping effect for the radiation of a sonic boom.

For the creation of a data basis for all pressure wave effects, a series of full-scale tests was carried out with one and two ETR500 trains running through the tunnel at different speeds. For the production of an audible sonic boom effect, both trains ran in parallel through the tunnel. The tunnel was extensively instrumented over its total length inside (pressures, velocities, temperature) and outside (microphones and pressures) for the complete resolution of the pressure wave effects.

With simulative techniques, pressure wave generation was investigated using a 3D Euler code, and a parametric study was undertaken to optimise the design of tunnel entrances and hoods for the minimisation of the entrance pressure wave. Also a model pressure wave generator on the scale of 1:35 was used. This in turn ensured the validation of a 2D-axi-symmetrical code for the prediction of the pressure waves.

Wave propagation was computed with a 1D-code using weighting function methods, focussing on unsteady skin friction phenomena for smooth and rough walls. An attempt was made to simulate the wave propagation process in a model apparatus.

Radiation of the wave was studied using a scale 1:130 piston-driven model pressure wave generator and a CFD code using the linearised 2D Euler equations based on the classic Mac-Cormack finite-volume algorithm. A set of infrastructure counter-measures in the tunnel was developed with this code.

All in all and after a process of optimisation, all modelling techniques used showed very good agreement with the reference data from the full-scale tests. This is true for all the pressure wave effects (generation, propagation and radiation).

With these tools, it was possible to develop a number of technical solutions in parametrical studies. Several combinations of hoods on the entrance portal were tested and (for the

Terranuova Le Ville tunnel) it was possible to find some effective designs. A relatively small constant-area hood can reduce the pressure gradient to less than 50% (Figure 8). The high accuracy of the CFD-calculations and the model tests is good enough to reproduce even 3D-effects for the layout of more advanced solutions.

Pressure transfer into the vehicle was simulated numerically and validated using the measured pressure field. It was possible to eliminate differences between measurement and computation by simulating the volume change in the train due to the "compressibility" effect of the flexible vehicle body structure under the unsteady pressure load. This leads to valuable indications for the necessary stiffness of the vehicle body construction to avoid comfort limitations inside the coach.

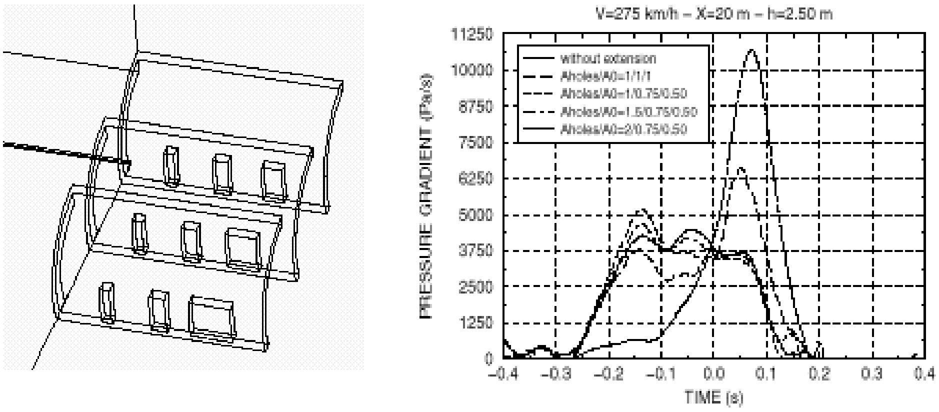

Figure 8: Study of portal extensions with 3 different window types and their effect on the gradient of the entry wave, which can be halved with an optimised extension [17]

Confirmation of the link between the **wake flow and the tail coach oscillations** has been provided by Japanese measurements on the STAR21 experimental train at speeds of up to 315 km/h, showing that these lateral oscillations are several Hertz as a peak value [7, 8]. This frequency with its related amplitude causes discomfort to passengers on the train because of its "nausea" discomfort effect. The lateral oscillations in a tunnel were found to be 10 times higher than in the open air because of the asymmetric flow expansion at the tail.

The Japanese RTRI presented an initial CFD study of the train wake in 1995 where they suggested an improved tail shape, which is blunter than the original head geometry, for a drastic reducion of the oscillations in tunnels [21]. The suggested tail shape reduces the lateral oscillations in the tunnel to a value only 2 times higher compared to the value for open air conditions.

These Japanese investigations were related to the Shinkansen high-speed train family, and the results and suggestions therefore cannot be transferred to the technology of European high-speed trains such as the ETR, ICE, TGV without re-examination.

Therefore the Brite/Euram-project RAPIDE (Railway Aerodynamics of Passing and Interaction with Dynamic Effects) was launched in 1998, consisting of DB, FS, SNCF, the railway manufacturer ADtranz and several other partners from academic institutions. Within this project beside the aerodynamic examinations, the bogie dynamics of the train were to be investigated in parallel as this problem of the aerodynamic/dynamic coupling is really crucial for modern railways with respect to sustained passenger comfort [16, 18].

Generally, all the subjects described above were investigated with numerical methods as well as with model simulation techniques. Full-scale tests formed the data base for the validation of the simulative tools. In all cases, the air flow around the German ICE2 train was investigated. To obtain consistent data sets the geometry of the train had to be simplified for the CFD and the model-scale tests. This geometry was used for all investigations.

Two different modelling techniques were used in the model-scale tests. One was the "standard" wind tunnel experiment with scale 1:15 and 1:7 models (MIRA); the other used the moving model rig of AEAT Rail, which is capable of firing a 1:25 scale model of a train at speeds of 280km/h over a 150m long test track. This setup was already used in the TRANSAERO tests and has now been further improved.

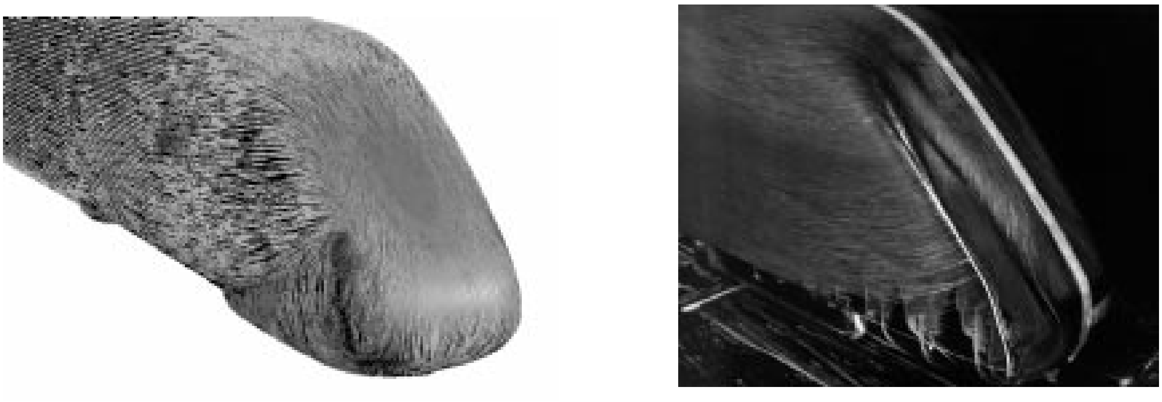

Figure 9: Wall flow pattern on the surface of the trailing vehicle (CFD-calculation 1:1 and model scale 1:7)

The latter experiment was also used for the investigation of train-passing effects governing slip stream and wake flows. The pressures on structures and other trains were recorded.

The slipstream around the whole ICE2 train was calculated by means of CFD. Here the work was shared between the partners in the calculation of the leading vehicle, the boundary layer development along the intermediate coaches and the unsteady wake flow around the trailing vehicle. Commercial RANS-CFD-codes were used for this purpose. Figure 9 shows a comparison of the skin friction lines of the trailing vehicle between the simulation and the wind tunnel test [6].

For the validation of the results an extensive series of full-scale tests was carried out. The boundary layer development around the ICE2 train was measured with LDA and a rake of multi-pressure-probes at several positions along the train.

The reactions of movable objects, tools, test dummies and test cylinders on the passing of the train were investigated in the open field as well as on platforms. These experiments were supported by measurement of the dynamic slip stream and pressure field near the track and on the ground.

Passing tests of the ICE2 with a specially equipped freight train were carried out. The focus lay on the measurements of a swap-body covered with a light canvas, where heavy dynamic effects due to the rapid movement of the canvas could be expected. A conventional, covered wagon was equipped as a reference vehicle.

CONCLUSIONS

Joint research projects provide a common basis of knowledge and strongly support the harmonisation of existing national rules and guidelines for train design and operation with respect to the aerodynamic and aero-acoustic constraints.

All of the related questions simultaneously involve high-speed rolling stock, infrastructure and operating conditions, and are typical of the systemic approach that should govern most of railway operation problems. That means efficient, economically optimised solutions cannot be found on one single component of the system, but need to be studied considering the whole railway system.

As a consequence, solving these problems is compulsory to ensure the efficient interoperability of the future trans-European high-speed network.

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