J. Wind Eng. Ind. Aerodyn. 146 (2015) 195–206

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

# A validated numerical investigation of the effects of high blockage ratio and train and tunnel length upon underground railway aerodynamics

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ARTICLE INFO

*Article history:*
Received 22 July 2014
Received in revised form
11 September 2015
Accepted 12 September 2015
Available online 1 October 2015

*Keywords:*
Underground railways
Aerodynamics
High blockage ratio
Ventilation
Computational fluid dynamics

ABSTRACT

In order to ensure the safety and comfort of passengers and staff, an underground railway requires an extensive ventilation and cooling system. One mechanism for underground railway ventilation is the movement of air induced by trains, termed the 'piston effect'. This study investigated the effect of altering the blockage ratio of an underground train upon the ventilating air flows driven by a train. First a computational model was developed and validated with experimental data from literature. This model was scaled to represent an operational underground railway with high blockage ratio and the blockage ratio varied to evaluate the effects upon ventilation. The results of this study show that ventilating air flows can be increased significantly during periods of constant train motion and acceleration, by factors of 1.4 and 2 respectively, but that the train drag will increase at the same rate. During deceleration negligible increases in ventilation flows are found but drag increases by a factor of 4.



## 1. Introduction

Underground railways have been in existence since the opening of the Metropolitan Railway in London, UK in 1863, and new systems continue to be developed and existing ones upgraded or expanded (Botelle et al., 2012; Botelle and Payne, 2010). In order to ensure the safety and comfort of passengers and staff, an underground railway requires an extensive ventilation and cooling system. This is needed firstly to provide for human physiological and comfort requirements but also to manage air conditions in emergency situations, such as fires. Underground railway ventilation is a complex and dynamic system, influenced by many different flows and conditions including those induced by train movement.

Train induced air flows in tunnels, also known as the 'piston effect', are driven by the presence of a tunnel wall adjacent to a moving train. When moving through open space, the air displaced by a train can move to the side of the vehicle in all directions. However, when the train passes through a tunnel, the ability for the air to displace to the sides of the vehicle is reduced. As the air cannot completely pass to the rear of the train, much of the air will flow in front of the train. This creates a high pressure region at the train front whilst at the back of the train a low pressure region is formed, along with the creation of a wake, which acts to suck air from behind the train. The pressure difference between the front and back induces air flow down the side of the train.

Train induced air flows can have a positive impact on the underground railway environment through the ventilation of tunnels and station areas but can also introduce undesirable effects such as high pressures and platform velocities which may cause discomfort to people or damage to the infrastructure. Generally, underground railways are designed with features to enhance and control train induced air flows. Draught relief shafts may be constructed near stations to allow air exchange with the outside environment, the reduction of high pressures and the reduction of platform air velocities. Air shafts may be utilised in between stations to enhance air exchange operating either mechanically or non-mechanically. Cross passages between running tunnels are often provided to reduce high pressure transients, train drag and high platform velocities. An extensive study was carried out in the 1970s under the direction of the US Department of Transportation into the design of underground railways and has since been used as a major guide for the construction of many systems (Transit Development Corporation, 1975).

In existing high blockage ratio underground railways significant problems are experienced with managing the ventilation, often resulting in issues with overheating. In this paper the effect of altering the blockage ratio in such an environment is investigated to understand the impact on tunnel air flows and train drag, and hence the potential for realising enhanced ventilating air flows.

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http://dx.doi.org/10.1016/j.jweia.2015.09.004
0167-6105/

## 2. Previous work

In recent years, numerical and experimental work has been performed in order to investigate the effects of train induced flows on underground railway environments. Pope et al. (2000) performed an extensive parametric study of an underground railway system to investigate how air velocities and temperatures are affected by train induced flows in various underground configurations. Lin et al. (2008) considered the performance of draught relief shafts through experimental measurements and numerical simulations. Eckford and Pope (2006) studied the effect of increasing the air exchange through train induced flows, draught relief or forced ventilation. It was found that if the air exchange is increased 1.6 times, by whichever means, then a 4 °C reduction in tunnel temperatures could be achieved. Ono et al. (2006) analysed the scheduling of mechanical ventilation systems based on train movements. They found that, for most of the day, train induced flows were sufficient for ventilation and that only short periods of mechanical assistance were required. Kim and Kim (2006) used experimental and numerical methods to investigate the behaviour of train induced flows and train aerodynamics. This work was later extended by Kim and Kim (2009) to consider the effect of ventilation shaft locations. Ke et al. (2001) studied the effect of ventilation shaft length, cross sectional area and train speed on the ventilation rate and the thermal environment. They found that increasing air flows decrease tunnel temperatures up to a point after which heat from traction and braking undermine any further improvements. El-Bialy and Khalil (2010) investigated the thermal comfort on a station in the Cairo Metro using experimental and numerical methods. Yan et al. (2013) compared the performance of underground railway tunnels with one or two ventilation shafts. Gonzalez et al. (2014) performed a numerical investigation of train induced flows in a tunnel, incorporating mechanical and non-mechanical ventilation shafts, and show that running mechanical shafts in support of train induced air flows can result in energy savings. Xue et al. (2014) analysed the effect that the location of draft relief shafts and louvres had upon ventilation through numerical analysis and experimental measurements in an operational railway. Huang et al. (2013) used the model presented by Kim and Kim (2006) to investigate the use of solid curtains at extreme ends of a tunnel in improving ventilation performance. It was found that such devices could improve ventilation rates significantly but practical problems would make implementation difficult. Ampofo et al. (2003) considered various methods of delivering cooling in underground railways, with particular attention to the situation in the UK. They showed that the improvement in ventilation capacity can reduce tunnel temperatures but that implementation could prove problematic.

The mechanism of the piston effect itself has also been investigated widely, mainly in the context of high speed trains. Ricco et al. (2007) carried out an experimental and numerical investigation into the pressure waves induced by a train running through a tunnel and noted the importance of train nose shape and the presence of a recirculation zone at the train nose. It was also noted that for a constant blockage ratio, the shape of the train nose was not significant. Baron et al. (2001) studied the effect of pressure relief devices on the pressure waves generated by high speed trains. Ko et al. (2012) studied induced pressures in tunnels through field measurements and found that the cross sectional area of the tunnel is a major influence on the magnitude of induced pressures. It was also found that pressure peaks were proportional to train speed. The performance of trains in tunnels was investigated by Raghunathan et al. (2002). It was found that the shape of a train nose can effect the performance of a high speed train significantly. Many authors have investigated the effect of tunnel hoods on induced pressures. Howe (2004) studied the optimal distribution of orifices in a tunnel hood in order to suppress micro pressure waves on train entry. An experimental and numerical investigation was carried out by Bellenoue et al. (2001) into the effect of a tunnel hood on pressure waves and found that the reductions in pressure change are independent of blockage ratio. It was found by Mok and Yoo (2001) that a hood could reduce the pressure gradients of the compression waves produced by train entry by 20%. Rabani and Faghih (2015) found that the speed and blockage ratio of a train are the main factors which affect the pressure wave and the shape of the train effects the gradient in reaching the maximum pressure.

There are a number of factors which influence the behaviour and volume of air flows induced by trains, including train velocity, tunnel and train properties, the frequency of trains and the blockage ratio – the ratio of the train to tunnel cross sectional areas (Vardy, 1996a, 1996b).

In most previous work, the blockage ratio is investigated in terms of the influence upon pressure waves, a phenomenon one would wish to reduce. In this work, focus is given to the impact of the blockage ratio on the magnitude of the induced air flows which are useful for ventilation in a low speed, underground railway environment. First a numerical model is developed and validated with available experimental data, and scaled to represent a full scale environment. The effect of the blockage ratio upon train drag and outlet air velocities is investigated with particular consideration given to the different effects of pressure and viscous drag forces. The relationship between tunnel and train length and train drag and outlet air velocities is also presented and interpreted.

## 3. Methodology

A transient, three-dimensional computational fluid dynamics (CFD) simulation was used to model the induced air flows generated by train movement in a tunnel. The study is formed in two parts; a validation and verification of a CFD model of an underground railway and the examination of the effect of high blockage ratio and train and tunnel length upon tunnel air flow.

An idealised scale model representation of an underground railway environment was employed in order to simplify the physical phenomena and modelling process and is modelled using CFD. This model is validated with available experimental results from the literature. The model was scaled geometrically to represent the full scale, the train velocity varied to examine the effects and the geometry altered to represent an existing underground railway operating at high blockage ratio (Victoria Line, London Underground, UK). This process is carried out to establish the impact of blockage ratio and train and tunnel length in current underground railways. The blockage ratio and train and tunnel length are all varied independently and the impact upon tunnel air flows and train drag is shown.

### *3.1. Model set-up*

The scale model configuration used in this study is duplicated from the experimental set-up presented by Kim and Kim (2006) and used subsequently by various authors (Kim and Kim, 2009; Huang et al., 2010, 2011). The model is shown schematically in Fig. 1, and describes a 1/20 scale model of an underground railway.

The tunnel does not include any features such as shafts or passages to allow the investigation of the train induced flows without interference from other factors. The set-up consisted of a tunnel, both ends open to the atmosphere, in which a model train was passed. The tunnel was 39 m long, 0.21 m wide and 0.25 m high, while the train was 3 m long, 0.156 m wide and 0.225 m