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# Enhancing the piston effect in underground railway tunnels

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ABSTRACT

The air flows induced by train movement in tunnels can be used for the purposes of underground railway ventilation. The magnitude of such air flows depends strongly upon the blockage ratio (the ratio of the train and tunnel cross-sectional areas) of the train. This study investigates the impact on the generated air flows due to the alteration of the aerodynamic resistance of the train, as a means of varying the blockage ratio. The alteration in aerodynamic resistance was achieved by using an aerofoil at a variety of different angles of inclination. A two-dimensional computational fluid dynamics model of a train travelling through a tunnel was developed and validated using experimental data from literature. This model was then used to investigate the influence of an aerofoil upon the volume of displaced air and the effect upon the aerodynamic work done by the train (work done by the train due to air drag). The results of this study show that ventilating air flows can be increased by 3% using an aerofoil at a fixed angle of 10° without increasing aerodynamic work. Through using a combination of different angles during different phases of train motion, a maximum increase in air displacement of 8% can be achieved, while not increasing the aerodynamic work done by the train. This equates to the train generated air displacement delivering an extra 1.6 $m^3\ s^{-1}$ of air supply during the period of train motion.

## 1. Introduction

The London Underground carries 1.305 billion passengers per year (Transport for London, 2015a) with numbers continually increasing (Transport for London, 2015b). In order to meet demand, train frequencies are being increased. This growth has placed the existing infrastructure under considerable strain. In particular, the ventilation systems which were designed for an underground network originally conceived many years ago is often unable to maintain a comfortable environment for passengers and staff. Summer temperatures in London Underground stations can regularly exceed 30 °C (Botelle et al., 2010). Problems of this nature are found in systems around the world and with the added challenge of climate change (Jenkins et al., 2014) are expected to worsen.

Transport authorities are therefore seeking methods of improving underground railway environmental conditions. Approaches such as the upgrade of ventilation fans, installation of air conditioning on trains, construction of new ventilation shafts and the adoption of groundwater cooling systems have all been added in recent years. However, these approaches involve high construction or ongoing costs and high energy use. Additionally, the significant nature of some of these interventions may also cause considerable disruption to normal train operations during construction.

An important mechanism for the ventilation of an underground railway is a phenomenon called the ‘piston effect’. The effect is generated by a train moving through a tunnel. Since the train is confined by the tunnel walls, a pressure gradient is generated along the train and air is pushed ahead of the train and sucked from behind, thus generating an air flow. The main factors which influence the magnitude of the piston effect are the blockage ratio (defined as the ratio of the train cross-sectional area to the tunnel cross-sectional area) and the train speed, length and nose shape (Cross et al., 2015; Baron et al., 2001). The magnitude of such air flows are significant and in a newly designed underground system in a temperate climate can be sufficient for ventilation during normal operations (Bennett, 2004).

This study introduces a potential method of enhancing the piston effect, determined by the use of a validated CFD investigation. The concept is to attach aerofoils to each side of a train, i.e. between the sides of the train and the tunnel wall, in a similar manner to that of a spoiler on a car. The effect of the aerofoil is to increase the aerodynamic resistance of the train. As the air flow patterns around the train are changed, the volume of air displaced by the train will increase (Cross et al., 2015; Baron et al., 2006). Positioning the aerofoil at different angles allows the air flow patterns to be varied and therefore the volume of air displaced. A plan view of the aerofoil configuration is shown in Fig. 1.

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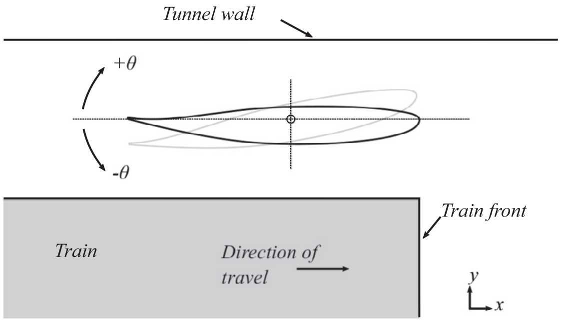

**Fig. 1.** Sketch of the aerofoil positioned between the side of the train and the tunnel wall.

A particular angle of inclination of the aerofoil can be determined to maximise the air displacement, minimise the aerodynamic work done by the train or as a compromise between the two parameters. A range of angles is found for increasing air displacement while not increasing aerodynamic work for different phases of train travel and a sequence of angles is given to maximise the air displacement while not increasing the aerodynamic work.

The aim of this study is to investigate the concept of using an aerofoil to alter the air flows around a train for the purposes of enhancing the piston effect. In particular, the effect on the air flows around the train are considered and the effect on the pressure and viscous drag components, as well as induced air flows. Further aspects of an aerofoil configuration will need to be considered further before application, including the size and position relative to the front and side of the train and how it may be accommodated within the constraints of a particular train-tunnel configuration. As such, the results are intended to provide insight into the effects of air aerofoil on the air flows around trains for a general train-tunnel configuration, not a specific case.

## 2. Previous related work

A number of studies have considered the influence of ventilation and the piston effect upon underground railway temperatures and energy use. Ampofo et al. (2004) considered various methods of delivering cooling in a UK underground railway system and show that increasing the ventilation rate can significantly reduce the temperature in tunnels and trains. Eckford and Pope (2006) investigated increasing the ventilation rate using mechanical ventilation, train induced flows and draught relief and found that increasing the air exchange by 60%, by any means, reduced the temperatures by 4 °C. López González et al. (2014) carried out a numerical investigation of the airflows in a station within a network of tunnels and shafts, and found that the influence of the piston effect could give energy savings of up to 3%. Yuan and You (2007) carried out an experimental and numerical investigation of the air velocity and temperature conditions on an underground station platform and optimised the ventilation to give a lower platform temperature. Ono et al. (2006) considered the operation of mechanical ventilation based on the scheduling of trains. Train induced air flows were found to be sufficient for ventilation for the majority of the day with mechanical ventilation only required at peak periods. Casals et al. (2014) presented a breakdown of the energy consumption in a Barcelona underground station. The authors found that ventilation accounted for 14% of the energy consumption but believed that this could be reduced by 30% if the train induced air flows could be better harnessed for ventilation purposes.

The influence of train geometry upon the piston effect have been considered in terms of improving ventilation and reducing undesirable pressure effects. Cross et al. (2015) considered the air flows and drag generated in high blockage ratio underground railways, finding that increasing the blockage ratio by 30% will double the air flow but also the drag on the train by the same amount. Ricco et al. (2007) investigated, numerically and experimentally, the pressure waves generated by a train passing through a tunnel. They noted that the size of a separation bubble at the train nose increases the effective blockage ratio of the train, which in turn increases pressure peaks, and is influenced by the shape of the nose. Gilbert et al. (2013) carried out an experimental study into the gusts generated by trains in tunnels, finding that they are strongly dependent on the length and the cross sectional area of the tunnel. Choi and Kim (2014) investigated increasing the nose length and cross sectional area of a tunnel to reduce the drag of a subway train with reductions of 50% found from either method.

In previous studies, the impact of the piston effect upon underground railway conditions and energy use have been investigated as well as the aerodynamics of trains in tunnels. The literature established that the piston effect benefits underground railway conditions and that the blockage ratio is a major influencing factor upon the air flows. In this work a mechanism for increasing the aerodynamic resistance for higher ventilating air flows, but which does not have a large negative effect upon the train aerodynamics, is investigated. First a benchmark numerical model is developed and validated with available experimental data. The effect of varying the blockage ratio using an aerofoil to alter the aerodynamic resistance is studied with consideration given to the air displacement and aerodynamic work done by the train. The effect of the aerofoil on the air flow behaviour and pressure and viscous forces acting upon the train is also presented.

## 3. Methodology

A transient two-dimensional (2-D) computational fluid dynamics (CFD) simulation was used to model the induced air flows generated by the train movement in a tunnel. The study consists of two parts; the validation and study of a benchmark configuration without an aerofoil and the examination of the effect of an aerofoil on the benchmark configuration.

### 3.1. Benchmark configuration

The benchmark modelling domain was a 2-D horizontal cross section of an idealised train-tunnel configuration. The model represents a train as a blunt ended rectangle positioned symmetrically between smooth tunnel walls, with the tunnel ends open to the atmosphere. The air flows around a train are 3-D in nature, in particular the air flows at the corners of a train will vary significantly from that between the corners. The 2-D model is used by assuming that the flow through the train gap does not vary significantly with the vertical position, away from the corners of the train. Moreover, the flows represented in the 2-D model are taken to represent the flows in a general train-tunnel configuration, not a specific case, and as such are considered sufficient for the purposes of this study. Additionally, a three-dimensional model of the train-tunnel configuration with an aerofoil would entail using a mesh of a prohibitively large size, given the computational resources available. The model is geometrically simple to avoid interference from other factors. Fig. 2 shows the modelling domain and characteristic lengths.

The train length ($T_x$) and width ($T_y$) are 50 m and 2.48 m, respectively, and the tunnel length ($L_x$) and width ($L_y$) are 500 m and 2.96 m, respectively. The width of the gap between the train side and tunnel wall, the train-tunnel gap ($L$), is 0.24 m on each side, so that the train is positioned symmetrically within the tun-