

# Calculations of sound radiation associated with 'tunnel boom' from high-speed trains

V.V. Krylov, W. Bedder

Department of Aeronautical and Automotive Engineering,  
Loughborough University,  
Loughborough, Leicestershire, LE11 3TU. UK

## Summary

This paper presents the results of the theoretical calculations of sound radiation from tunnel portals by air shock waves generated by high-speed trains travelling in underground tunnels. This phenomenon, also known as 'tunnel boom', is associated with very loud and sharp noise, similar to that of cannon shots. This noise may be very disturbing for local residents and wildlife. A simple analytical model has been developed to calculate the generated sound. The model takes into account the ground effect outside the tunnel and uses Rayleigh integral to calculate the sound pressure. The model can predict the acoustic frequency spectra and the waveforms generated at arbitrary distances and directions outside the exit tunnel portal. Numerical results have been produced for several selected tunnels in the UK located along the planned high speed railway route HS2 and identified as being capable of generating tunnel boom. Potential implications of these results are discussed, as well as possible mitigation measures.

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## 1. Introduction

When a high-speed train enters a tunnel it generates a compression wave that propagates through the length of the tunnel to the exit portal at the speed of sound [1-9]. Under some circumstances the pressure wave steepens within the tunnel, forming a pressure discontinuity within the tunnel. Part of this pressure wave is reflected internally at tunnel exit, with the emitted part creating a very strong acoustic wave, which can be audible several kilometres away [2, 7]. This phenomenon is known as 'tunnel boom'. The phenomenon of tunnel boom is unique to railway systems in which the train speeds are high enough to create a significant compression wave upon entry to the tunnel, and in which the tunnel is long enough to develop this compression wave into a pressure discontinuity. In order for the compression wave to develop into a pressure discontinuity within the tunnel, the wave must be exposed to nonlinear effects that may occur under certain conditions.

As high speed railway systems become more common, and as the speeds of the systems increase, more attention is being paid to the tunnel boom phenomenon. Use of tunnels will be wide spread in the newly planned high-speed railway system in the

UK (HS2 system). About 50% of all HS2 lines will run within tunnels or cuttings as they are essential to keep train speeds high. In addition, tunnels can be considered to have an overall noise control effect as they shield receivers from general train noise.

In this paper, the results of calculations of sound radiation associated with tunnel boom are reported. The model used for calculations takes into account the ground effect outside the tunnel by adding the contribution of the reflected field. Tunnels on the planned HS2 route are identified where tunnel boom may occur, and some numerical results are produced for several selected tunnels.

## 2. Outline of the theory

A theoretical model of tunnel boom must take into account different stages in the development of the phenomenon. The first stage is the generation of the compression wave by the train at tunnel entrance. The parameters of this wave define the second stage, which is the nonlinear evolution of the initial pressure wave during its propagation along the length of the tunnel. This evolution results in wave steepening and in formation of a shock wave (pressure discontinuity) that reaches the tunnel exit.

The third stage is sound radiation by vibrating air particles at the exit of the tunnel. This process defines acoustic waves radiated away from the tunnel portal.

## 2.1 Defining the compression wave at tunnel entrance

According to [1] (see also [7, 8]), the peak pressure of the compression wave as the train enters the tunnel can be described as follows:

$$\Delta p = \frac{1}{2} \rho_0 V^2 \frac{1 - (1 - R)^2}{(1 - V/c_0)[V/c_0 + (1 - R)^2]}. \quad (1)$$

Here  $V$  is the train speed,  $R$  is the ratio of the cross-sectional area of the train to that of the tunnel,  $\rho_0$  is the mass density of air, and  $c_0$  is sound velocity. It can be seen from (1) that the peak pressure of the initial pressure wave depends strongly on the train speed  $V$ .

## 2.2 Relating the pressure wave at tunnel exit to the acoustic radiation

After the compression wave parameters have been defined for a specific tunnel entrance and train speed using (1), the pressure discontinuity reaching the tunnel exit should be determined. This can be found using the theory of nonlinear wave propagation [8]. The specific wave profile to be used to represent the pressure discontinuity at the tunnel exit will be specified in one of the following sections. Here, an expression for air particle vibration velocity at the tunnel exit associated with the nonlinear compression wave reaching the exit will be specified first. The vibration velocity associated with the pressure discontinuity is required in order to calculate the radiation from the tunnel modelled as a vibrating piston.

To find an expression for this parameter the tunnel is modelled as a semi-infinite tube with an infinite baffle at exit [2]. The particle vibration velocity at the tunnel exit  $U$  can be expressed following [2] (see also [7]) as

$$U = \frac{f(\omega)}{\rho c_0 (1 - J_1(2ka) - iS_1(2ka))} e^{-i\omega t}. \quad (2)$$

Here  $f(\omega)$  is the frequency spectrum of the nonlinearly evolved wave form incident on the tunnel exit,  $J_1(2ka)$  is a Bessel function of the first kind, and  $S_1(2ka)$  is a Struve function,  $k$  is a

wavenumber, and  $a$  is the radius of the tube modelling the tunnel. The incident wave's frequency spectrum  $f(\omega)$  can be obtained by taking the Fourier transform of the yet to be defined wave form in the time domain,  $f(t)$ .

In the above-mentioned papers [2, 7], the tunnel portal as sound radiator has been modelled as a vibrating piston in an infinite baffle, that is to say it represents the train and track as coming out of a hole in infinite vertical wall. In the present paper, a more accurate representation of the tunnel portal is introduced that takes into account reflection of the radiated sound from a real horizontal ground by considering a mirror tunnel exit (see Figure 1), with the vibration velocity defined by the sound reflection coefficient from the ground. This secondary (mirror) tunnel portal has an associated reflection coefficient,  $R$  (taken as 0.8 for calculations in this work).

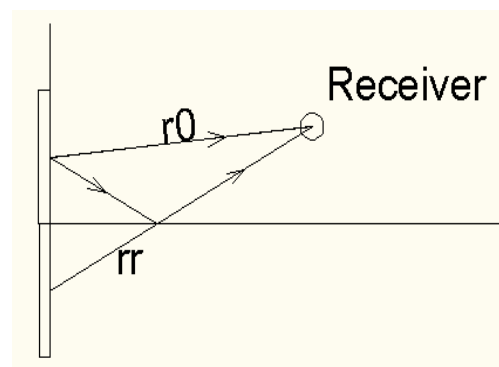


Figure 1. Using a mirror image of the tunnel exit to account for sound reflection from the ground (side view).

For simplicity, it is assumed in this paper that a tunnel exit has a rectangular shape. A frontal view of the rectangular tunnel exit and its mirror image (in green) can be seen in Figure 2, where vertical angle  $\psi$  and horizontal angle  $\theta$  define the position of a receiver in respect of the geometrical centre of the system comprising the tunnel portal and its mirror image.

Needless to say that the approach described above can be easily extended to any shape of the tunnel portal, including semi-circular or semi-elliptical ones. Also, different types of ground can be considered using appropriate values of the ground reflection coefficient  $R$ , including ideally rigid ground characterised by  $R = 1$ .

Application of the Rayleigh integral to the combination of the two vibrating pistons with

particle vibration velocities shown in Figures 1 and 2 gives the resulting acoustic field at the point of the receiver as a superposition of the acoustic fields radiated by each of these pistons. Particle vibration velocities of the main and of the mirror pistons are equal to  $U$  and  $R \cdot U$  respectively, where  $U$  is defined by the expression (2). In the far field of radiation for both pistons, their individual contributions can be described by their individual vertical radiation angles in respect of the normal directions to the portals  $\varphi_1$  and  $\varphi_2$  and their individual distances to the receiver  $r_1$  and  $r_2$  measured from the geometrical centres of each of the pistons.

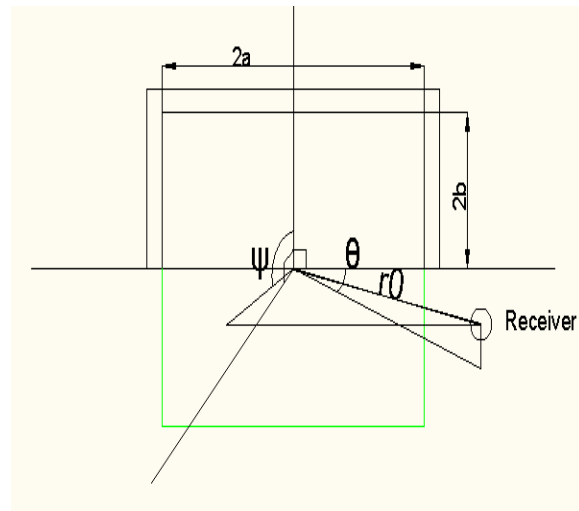


Figure 2. Frontal view of the tunnel exit and its mirror image (in green).

Values of angles  $\varphi_1$  and  $\varphi_2$  as well as  $r_1$  and  $r_2$  can be easily defined for any point of observation  $\psi$ ,  $\theta$  and  $r_0$  using simple trigonometry.

The resulting acoustic radiation is expressed as the acoustic pressure field with respect to frequency at locations surrounding the tunnel portal, based upon the supplied data on the pressure wave reaching the tunnel exit,  $f(\omega)$ . Whilst the frequency spectrum of the produced boom is of interest, the pressure with respect to time of the boom is also required. This can be found by applying the inverse Fourier transform to  $f(\omega)$ . This is too complex to perform analytically, so it is carried out numerically in the present work.

### 2.3 Tunnel length required for shock development

In order for tunnel boom to occur, a number of

conditions must be met: The tunnel must be of a suitable length in order for the nonlinear compression wave steepening to occur, in addition to the train/tunnel area ratio, and the train speed being large enough to allow the compression wave to steepen to its steady state within that tunnel length.

The approach based on the theory of nonlinear acoustic wave propagation can predict the distance required for a compression wave to develop into a pressure discontinuity [8]. The theory states that under the correct conditions for tunnel boom to occur, the pressure discontinuity developed within the tunnel will reach a steady state upon full development. That is to say that, if the distance required for full wave development is 2000m and the tunnel is 3000m long, the wave can be assumed to not change between these 2 points.

The length of full development depends on the parameters of the initial compression wave created by the train. It can also take into account the wall friction within the tunnel, that can introduce additional dissipation of the wave energy and delay the shock formation. However, exclusive of tunnels with ballasted track, this factor is found to have minimal impact on the distance required for formation, so it is not considered in the calculations made in this paper for potential HS2's tunnels.

The distance required for shock formation can be determined as

$$L_{sf} = \frac{Xc}{\varepsilon 3\pi}, \quad (3)$$

where  $\varepsilon$  is a factor expressed as

$$\varepsilon = \frac{\gamma + 1}{2\gamma} \frac{\Delta p}{p_0}. \quad (4)$$

As defined in Equation (1),  $\Delta p$  is the value of peak pressure for the compression wave induced by the train,  $X$  is a length based upon the development of a Gaussian shaped pulse (of the initial compression wave) to a discontinuity (to the shock wave). The value of  $X$  is defined as  $(e/2)^{0.5}$ , or 1.166.

From the equations (3) and (4), predictions can be made as to on which tunnels on the planned high-speed railway line the phenomenon of tunnel boom could be experienced. For the most common tunnel type on the planned HS2 system in the UK, the double configuration type, with the train running at 225 mph, the shock development distance may be as short as 1800 m. This means that tunnels of equal

or greater lengths could experience the fully developed pressure discontinuity waveform at exit, and thus produce the tunnel boom.

## 2.4 Defining the pressure wave reaching tunnel exit

In the case of the fully steepened pressure discontinuity, the peak pressure of the compression wave at the tunnel exit is known already through Equation (1). The fully developed wave form is defined using the nonlinear acoustic theory as well as through experimental evidence, and recordings of the pressure variation within the tunnel. In the present work, the incident pressure discontinuity reaching the exit of a typical tunnel (assumed to be long enough to produce full compression wave steepening) was used in the form described in [7].

## 3. Results and discussion

### 3.1 Some generic calculations

Before predictions for specific tunnels and sites are produced, it is useful to extract some generic results for the case of fully developed shock compression wave to explore how the nature of the experienced boom changes. These results consider the way that the tunnel boom varies with regard to the receiver placed at different angles in order to appreciate the directionality of the radiated sound. In addition, the distortion of the acoustic boom with distance from the tunnel portal will be considered.

Figure 3 shows the calculated waveform and frequency spectrum of a tunnel boom at distance of 100 m from the tunnel portal in the direction of 45 degrees in respect of the track. The results have been obtained for the train travelling at 225 mph, its typical operation speed, for the typical configuration HS2 twin bore tunnel of 8.9 metres diameter.

The results of the calculations also show that the tunnel boom is highly directional in its nature. For the normal direction, along the track, the boom contains frequencies up to and exceeding 1000 Hz (not shown here), whereas, as it can be seen from Figure 3, for 45 degrees direction the frequency spectrum is concentrated below 100 Hz. Generally, as the horizontal observation angle increases, there is a significant reduction in the weighting of the higher frequencies, as expected. This can be portrayed, as it is normally assumed, that a lower frequency boom is perceived as a dull thud, rather

than a sharp bang, which is less offensive to local residents.

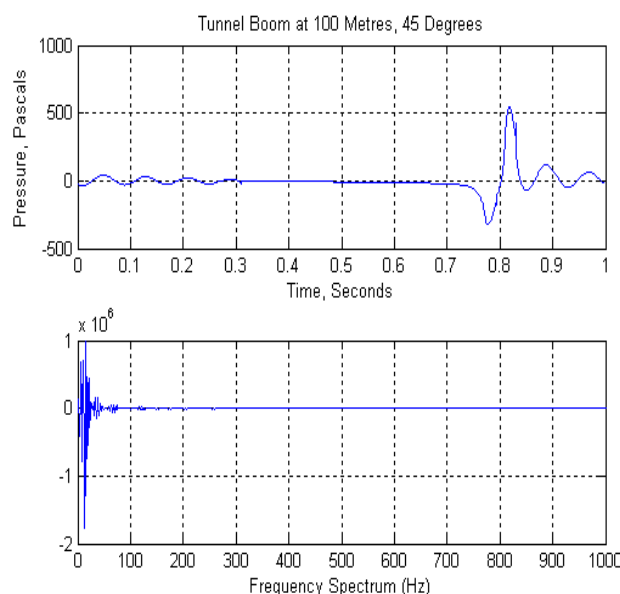


Figure 3. Tunnel boom at 100 m and 45 degrees to the exit portal

Peak sound pressure levels are also reduced with the increase of the observation angle. Table 1 shows the associated peak sound pressure levels calculated for the three values of the horizontal direction angle from the time waveforms at each of these angles.

The variation of the boom with distance from the tunnel portal is shown in Table 2 for a fixed angle of observation of 45 degrees, based upon the above-stated generic tunnel and train conditions.

Table 1. Peak sound pressure variation with the angle of observation at distance of 50 m

| Horizontal angle, degrees | Peak sound pressure level, dB |
|---------------------------|-------------------------------|
| 15                        | 164                           |
| 45                        | 152                           |
| 90                        | 149                           |

Calculations of spectra and waveforms have been carried out for the distances of 50 m, 100 m, 200 m and 400 m. It follows from Table 2 that the radiated sound wave forms evolve with distance from the portal. The waveforms of the boom at 200 and 400 metres actually contain sharper pressure peaks than the 100 metre waveform, although both are quieter.

Table 2. Tunnel boom variation with distance from the portal

| Distance from the portal, m | Peak sound pressure level, dB |
|-----------------------------|-------------------------------|
| 50                          | 152                           |
| 100                         | 149                           |
| 200                         | 145                           |
| 400                         | 139                           |

It is interesting to compare the generic calculations described above with the experimental tunnel boom results at the Euerwang tunnel, Germany (Southern portal) for the case when the ICE train is travelling at 300 km/h, at 5 metres from the tunnel portal boundary [10]. The experimental result for the peak sound pressure level is 144 dB(C). The model described in the present paper predicts the peak sound pressure level of 154 dB. As the predicted frequency spectrum has its principal components between 20 and 30 Hz, this result becomes closer to the experimental data when the C-weighted spectrum is applied, which gives 149 dB(C) for the prediction.

There is a number of notable differences between the model's approximations and the real physical tunnel portal. In particular, the model approximates the tunnel portal as coming out of a 90 degree cliff of infinite height. In reality the portals protrude out of shallow gradient hills of finite height. In addition, the experimental tunnel portal slopes out of the tunnel portal, and hence is not perpendicular to the ground. Finally, the model currently estimates the portal as a rectangle, whereas in many cases (but not all) the tunnel portal is in reality a flat bottomed oval. These imprecisions may explain the differences between experimental results and theoretical predictions.

### 3.2 Assessment of tunnels on the HS2 route

There are 25 tunnels on the HS2 line. The information about the planned tunnels is available from the HS2 LTD website, which includes a comprehensive set of plans exhibiting HS2's route. All of the required details are included into the maps for the HS2 Phase 1 (*London Euston – Birmingham International*): train speeds, tunnel dimensions and lengths. Whilst on the maps for Phase 2 (*Birmingham International - Manchester Piccadilly* and *Birmingham International - Leeds New Lane*), some of this data are yet to be

confirmed. Note that the start and finish distances given on the HS2 LTD website indicate the distances along the route of the tunnel portals from the departing station.

For each of these 25 tunnels, we have calculated the length required for the complete steepening of the compression wave propagating through the tunnel, using (3) and (4), and compared it with a tunnel length. From this it can be deduced which tunnels will experience tunnel boom.

In particular, tunnels 1, 2 and 3 on Phase 1 of HS2 may present the correct conditions for the pressure discontinuity propagating through the tunnel to develop completely before reaching the tunnel exit, hence creating the tunnel boom at the exit portal. In addition, tunnel boom may also occur on tunnels 4 and 5 of Phase 2 of HS2 (*Birmingham International - Manchester Piccadilly*). Hence these tunnels should be analysed with the fully developed shock waveform. In total, there are 9 locations out of 25 at which the phenomenon of tunnel boom could be observed.

With regard to the other tunnels on the route, these can be analysed with respect to the defined compression wave produced by the train at entrance, or by a compression wave that is not fully developed into a shock wave. Both these cases are beyond the scope of this paper that deals with fully developed shock waves only to make the predictions for tunnel boom:

### 3.3 Example calculations of tunnel boom on the HS2 route

The aim of this section is to show predictions of the expected peak sound pressure levels of tunnel boom for the first two tunnel portals along the planned HS2 route.

#### 1. HS2 Phase 1, Tunnel 1, Southern Portal- Euston Station

This 7.7 km long tunnel has potential to create a boom when the train is south bound. The boom has been calculated for the train's maximum design speed of 225 km/h at the entrance to the northern portal. The obtained estimate of peak sound pressure level at one of the locations, 149 dB at 100 m and 47 degrees, is relevant to the first row of residences closest to the portal along the roads running adjacent to the track.

#### 2. HS2 Phase 1, Tunnel 2 - Northolt – West Ruislip

The Northolt tunnel portal is located in the densely populated area with buildings. Two notable locations within the portal vicinity are the primary and secondary schools, and the predictions have been made for these sensitive locations. The predicted peak sound pressure level at 200 m and 17 degrees is 152 dB.

The above examples show that peak sound pressure levels at both locations are high enough, and the unabated consequences of tunnel boom may be severe. Consequences amongst high levels of discomfort and annoyance to local residents could include even noise-induced damage to hearing.

### 3.4 Possible methods of controlling tunnel boom

Some possible mitigation measures are mentioned below that may assist in reduction of tunnel boom.

Tunnel liners, as discussed in [7], act to prevent the full steepening of the compression wave within the tunnel. The experiments conducted on the German high speed line demonstrated that this type of mitigation can be quite effective; reducing the magnitude of the emitted boom and also reducing the weighting of the high frequency components.

Tunnel hoods, used to great effect on the Japanese Shinkansen lines [7, 8] act to reduce the gradient of the compression wave created at the tunnel entrance, delaying the full steepening of the wave.

An array of Helmholtz resonators placed within the tunnel [8] can act to attenuate the compression wave and prevent its steepening to a shock, thus implementing the concept of a shock-free tunnel.

## Conclusions

Calculations of sound radiation associated with tunnel boom from high-speed trains have been carried out taking into account acoustic reflections from the ground. The combined semi-analytical modelling of the tunnel boom carried out in the present work is capable to produce results of the same order as experimental findings.

It has been shown that the phenomenon of tunnel boom is highly directive, meaning that the worst exposed locations will be at the smallest angles off the track axis.

Due to high levels of generated impulsive sound, tunnel boom has the potential to be damaging to hearing. Because of this, mitigation is likely to be required at most if not all of the 9 identified tunnels on HS2 route. Simply reducing

the train speed cannot be considered as a viable technique.

Further analytical and experimental investigations into the phenomenon of tunnel boom would help to improve its understanding and to develop suitable mitigation techniques.

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