AERODYNAMIC LOADING OF TRAINS PASSING THROUGH TUNNELS

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ABSTRACT

Due to an unforeseen delay in the procurement of sealed passenger rolling stock for the new HSL-Zuid line in the Netherlands, conventional HST-Prio trains will operate until the ordered rolling stock is delivered. The possible magnitude of the pressure waves in the HSL-Zuid tunnels has led to concerns over the structural integrity of the train windows and doors. In order to address these concerns, aerodynamic calculations were undertaken for three tunnels on the HSL-Zuid line, using the one-dimensional ThermoTun tunnel aerodynamics programme. Validation of these calculations was obtained through measurements undertaken in the Dordtsche Kil tunnel, when an HST-Prio train travelling at up to 160 km/h crosses a Thalys TGV train travelling at up to 300 km/h. The calculations and measurements provided reassurance to the operator (HSA) that the proposed use of the existing unsealed passenger rolling stock would not lead to any structural failures of the trains during operation.

INTRODUCTION

The new HSL-Zuid line runs from Amsterdam via Schiphol and Rotterdam to the Belgian border, with connections to the Hague and Breda (see Fig. 1). The line crosses major waterways, motorways and countryside. There are 170 structural works on the HSL-Zuid line, including cross-overs, dive-unders, sunken sections and four tunnels. The tunnels include the 1.5km long Dordtsche Kil Tunnel and the 8.6km long Groene Hart Tunnel, both comprising single-track tunnels connected by pressure relief openings and with ventilation shafts that rise to ground level.

Services on the HSL will be operated by HighSpeedAlliance (HSA), a joint venture between Netherlands Railways and KLM. Due to an unforeseen delay in the procurement of sealed high speed TSI passenger rolling stock, the operator was obliged to put conventional unsealed rolling stock (HST-Prio) into service on the HSL-Zuid line. This stock consists of luxury passenger coaches hauled by TRAXX locomotives. The existing high-speed Thalys TGV rolling stock will be operating concurrently along the same rail lines, with a top speed of up to 300 km/h. Aerodynamic loads and pressure waves within the HSL-Zuid tunnels caused by passing TGV's were researched in order to determine the operational boundaries for unsealed trains and TGV's for temporary operation on the HSL-Zuid line.

Three different tunnels have been selected for analysis:

- Ringvaart Aquaduct: a short 100m cut-and cover dive-under crossing a waterway, comprising a single dual-track tunnel bore.
- Dordtsche Kil Tunnel: a 1.5km immersed tube tunnel crossing a waterway. The tunnel has separated tunnel bores, connected by pressure relief openings and six ventilation shafts per tunnel bore.
- Groene Hart Tunnel: an 8.6km bored tunnel, passing under scenic countryside. The tunnel consists of a single 15m diameter tunnel bore with the tracks separated by a wall. The approach to the bored section is by cut-and-cover tunnel with perforated roof. The two track sections are connected by pressure relief openings. Ventilation shafts in the bored tunnel section provide escape routes to ground level.

Fig.1: Overview of HSL-Zuid Line

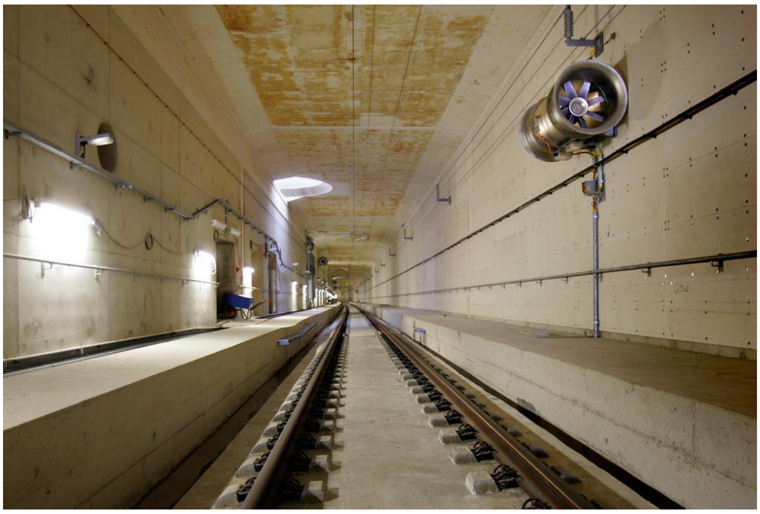

Fig.2: View of Dordtsche Kil Tunnel

CALCULATIONS

In order to provide initial estimates of the magnitude of the pressure forces on the train windows and doors, aerodynamics calculations were undertaken for the Aquaduct Ringvaart, Dordtsche Kil and Groene Hart tunnels. The software employed to undertake the calculations was ThermoTun, developed by Professor Alan Vardy of Dundee University, UK. ThermoTun employs the one-dimensional Method of Characteristics to model tunnel networks, and allows train traffic to be specified. The programme has been extensively validated against experimental data for several rail tunnel projects, including London Transport's Victoria Line, the Mühlberg and Einmalberg tunnels in Germany, and the Grauholz Tunnel in Switzerland. In all of the above cases, it was found that a high degree of accuracy for the maximum pressure transients was obtained if the appropriate tunnel and train parameters were entered into the programme.

General Modelling Assumptions

Modelling assumptions and parameter estimations are crucial to the accuracy of the ThermoTun model. Although they have been carefully chosen during the construction of the model using known values and experience, verification of simulations through experimental data ensure that they are realistic. Modelling parameters of particular importance include geometric and aerodynamic losses due to the tunnel system, geometric and aerodynamic losses due to the trains and the behaviour of the train traffic. The following sections give an overview of these.

Tunnel, shaft and train geometric and aerodynamic losses

Interactions between tunnel sections require a mathematical description, so that realistic flow behaviours across them can be calculated. In order to model such flow behaviours, non-dimensional aerodynamic loss factors are defined across each type of boundary for air flow in either direction. These loss factors or 'K-factors' are defined as the "non-dimensional difference in total pressure" across a boundary or along a system component:

$$K_i = \frac{\Delta P_t}{\frac{1}{2}\rho U_i^2}$$

Entry losses to a system component are called K_{IN} and exit losses are referred to as K_{OUT}. The K-factor losses can be referred to as geometric losses as they depend primarily on the shape and size of tunnel section or orifice.

K-factors are inserted into the Bernoulli equation in ThermoTun where the sum 'B' is assumed to be equal in all tunnels except for local losses, Vardy (2001). This allows pressure loss calculations to be performed across boundaries. The equation used by ThermoTun is as thus:

$$\frac{2}{\gamma - 1} c_i^{\ 2} + (1 + K_i) U_i^{\ 2} = B$$

Where: γ = principal specific heat capacities of air, c = local speed of sound, U = mean air velocity. General K_{IN} and K_{OUT} factors are defined in Table 1 for the various boundary types found within the HSL-Zuid tunnel systems.

LOSSES			K_{IN}	K_{OUT}
Tunnel	to	Tunnel	0	0
Tunnel	to	Cross-passage	0.75	1
Tunnel	to	Vent shaft	0.75	1
Tunnel	to	Atmosphere	0.6	1
Shaft	to	Atmosphere	0.6	1

Table 1 - Loss Coefficients for Tunnel Boundaries

All K-factor values have been assessed by referring to the geometric data found on the as-built drawings and with reference to known values available in textbooks, such as Miller (1990). Aerodynamic losses account for losses including form drag and skin friction losses when trains travel through a tunnel. The train form drag is described by the train nose and tail loss coefficients, and is calculated by reference to the train and tunnel geometric parameters including the perimeters and cross-sectional areas. Skin friction losses for the tunnel sections and trains are accounted for by defining a skin friction coefficient, which is based on an average surface roughness and the non-dimensional Reynolds number. In tunnel applications, the Reynolds number is assumed to be of magnitude $Re=10^6$.

Train geometry and aerodynamic characteristics

The train geometry and aerodynamic characteristics are the same for all three HSL-Zuid tunnels investigated. The trains involved are the HST-Prio and the faster Thalys-TGV train.

To effectively describe train characteristics each ThermoTun train model is composed of a locomotive wagon and a passenger wagon, to account for varying parameters along the length of the train. Table 2 describes the geometry and assumed aerodynamic characteristics of the wagons used to compose the train models in ThermoTun.

WAGON DATA						
Wagon Ref	Length (m)	Cross-section Area (m^2)	Perimeter (m)	Skin Friction Factor	Nose Loss Coefficient	Tail Loss Coefficient
TGV Loco	20	10.29	12.1	0.0035	0	1
TGV Coach	160	8.55	11	0.0035	0.2	1
TRAXX Loco	20	11.4	12.8	0.0055	0.2	1
ICRm Coach	375	9.45	13	0.0055	0.2	1

Table 2 - Wagon Data for TGV and HST-Prio Trains

The TGV train comprises one TGV Loco wagon at the front, eight TGV coach wagons and a TGV locomotive wagon at the rear. The HST-Prio train comprises one TRAXX Loco and seven ICRm coaches. The coaches are modelled as a single wagon to economise on calculation time.

Fig 3: HST-Prio and Thalys PBKA TGV trains

Train traffic

The aerodynamic calculations investigated pressure variations on the HST-Prio train when the Thalys-TGV and the HST-Prio trains are travelling in opposing directions. 5 different speed combinations or sets were investigated, as shown in Table 3.

TRAIN SPEED COMBINATIONS		
Run Number	TGV Speed (km/h)	HST-Prio Speed (km/h)
1	300	220
2	300	160
3	250	160
4	200	160
5	160	160

Table 3 - TGV and HST-Prio Speed Sets

It should be noted that 'Run Number 1' with the TGV at 300km/h and the HST-Prio at 220km/h is for reference purposes only. The maximum operational speed combination of the two train types is 'Run Number 2' with the TGV at 300km/h and the HST-Prio at 160km/h.

The trains cross at different points within the tunnel complex, depending on the time they enter the tunnel bore and the speed they are travelling at. Different crossing points are simulated within ThermoTun and the static pressure experienced by the HST-Prio train is recorded at locations illustrated in Fig. 4.

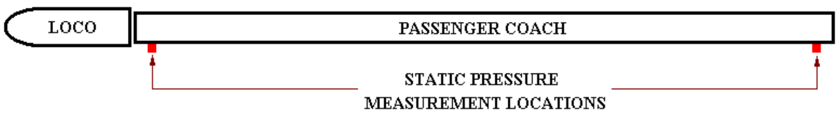

Fig. 4 - Static Pressure Calculation Locations on HST-Prio

Calculation Results and Interpretation

The calculations for the Dordtsche Kil Tunnel will serve to illustrate the results obtained from ThermoTun. The Dordtsche Kil tunnel complex comprises two single track tunnel bores connected by multiple $0.38m^2$ openings at high level. Pressure relief shafts of 9 m^2 cross-sectional area were located at six positions along each tunnel bore, to reflect the as-built drawings. Fig. 5 illustrates a typical example of the pressure results obtained from ThermoTun for the train speed combinations described in Table 3, applied to the Dordtsche Kil Tunnel. The peak suction pressure calculated for the Dordtsche Kil Tunnel was -2kPa, when a TGV crosses an HST-Prio train approximately 1 km away from the east portal.

From independent laboratory tests, it is known that the windows on the HST-Prio trains will most likely fail in fatigue mode after 300,000 pressure cycles when subjected to a cyclical pressure differential of alternating +/-1.9kPa. Although the ThermoTun calculations related to the external pressures on the coaches rather than the pressure differences between the coach interiors and the external tunnel environment, it was decided that a programme of testing was required to validate the ThermoTun calculations and to resolve the issue of whether any structural integrity problems were likely to occur during operation of the HST-Prio trains within the HSL-Zuid line.

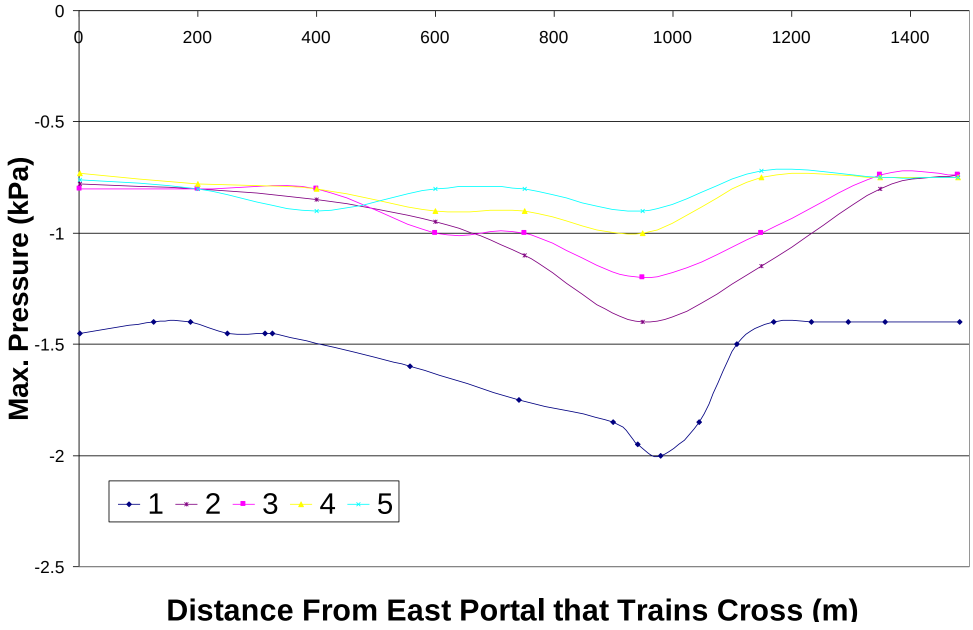

Fig. 5 - Static Pressure variations for crossing positions in Dordsche Kil Tunnel (at rear of coach)

EXPERIMENTAL MEASUREMENTS

Measurements were performed on a HST-Prio configuration. The HST-Prio consisted of a TRAXX locomotive, six ICRm coaches and one Lloyd's Register testing carriage. The TRAXX was supplied by SBB because of the 25kV energy supply requirement on the HSL-Zuid. The oncoming train consisted of one train set consisting of a Thalys PBKA TGV.

Due to engineering work in progress on several locations of the HSL-line, and the track length required for acceleration and braking to 300 km/h, the measurements were undertaken in the Dordtsche Kil Tunnel. The track available for measurement was between the 25kV/1.5kV separation point at Rotterdam Kijfhoek (chainage km 13) and Hazeldonk at the Belgian border (chainage km 53.3). The available track south of the tunnel was sufficient for the TGV to accelerate to 300km/h before entering the tunnel.

In order to maximize test time within the availability of the infrastructure, the passenger coaches and TRAXX locomotive were equipped with the required measurement equipment in advance of the tests. A video and communication link was established between the locomotive and the rear end for communication between the driver and the pilot. This enabled safe reversing at higher speeds, reducing cycle times.

Measurements were undertaken during train crossings on the open track and within the Dordtsche Kil Tunnel, at TGV speeds increasing to 300km/h. The HST-Prio train had a fixed maximum speed of 160km/h.

Measurement Set-Up

The set-up and operation of the measurement equipment was designed to satisfy the requirements of BS EN 14067-4:2005 and BS EN 14067-5:2006 for a ±1% accuracy of the peak-to-peak pressure reading, nominally stated by BS EN 14067-5:2006 as 4 kPa. In order to achieve the required accuracy, the following steps were undertaken:

- The pressure data sampling rate was set at 100 Hz. This follows the recommendations of BS EN 14067-5:2006 for a sampling rate of at least 5 v_{tr}/LN, where v_{tr}=train speed, and L_N=length of the train 'nose'. The selected pressure sensor had a response time of 1 millisecond, and was therefore capable of delivering the required sampling rate.
- The pressure tubing was tightly connected at all terminations, to avoid air leakage.
- The pressure tapping was set flush to the false windows (see Fig. 6), and designed to be as small as realistically possible (3 mm internal diameter), in order to reduce the effects of any dynamic pressure. Through tests on the open track, it was confirmed that the dynamic pressures are limited to just a few Pascals (typically less than 5 Pa).
- The external static pressure was measured relative to the interior coach pressure. The interior pressure was measured using a sealed reservoir as a reference.

Fig. 6: Measurement set-up with false window

Three ICRm coaches were instrumented with static pressure sensors – the first, fourth and seventh coaches behind the locomotive. Fig.7 shows the instrumentation locations for the seventh coach.

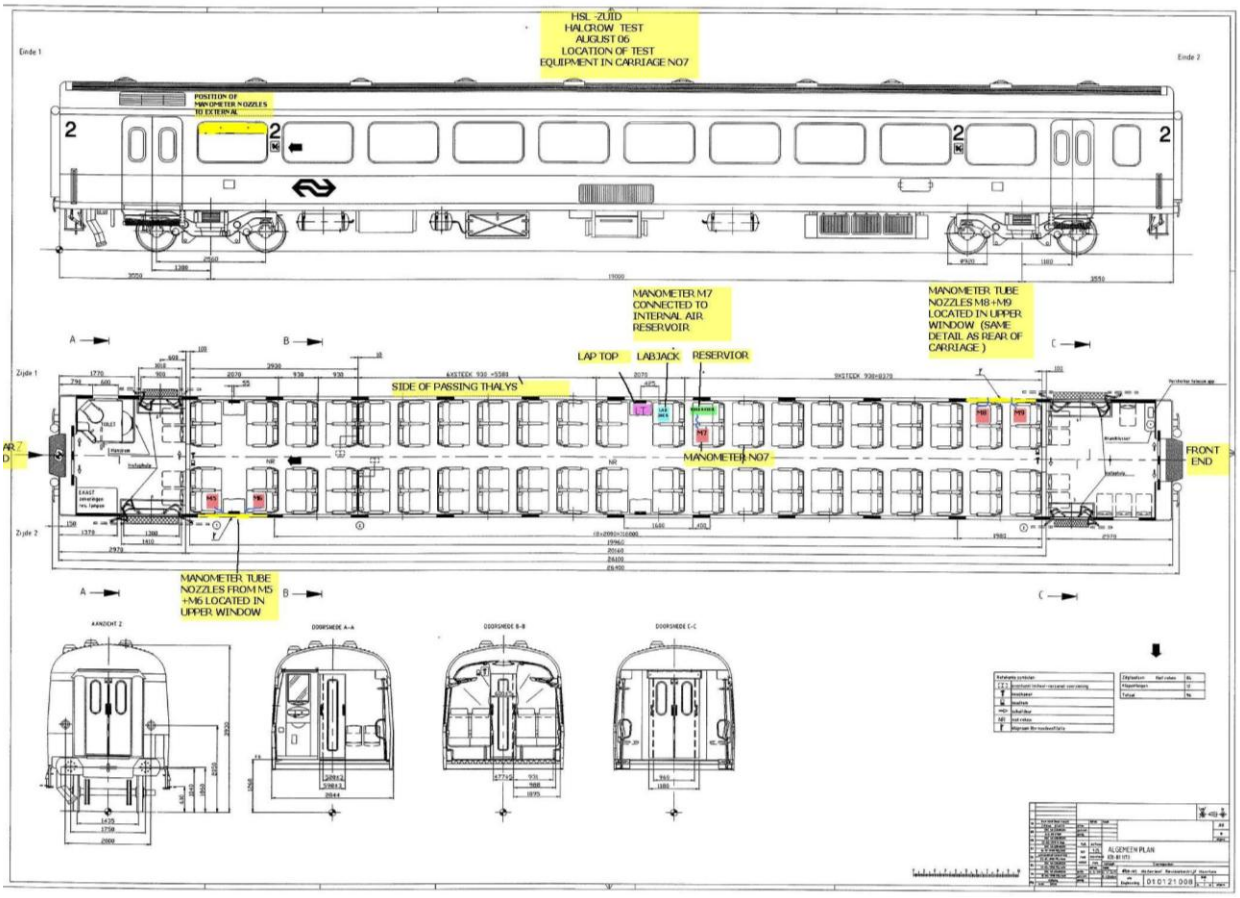

Fig.7: Instrumentation Locations for ICRm Coach 7

Crossings were arranged to occur in the middle of the tunnel. In order to facilitate this, the acceleration rates of both the TGV and HST-Prio were measured using GPS systems. The measured accelerations rates allowed two starting locations to be calculated - one for speeds up to 200 km/h and one for 250km/h and faster. To ensure crossings in the middle of the tunnel, specific time delays between start of the TGV and the HST-Prio movements had to be taken into account due to the different accelerations and distances.

The actual locations of the actual train crossings had to be accurately estimated, since this significantly affected the magnitude of the pressure pulses in the tunnel. For open track measurements, the location was registered by GPS fitted in both trains. However, GPS signals cannot penetrate through tunnels. Due to limited availability of the infrastructure and TGV in preparation for the tests, train speeds through the tunnels were kept as constant as possible through the deployment of cruise control in both trains. A measurement accuracy of ±2 km/h was estimated for the in-tunnel train speed measurements. The accuracy of the train speeds regulated by cruise control was verified by the GPS-readings made during the measurements on the open track. By measuring the entry and exit times of the trains, it was possible to estimate the location of the crossings within the tunnel.

After each run, the trains reversed to the starting location. During this process, the measurement data and crossing location were evaluated in order to determine whether an increase in the train speeds was admissible from a safety perspective.

Measurement Results

Fig. 8 indicates the measured and calculated pressure fluctuations outside coach 7, for the case of an HST-Prio train travelling at 160 km/h crossing a TGV train travelling at 300 km/h within the Dordtsche Kil tunnel. Considering the uncertainties in the measurements of train speeds and crossing location, there is a good agreement between the measurements and calculations. The pressure differences between the outside and inside of the coaches were measured to be less than 0.6 kPa in every instance, due to leakage across the coach body. The measurements therefore indicated that the mechanical integrity of the trains doors and windows on ICRm coaches will not be compromised due to repeated journeys through the HSL-Zuid line.

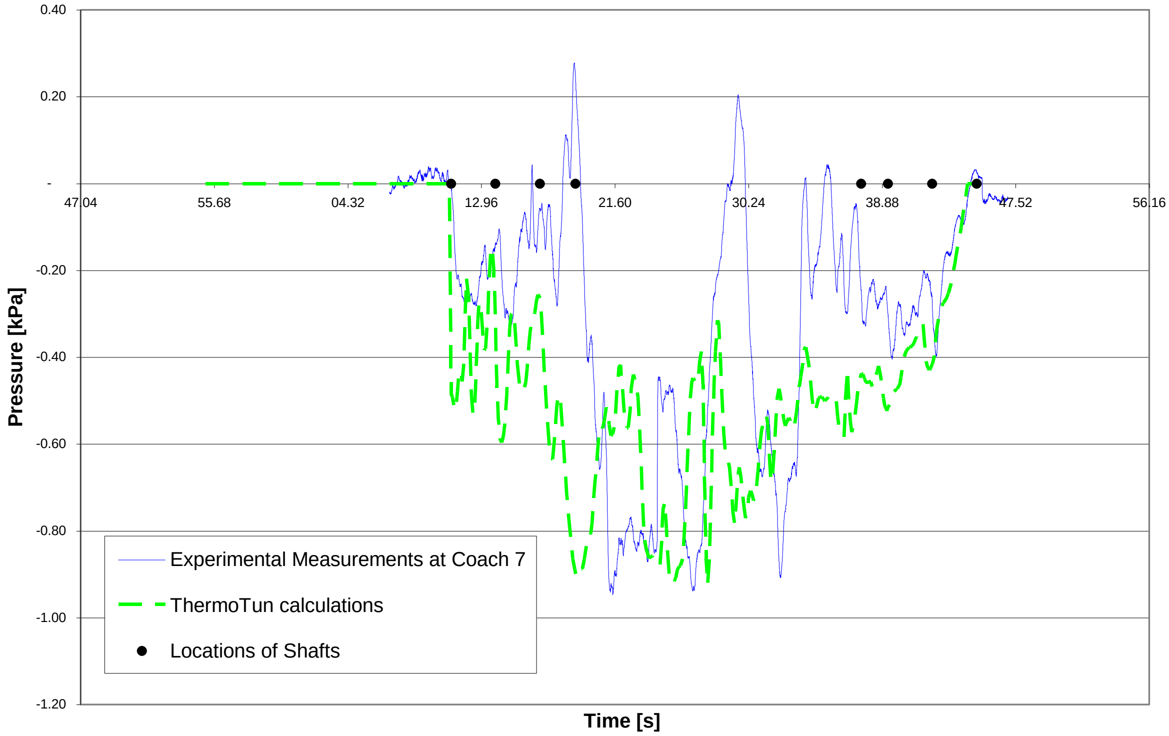

Fig. 8: Experimental and calculated pressure fluctuations outside coach 7

CONCLUSIONS

A series of calculations and measurements were undertaken in order to verify the mechanical integrity of doors and windows on commuter HST-Prio trains that are planned to travel through the new HSL-Zuid line in the Netherlands. The measurements confirmed that the in-tunnel pressure loadings were likely to be significantly below the relevant fatigue limits, and this provided the necessary reassurance for HSA to put the HST-Prio trains into service through the HSL-Zuid line.

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