High Speed Rail Tunnel Aerodynamics: Transient pressure and loadings on fixed tunnel equipment

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Summary: Trains entering tunnels at high speeds can generate highly transient air velocity and pressure fields inside the tunnel, from time of entry until well after they leave the tunnel. The parameters affecting the induced velocity and pressure fields include train speed, train to tunnel blockage ratio, train to tunnel length ratio, shape of train nose and tail, and the number, spacing intervals and area of pressure relief shafts. Compression waves induced by the train nose and tail propagate along the tunnel at the speed of sound, and compress and accelerate air in front of it, until they reach the exit portal. These will then reflect as refraction waves, interact with other travelling waves and set up complex wave patterns and airflows. Some of the rapid pressure changes can create aural discomfort for passengers. The designer has to ensure that the cross sectional area of the tunnel is large enough so as not to exceed these maximum pressure thresholds. In cases where the required tunnel cross section cannot be met, other engineering solutions like the provision of pressure relief shafts are considered. Apart from provision of pressure relief, a separate mechanical ventilation system is needed to provide a safe environment during an emergency fire incident, as well as a comfort for passengers in a train congestion scenario. While large axial fans in supply and extract configuration have been the traditional solution, other approaches are possible like Saccardo nozzles and jet fans, as used in the Channel Tunnel Rail Link (HS1). Thus the issue of transient forces and moments on installed equipment such as fans, signs, brackets and panels in high-speed tunnels are discussed, drawing on the experience of HS1.
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Index Terms: high speed rail tunnel aerodynamics, transient pressure, transient loads on fixed equipment

1. BACKGROUND

When a train passes through a tunnel it induces pressure waves which travel up and down the tunnel at the speed of sound, passing over any trains in the tunnel and causing the pressure inside the trains to fluctuate. These variations in pressure are experienced by passengers and can manifest themselves as discomfort in the inner ear.

If the train is sealed, the pressure inside the train will be different from the pressure outside the train. The inside pressures are used to assess comfort criteria, while the outside pressures are used for the TSI criteria (Technical Standard for Interoperability – limit 10kPa), mandated in Europe.

These pressure fields need to be predicted by designers, to allow for adequate pressure relief during normal train operations, under a variety of train speeds. The impact of rapidly changing pressure and velocity fields on fixed equipment and the resulting forces and moments have to be assessed, to ensure safe operation of the railway. These loads have to be considered both from a fatigue point of view, as well as a peak maximum magnitude.

The aim of this paper is twofold; first it presents the results of a methodology of sizing high-speed tunnels for a range of train and tunnel configurations, and to discuss the impacts on rail infrastructure planning, as far as rail tunnels are concerned. In addition, it shares the experience gained during design to predict transient loads (forces and moments) on tunnel fixed equipment in an existing high-speed single-track tunnel.

2. PRESSURE SIMULATIONS

2.1 Computer simulation code:

Arup developed TunX as a one-dimensional finite difference code for predicting pressure transients for a variety of trains and tunnel configurations.

The formation and propagation of these waves are unsteady thermodynamic processes which can be described by equations representing Newton's Second Law, the conservation of mass and momentum and isentropic flow.

TunX solves these equations numerically in a time-stepping manner. The tunnel network (including vent shafts and cross passages) is first divided into a number of elements of equal length through which air and trains can pass. Losses at portals, vent shafts, noses and tails of trains etc. are represented by pressure loss coefficients. For sealed trains, further elements inside the train connect to the air outside the train via "holes" with a user-specified time-constant representing the efficacy of sealing.

To find the optimum tunnel area to pass a given pressure comfort criterion, a purpose-written optimiser known as MultiTunX performs multiple runs of TunX automatically. The tunnel area is treated as a design variable to be optimised. The automatic process can be extended to be applied to, for example, a list of tunnel lengths or train speeds. For two trains running in opposite directions through a 2-track tunnel, simultaneous entry of the trains is not necessarily the worst case. MultiTunX tries a range of time-offsets and finds the optimum tunnel area that passes the comfort criteria for all time-offsets.

2.2 Code validation

Tunx has been validated against predictions and measured data and predictions, and against measurements carried out by Arup in a UK tunnel during 2001.

Figure 1 presents examples of measured and predicted traces of pressure transients at 80m from the south portal for a Class 91 train entering a tunnel at a speed of 104 mph (167 kph).

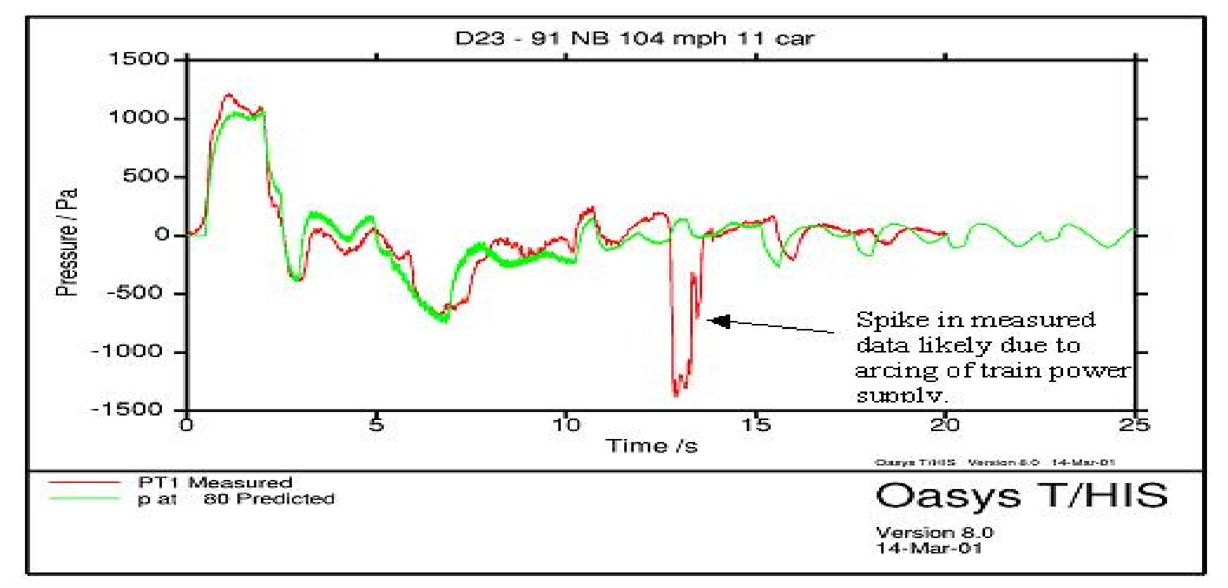

Figure 1: Measured versus predicted pressure transients

2.3 Scenarios

The scenarios modeled assumes a 200 m long streamlined high speed train, with a cross sectional area of $11m^2$ sealed with time-constant 10sec, entering a tunnel at a speed of 350 kph. The sample tunnel length is 1.6km, and the pressure criteria to comply with are both:

- TSI (<10kPa pressure change in whole event)
- UIC 2005 baseline pressure comfort criteria (1kPa/1sec, 1.6kPa/4sec, 2kPa/10sec)

The objective is to optimise the tunnel cross-sectional area to meet comfort criterion exactly, with and without pressure relief shafts.

The set of simulations begin with a single train entering a single track tunnel, and then continues to the case of two trains entering a two-track tunnel in opposite directions at different time intervals.

2.4 Single track tunnels

2.4.1 Pressure transients

The first set of simulations focus on a single train entering the tunnel, and the cross-sectional area is optimised to meet comfort criterion exactly, without pressure relief shafts. The simulation is then run again with one or more pressure relief shafts. Figure 2 illustrates the range of positive and negative pressures induced with and without the pressure relief shaft.

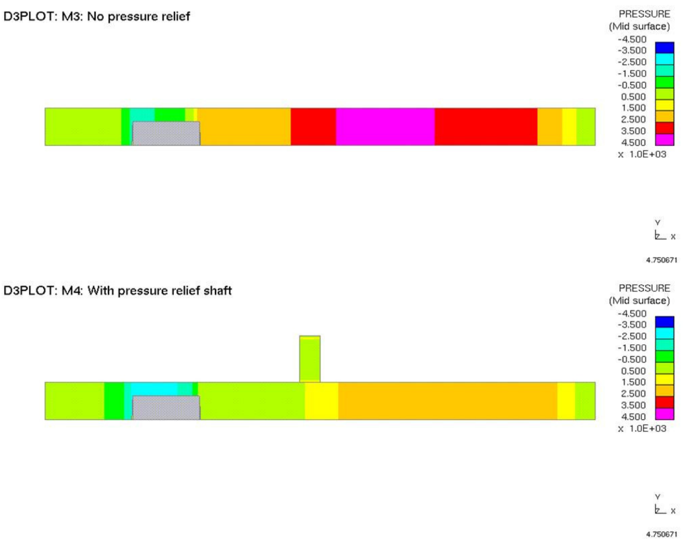

Figure 2: Still image of pressure waves from a single train – with and without a relief shaft

Note that the height of tunnel, train, and dimensions of shaft are exaggerated in these plots for clarity.

The addition of a pressure relief shaft breaks up the pressure waves; the changes of pressure become smaller but more numerous. Figure 3 illustrates pressure at a point near the rear of the train, outside the train's sealing system, with and without pressure relief shaft.

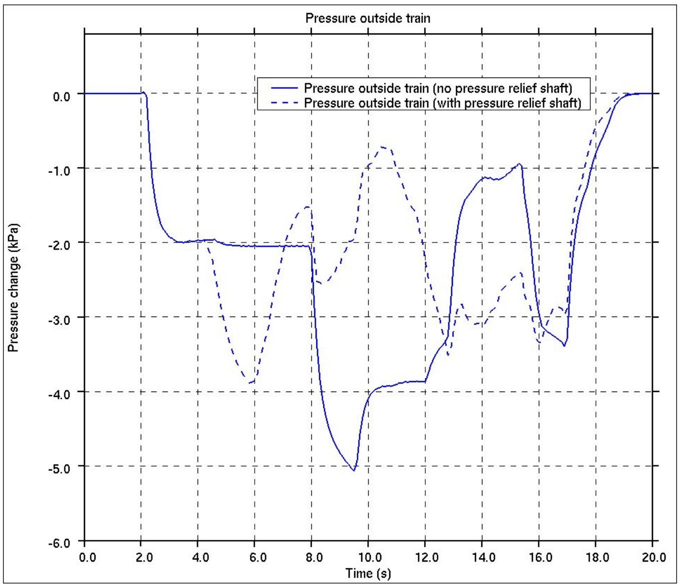

Figure 3: Pressure variations with time outside the train, with and without a relief shaft

To assess the effect on aural comfort, consider the pressure inside the sealed train.

Without pressure relief shafts, the comfort criterion 2kPa / 10sec is met exactly. This is shown in Figure 4, whereas with a pressure relief shaft, the maximum pressure change in 10 sec is reduced to 1.3kPa (36% reduction). This illustrates the positive impact of a pressure relief shaft on the rate of pressure change, to which the human ear is most sensitive.

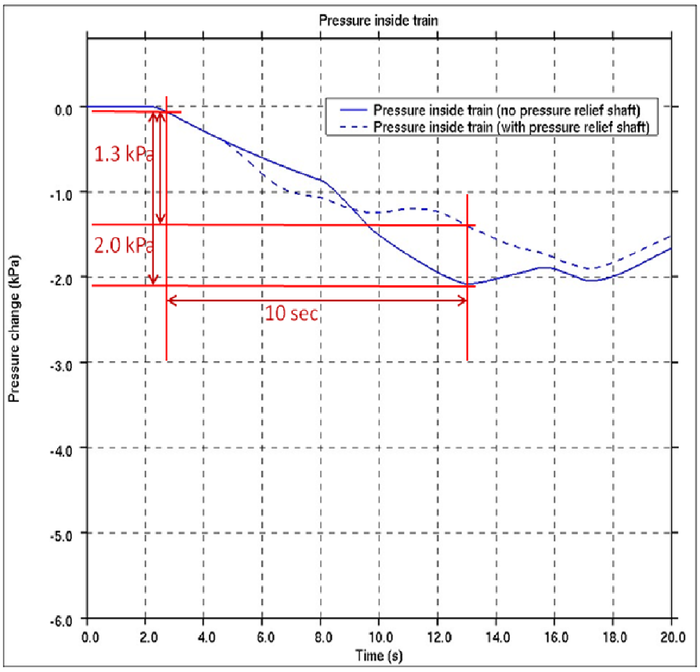

Figure 4: Pressure variations with time inside a single train with and without a relief shaft

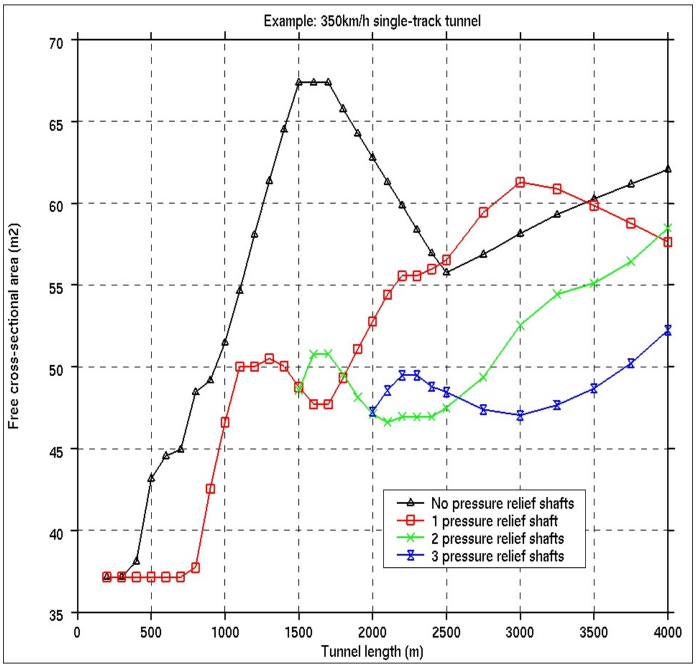

Figure 5: The impact of pressure relief shafts on the optimum cross sectional area of a tunnel – single train @ 350 kph

2.4.2 Tunnel area optimization

This section shows the result of optimising the tunnel area to meet the comfort criteria (and also ensure that the TSI is met), for different tunnel lengths and different numbers of pressure relief shafts.

The pressure relief shafts are positioned in each case such that the tunnel is divided into equal lengths. Each point on the graph is the result of a set of optimisation calculations. The optimisation calculations are performed and repeated automatically for different tunnel lengths.

In this particular exercise, for different tunnel lengths, the impact of one, two or three pressure relief shafts are assessed for a given single train passing at a speed of 350 kph. Figure 5 shows that in the example modelled, a 1.6 km tunnel needs a cross-sectional area 67.5 m^2 without relief shafts, or 47.5 m^2 with one relief shaft, to meet the comfort criteria. The fluctuations of required tunnel area observed are a result of wave harmonics and are a function of tunnel to train length ratio.

Alternatively the effect of train speed on the free cross sectional area of a single track tunnel can be studied. This is of particular interest to train operators who wish to reduce journey times, and therefore wish to raise the line speed of their train operations on long distance services

Figure 6 illustrates the increase in tunnel cross section needed to accommodate higher train speeds, without causing aural discomfort. For example a 3 km tunnel with a 48 m^2 free cross sectional area and one relief shaft can accommodate a 300 kph train speed, but would need to be enlarged to 75 m^2 to provide the minimum required passenger aural comfort for a 400 kph train service. This kind of information is extremely valuable at the initial stages of rail infrastructure planning when tunnels are being designed and built, as later changes and enlargements to tunnel structure will not be feasible.

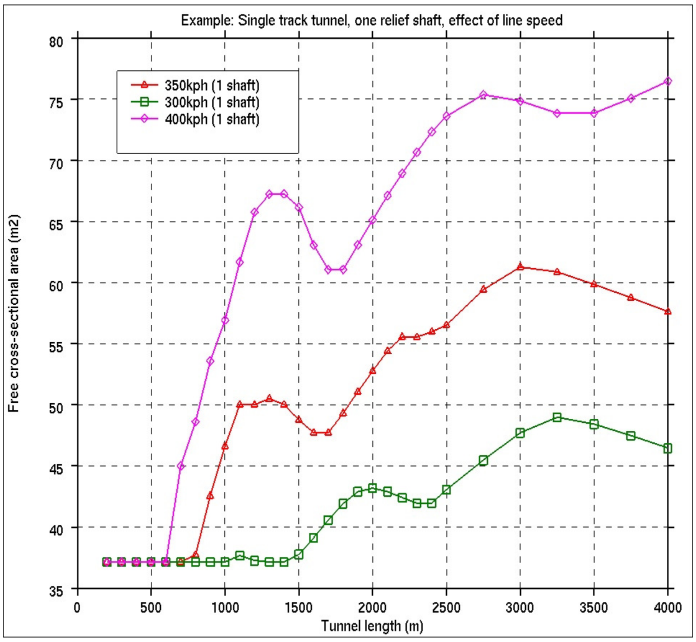

Figure 6: The impact of train speed on the optimum cross sectional area of a single-track tunnel

2.5 Two-track tunnels

2.5.1 Pressure transients

The pressure transient simulations are repeated for a two-track tunnel with and without pressure relief shafts for trains entering the tunnel in opposite directions at different time intervals.

2.5.2 Tunnel area optimization

The same tunnel sizing exercise is repeated for various lengths of a two-track tunnel with one pressure relief shaft at two train speeds.

The code optimizes the tunnel size to cope with any combination of train entry-times; so for each tunnel length, about 30 different cases are checked to find a tunnel size that fulfils the aural comfort criteria for all those combinations. In total, each line on the graph takes over 1000 separate analyses, all done automatically.

Figure 7 shows the impact of train speed on free cross sectional area required to comply with the passenger aural comfort criteria. It can be seen that operating trains in double track tunnels will require a 30-40% larger area for a 400 kph train speed, compared to 350 kph. In many infrastructure projects, this can be a large price to pay for reduced journey times, and a cost-benefit analysis becomes mandatory in the initial infrastructure planning stages.

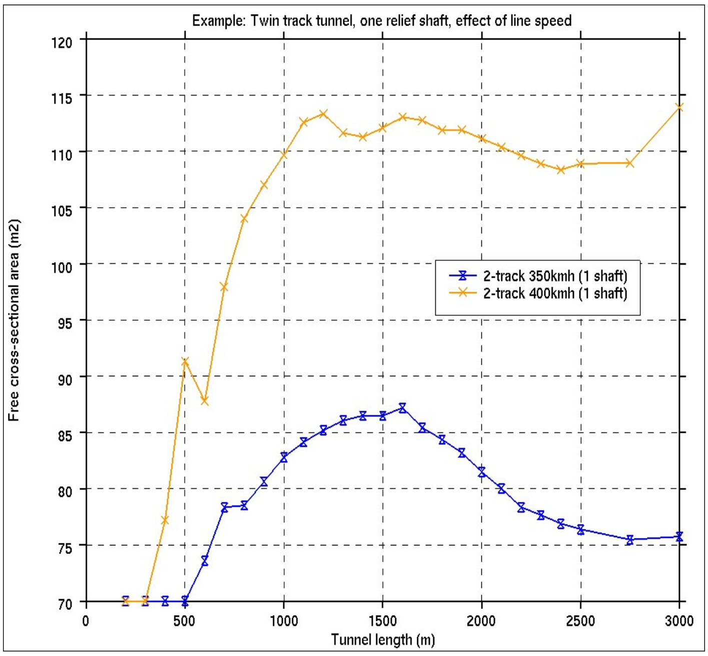

Figure 7: The impact of train speed on the optimum cross sectional area of a two-track tunnel

3. TRANSIENT LOADS ON EQUIPMENT

3.1 HS1 tunnel

In this section, transient forces and moments on fixed tunnel equipment such as signs, cables, way-side boxes in a typical high-speed single-track rail tunnel is presented. While the study focuses on tunnels on the Channel Tunnel Rail Link (HS1) route (Dover to London), general conclusions can be extended to other high-speed rail tunnels.

The pressure wave associated with the train nose has a strong peak generating a highly transient longitudinal and lateral velocity field in the tunnel. This *velocity* (as distinct from the pressure wave) impacts the electrical and mechanical equipment and systems installed on the tunnel walls and ceilings jet fans, signal boards, cable trays, fire pipes, leaky feeders, cross passage doors, etc, as seen in Figure 8.

Every time a train enters and passes through the tunnel, there are five distinct stages of flow development leading to a time-varying velocity and pressure field, as viewed by a piece of equipment fixed to the tunnel walls at any position along the tunnel:

1) Longitudinal piston effect plug flow in front of the approaching train
2) Short duration load as the train nose arrives
3) Longer duration longitudinal flow in the train/tunnel annulus as the body of the train passes the fixed equipment
4) Short duration load as the train tail end passes
5) Longitudinal piston effect plug flow in the trail of the departing train (same as 1)

The flow conditions for stages 1 and 5 are similar due to flow continuity requirements; hence the loads on the fixed equipment will also be similar, so only one needs to be considered. Stages 2 and 4 generate a short velocity and pressure wave pulse, but the loads due to the passage of train tail end are in the reverse direction and smaller in magnitude compared to the loads during the passage of train nose. Hence stage 4 loads will not be considered any further, as stage 2 loads, when reversed in direction, adequately cover them.

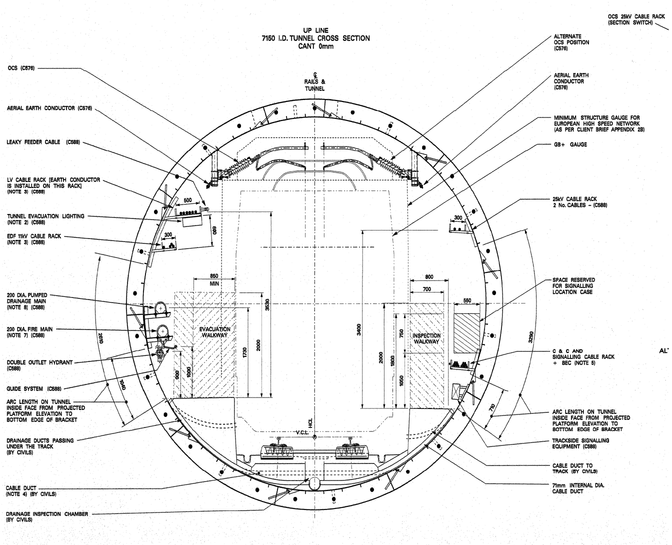

Figure 8: HS1 tunnel section (courtesy of RLE)

Furthermore the complexity of the case may be reduced by making the artificial assumption that there is an infinite resistance ahead of the train and thus there will be no piston effect flow at all, leading to 100% flow reversal over the train. While this is a very conservative approach, it eliminates the loads in stages 1 and 5 above, but accentuates the loads in stage 3. Since the flow in stage 3 represents higher air velocities anyway, with higher drag and skin friction forces, this conservative approach is recommended.

Therefore among the various stages of flow development, stages 2 and 3 are expected to contain the highest longitudinal, transverse and vertical forces and moments exerted on the tunnel fixed equipment. Hence only stages 2 and 3 flow scenarios need to be investigated in depth in order to estimate the maximum loading encountered and inform the design of the mounting brackets.

Note that the pressure wave (as distinct from the air velocity) travelling with the train nose does not normally affect equipment that has a short length in the direction of tunnel axis and is fully submerged in tunnel air, as the overall pressure force is zero; it only affects equipment partially exposed to the tunnel air (experiences an unbalanced short pulse transverse force, like a poster attached to the wall) or equipment which has a significant finite dimension in the direction of tunnel length and end surfaces (experiences different points of the pressure wave at any one time and hence an unbalanced short pulse longitudinal force).

Table 1 and 2 present the basic HS1 train and tunnel data, as well as the tunnel fixed equipment.

Table 1 – Tunnel and Train Basic Data

Parameter	Value
Tunnel int. diameter –single track	7150 mm
Tunnel full cross sectional area	36.5 m²
Train speed in tunnel	230 kph
Train cross section area	9.5 m²
Tunnel/train annulus section area	27 m²

Table 2 – Tunnel Fixed Equipment Selected for the Aerodynamic Loading Analysis

Tunnel fixed equipment	Size (mm)
Signalling Location Case	820H x 470W x 820L
Transformer (TAD)	220H x 90W x 360L
Tunnel Marker Post	480H x 560W x 0L
Leaky Feeder Cable	32 ∅ diameter

3.2 Methodology

The aim was to estimate the maximum loads experienced by selected fixed equipment due to passing trains in a single-track tunnel. Two approaches were adopted for the derivation of aerodynamic loads and results compared:

a) An independent first-order engineering desk study (e.g, slender body theory) estimating the likely velocity fields and the resulting forces and moments on tunnel fixed equipment that accompany the movement of the high speed train in the tunnel.

b) An interpretation of the CFD results of the velocity and pressure fields and the forces and moments. The CFD graphical results (CFX5) were used for this approach, and extrapolated to selected equipment with different dimensions, as shown in Table 2.

Note all forces, moments and air velocities are discussed in the x-y-z axes with z-axis along the tunnel, x-axis horizontal transverse, and y-axis vertical, as seen in Figure 9.

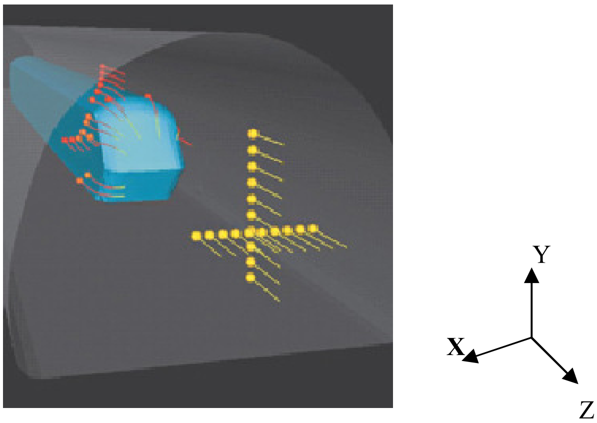

Figure 9. Frame of reference for HS1 tunnel

Of the four selected pieces of equipment, two were not directly affected by the pressure wave transients, as they are fully immersed in tunnel environment and have a short length. The leaky feeder is a continuous cable and has no end surface to be affected by pressure differential forces. The tunnel marker posts are also very short in length (in the z-direction, along the tunnel), and hence will not experience pressure differentials. So only the signalling location case and the TAD box will experience longitudinal forces due to the pressure wave of stages 2 and 4.

3.3 Results

Results of the first-order engineering desk study and CFD are shown in Tables 3 to 6, where forces and moments on all 3 axes are shown for each of the four pieces of tunnel fixed equipment.

Table 3. Forces on Fixed Equipment (desk study)

Tunnel Fixed Equipment	F_x (N) Stage 2/3	F_y (N) Stage 2/3	F_z (N) Stage 2/3
Signalling Location Case	363 / 0	229 / 0	180 / 130
TAD Box	47 / 0	19 / 0	6 / 7
Tunnel Marker Post	0 / 0	0 / 0	63 / 115
Leaky Feeder Cable	30 / 0	30 / 0	0 / 0

Table 4. Moments on Fixed Equipment (desk study)

Tunnel Fixed Equipment	M_x (Nm) Stage 2/3	M_y (Nm) Stage 2/3	M_z (Nm) Stage 2/3
Signalling Location Case	168 / 0	191 / 69	203 / 0
TAD Box	4 / 0	9 / 0.7	6 / 0
Tunnel Marker Post	15 / 28	18 / 32	0 / 0
Leaky Feeder Cable	20 / 0	20 / 0	0 / 0

Table 5. Forces on Fixed Equipment (CFD)

Tunnel Fixed Equipment	F_x (N) Stage 2/3	F_y (N) Stage 2/3	F_z (N) Stage 2/3
Signalling Location Case	129 / 25	71 / 4	95 / 149
TAD Box	16 / 3	6 / 3	2 / 8
Tunnel Marker Post	0 / 0	0 / 0	68 / 87
Leaky Feeder Cable	3 / 0	5 / 0	0.4 / 0.3

Table 6. Moments on Fixed Equipment (CFD)

Tunnel Fixed Equipment	M_x (Nm) Stage 2/3	M_y (Nm) Stage 2/3	M_z (Nm) Stage 2/3
Signalling Location Case	55 / 3	145 / 0.3	0 / 0
TAD Box	5 / 0.25	17 / 0.03	0 / 0
Tunnel Marker Post	N/A / N/A	N/A / N/A	0 / 0
Leaky Feeder Cable	22 / 0	18 / 0	0 / 0

It can be seen that the forces and moment estimates from the desk study were higher than the CFD analysis, which was expected, as conservative estimates of air velocity were made in the stage 3.

Note these forces and moments will be applied cyclically with every train passage, so a fatigue design approach (e.g. S-N curve, fatigue strength versus number of stress cycles) would be needed for the support brackets of the fixed equipment. Assuming a train schedule of 5 trains per hour, operating for 20 hrs a day, over a 25-year design life of the tunnel systems, the support brackets would experience more than a million cycles, as some of the load peaks occur more than once for each train passage. Hence the infinite life portion of the S-N curves (N above 10^6) would form the design specification for the bracket manufacturer.
It was thus recommended that the higher of the two figures quoted for the forces and moments be adopted for design to provide a margin of safety, even though some of the CFD extrapolated figures may be closer to reality.

4. CONCLUSIONS

The pressure transients induced by a high speed train entering a tunnel have a very significant impact on the free cross section of the tunnel at initial planning stages. Achieving the aural comfort of passengers is the key criterion for dimensioning tunnels and/or pressure relief shafts, for a given set of train speed, area and length. Increasing train speeds will be limited by existing tunnel size, even if the rolling stock is capable of higher speeds.

Separately, the rapidly varying velocity fields around the approaching train will impart drag forces and moments on tunnel fixed equipment along all three axes. Typical loads are shown for a single-track tunnel and have informed the fatigue design of brackets and fixtures to tunnel walls.

Acknowledgements
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