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Description of the flow equations around a high speed train inside a tunnel

Juan Manuel Rivero *, Ezequiel González-Martínez, Manuel Rodríguez-Fernández

School of Aeronautics, Universidad Politécnica de Madrid, Plaza Cardenal Cisneros 3, 28040 Madrid, Spain

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A B S T R A C T

The present article focuses on the analysis of the equations that describe the flow when a high speed train enters a tunnel. The disparity in time and length scales allows the problem to be decomposed in different regions and regimes when matched appropriately produce the full description of the flow. The aforementioned regions are the flow upstream and downstream of the train, the areas near the nose and tail of the train, and the flow in the gap between the train and the tunnel. The regimes are analysed based on the flow regions, time scales, length scales and velocity scales. All those regions and regimes are conveniently formulated and the flow key scales are analysed and described, which allows for a simplified and robust formulation. The aforementioned formulation is implemented in a computational program that needs some external coefficients, namely the pressure signature of the train, that should be obtained only once and it could be derived from experimental data or CFD. Comparison with experimental and numerical data from other references are provided. Finally, the thermal problem is briefly introduced and some comments on the tunnel cooling problem are considered.

1. Introduction

The aerodynamic effects occurring in a tunnel as a train moves through it, are totally different from those observed in the open air and their amplitude and severity grow as the train speed is increased (Raghunathan et al., 2002; Schetz, 2001). When a train enters a tunnel it generates an over pressure in front of it that is much larger than the one generated when it circulates in the open air (Baron et al., 2001; Choi and Kim, 2014). This over pressure is due to the confinement of the air between the tunnel and train walls (Cross et al., 2015). This induces a wave along the tunnel upstream of the train, leaving the air moving behind the wave, and forces part of the air to leave the tunnel through the region between the train and tunnel. The over pressure in front of the train grows as the train enters the tunnel, since the volume occupied by the train grows, and there is a larger amount of air that needs to flow from the front of the train to the entry portal which is at atmospheric pressure; that requires overcoming a larger friction force, and hence increasing pressure at the front of the train (Ko et al., 2012).

Once the train has completely entered the tunnel, the above mentioned scenario changes. An observer fixed to the train sees air coming to the front of the train with a speed lower than the train speed, and downstream, where the train wake has vanished, he sees that the velocity with which the air escapes is quite similar to the one with which it came in the front, due to the continuity and incompressible nature caused by the low Mach number (William-Louis and Tournier, 2005).

There is no momentum variation and the train resistance is due to the pressure difference in the front and the back of the train, and the friction in the train and tunnel walls (Raghunathan et al., 2002; Schetz, 2001). Once the tail enters the tunnel, a change in the aforementioned conditions is noted as a decrease in pressure which generates an expansion wave that travels in the train direction.

The compression and expansion waves get reflected when reaching the tunnel portals as well as being partially reflected when reaching the train inside the tunnel (Vardy, 2008; Yoon et al., 2001); this creates a vast and complex pattern that depends on the train speed, the tunnel length, the ratio between the train and tunnel diameter, the friction in the tunnel and train walls, which dampens the waves, and the existence of interior shafts and junctions that makes the problem even more complex. Nevertheless, the first compression and expansion waves are the most critical (Maeda et al., 2000; Yoon and Lee, 2001), since the rest get damped with time, particularly if the tunnel length is of the order of kilometres. As the distance travelled by the train inside the tunnel grows, the pressure loss between the entry portal and the train tail also grows, so that it can maintain the flow behind the train; as such the pressure behind the train goes below the ambient pressure.

The compressibility and friction effects in the tunnel become important for the description of the flow upstream as well as downstream of the train, and if the tunnel is long enough, the waves can be damped and

* Corresponding author.
E-mail addresses: j.riverof@alumnos.upm.es (J.M. Rivero), ezequiel.gonzalez@upm.es (E. González-Martínez), manuel.rodriguez@upm.es (M. Rodríguez-Fernández).

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disappear (Raghunathan et al., 2002).

The flow in the whole tunnel (far-field) needs to be considered as well as the flow near the vehicle. Both domains are strongly dependent on each other. One major flow feature inside the tunnel are pressure waves travelling along it (Anthoine, 2009; Ko et al., 2012) upstream and downstream of the train. The downstream and upstream evolution of the pressure waves have to be coupled with the flow over the train. In long tunnels a significant amount of thermal energy may be transferred to the tunnel environment. The quantity of heat released per unit time in the tunnel is the power consumed by the train. This thermal energy increases the temperature of the tunnel wall. The piston effect of the train only cools a small proportion of the tunnel length. The cumulative effects of trains circulating over long periods can raise the tunnel wall temperature to undesirable values (Baron et al., 2001; Barrow and Pope, 1987; Thompson et al., 2011). To approach this problem, it is necessary to describe the flow when the train is inside the tunnel and also the remaining flow in the tunnel until the next train arrives. In the present study we analyse the different flow regimes that appear inside the tunnel and around the train to have an approximation of flow velocities and temperatures to be used in the thermal problem.

In this paper we present the one-dimensional approach that has been widely used (Barrow and Pope, 1987; Hieke et al., 2011; Woods and Pope, 1981; Yoon et al., 2001). The main reason to use this approximation is that the tunnel length to tunnel diameter ratio is large (Liñán et al., 2016; Shapiro, 1953, 1964), this is also valid with the equivalent hydraulic diameter of the gap between train and tunnel. One dimensional flow equations are solved usually making use of control volume techniques (Baron et al., 2001; Ricco et al., 2007) which additionally need complex geometry routines in order to simulate the train evolution inside the tunnel (Maeda et al., 2000; Yoon et al., 2001); an even more complex scheme is needed if a full three dimensional resolution is desired (Ogawa and Fujii, 1997). Meanwhile, the discretization of the linearized version of Riemann invariants can provide comparable results while being at the same time a robust numerical scheme, as has been done and presented as an extra at the end of the present work.

The flow around the nose and tail is three dimensional, but the continuity, momentum and energy equations, applied in integral form to the appropriate control volume, allows an easy connection between the full tunnel with the gap between tunnel and train by using pressure loss coefficients for the nose and the tail of the train (Baron et al., 2001).

An analysis of each of the terms in the motion equations is performed in order to show their relative importance and to simplify the problem to be solved. The parameter assumed to be small is the squared Mach number based on the train speed (for a train circulating at 360 km/h the squared Mach number is lower than 0.09). This kind of formulation is useful for the design of high speed lines with dozens of tunnels where the health and comfort limits, pressure on the doors, etc., should be evaluated.

An asymptotic solution for an infinite tunnel is also presented, which could serve as a raw solution for fast pressure and velocity calculations in very long tunnels (of the order of tenths of kilometres).

The aiming of this theoretical development is to obtain a model that can be solved numerically in the order of minutes for problems that require the general information of the flow inside the tunnel, such as the overall power dissipated by the train along the tunnel, or the general temperature rise on the air. Particularly, the problem of temperature rise on the tunnel wall over long periods requires the calculation of hundreds of thousands of train runs; doing a complex computation for each passing would make the problem unsolvable, and that is where a simplified analysis such as the one proposed here can provide a general and robust tool for the computation of the flow inside the tunnel.

2. Governing equations in the tunnel far from train

As is well known, in a fluid flow with two different characteristic dimensions D_T and L_T (D_T is the hydraulic tunnel diameter and L_T the tunnel length), where $D_T \ll L_T$, the estimates of the order of magnitude of terms in the Navier-Stokes equations provide a characteristic transversal speed, v_t, very small compared with the characteristic longitudinal speed, u_c ($v_t/u_c \sim D_T/L_T \ll 1$). In addition the characteristic transversal pressure variation, $(\Delta p)_t$, is very small compared to the characteristic longitudinal pressure variation, $(\Delta p)_c$, independent of the Reynolds and Strouhal numbers (Liñán et al., 2016; Shapiro, 1953, 1964). The practical conclusion is that it is possible to consider a unidirectional flow with speed u and uniform pressure in each tunnel section, except near the nose and tail of the train (Baron et al., 2001). Additionally, if the Reynolds number $\rho u_c D_T/\mu$ is large, the flow is turbulent and the velocity and temperature (u, T) profiles are almost uniform in each tunnel section (White, 2003). As the pressure and temperature are uniform, all the remaining thermodynamic variables, like density ρ or specific entropy S, are also uniform. In the above conditions, the motion equations are (Shapiro, 1953; Woods and Pope, 1981; Raghunathan et al., 2002)

$$\text{Continuity:} \frac{\partial \rho}{\partial t} + \rho\frac{\partial u}{\partial x} + u\frac{\partial \rho}{\partial x} = 0, \tag{1}$$

$$\text{Momentum:} \rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial x} + \frac{\partial p}{\partial x} = -\frac{4\tau_T}{D_T}, \tag{2}$$

$$\text{Energy:} \rho c_p\frac{\partial T}{\partial t} + \rho c_p u\frac{\partial T}{\partial x} = \frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} + \frac{4u\tau_T}{D_T} + \frac{4q_T}{D_T}, \tag{3}$$

where t is the time, x the coordinate along the tunnel measured from the tunnel entry, $\tau_T = \frac{\lambda_T}{8}\rho u|u|$ the friction stress at the tunnel wall, with λ_T being the Darcy-Weisbach friction coefficient for turbulent regime of the tunnel wall, $q_T = \frac{\lambda_T}{8}\rho|u|\left\{c_pT_{wT} - \left(c_pT + \frac{1}{2}u^2\right)\right\}$ the heat received per unit area and time by the air through the tunnel wall (this is the Reynolds analogy for heat transfer on a wall caused by convection), c_p the specific heat at constant pressure, and T_{wT} the temperature at the tunnel wall (since for this problem $\frac{1}{2}u^2/c_pT \ll 1$, the kinetic energy will be neglected from the Reynolds analogy, so that $q_T = \frac{\lambda_T}{8}\rho|u|\{c_pT_{wT} - c_pT\}$). These terms (friction stress and heat transfer on the wall) account for the two-dimensional effects generated by the high gradients on the walls of train and tunnel. The state equation for perfect gasses is also used, $p = (c_p - c_v)\rho T$, where c_v is the specific heat at constant volume. For more details of this model, see appendix B.

It is worth to mention that the Darcy-Weisbach friction coefficient and the Reynolds analogy assume that the turbulent structure is not affected by the unsteady process that takes place inside the tunnel, which is a common approximation in these problems (Baron et al., 2001; Raghunathan et al., 2002; William-Louis and Tournier, 2005; Cross et al., 2015). This approximation is valid except at the points where the pressure wave passes. Since this time is very small compared with the whole time in the problem and since a key feature in the present work is to keep the formulation as simple as possible, we will not account for this effect.

3. Order of magnitude of $(\Delta p)_c$, u_c and $(\Delta T)_c$

We will denote ambient conditions with subscript "a", and tunnel values with the subscript "T". In order to estimate the pressure increment inside the tunnel it should be taken into account that it is generated by the train motion. By applying the momentum equation in integral form to a control volume between two sections upstream and downstream of the train, with a reference system fixed to the train, the characteristic pressure increment is obtained

$$(\Delta p)_c A_T \sim \mathscr{R} \sim C_D \rho U^2 A, \tag{4}$$

where A_T and A are the cross section of tunnel and train respectively, $\mathscr{R}$ is the aerodynamic drag of the train, C_D is the drag coefficient, and U is the train speed. According to (4), the order of magnitude of the pressure