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Detached-eddy simulation of the slipstream of an operational freight train

Dominic Flynn*, Hassan Hemida, David Soper, Chris Baker

Centre for Railway Research and Education, School of Civil Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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ABSTRACT

With increasing train speeds the subsequent increase in slipstream velocities can have a detrimental effect on the safety of persons in close proximity to the vehicle. Due to their uneven loading and bluff geometries, freight trains can produce higher slipstream velocities than passenger trains at given measurement locations. The highly turbulent non-stationary slipstream of a model-scale Class 66 locomotive and wagons was investigated using delayed detached-eddy simulation (DDES). The Reynolds number of the flow was 300,000 and results were compared for meshes of 25 and 34 million hexahedral cells. Good agreement was observed between the DDES and model-scale physical experiments. Slipstream velocities along the train side and roof were investigated and the bogie region was seen to produce the highest slipstream velocities. A comparison between time-averaged and ensemble-averaged data from the simulations gave comparable results. The technical standards for interoperability (TSI) analysis showed that the slipstream velocities generated were below half of the maximum permissible value of the standard whereas the pressure was 43% greater than the limiting value. Furthermore the presence of a periodic phenomenon is detected above the roof of the locomotive.

1. Introduction

The UK government aims to double the volume of cargo transported by freight trains on the UK rail network by 2030 (Department for Transport, 2007). The increase in traffic volume on the network can be supported in several ways: building new lines, re-opening old lines, and increasing train length or the speed of trains. The first two options are expensive and could take many years to complete. Route capacity could also be increased by lengthening freight trains, although this could lead to slower moving trains which would negate the effect of increasing train lengths. The final option is to increase the operational speed of freight trains. This would be a much simpler option to increase route capacity, though there are associated aerodynamic consequences.

When a train moves through air it generates a slipstream. Generally train slipstreams are characterised as highly-turbulent non-stationary regions of air, which to a static observer, appear as gradually-building gust punctuated with pulses of higher speed air. These air pulses are a result of gaps in the geometry of the vehicle and are generally much larger for freight trains than for passenger trains, therefore causing much larger pressure and velocity transients.

Due to the fact that aerodynamic forces increase almost proportionally with the square of velocity, an increase in train speed and thus slipstream velocities can greatly increase the risk of objects moving or persons becoming unsteadied. Between 1972 and 2005 there were 26 reported slipstream-induced incidents on the UK rail network; these incidents included movement of trackside equipment, pushchairs and luggage (Pope, 2006).

An investigation on the West Coast mainline studied the effect of increasing the allowable operational speed of freight trains, from the current 75 mph to 90 mph, on the slipstream velocities measured on station platforms (Figura-Hardy, 2002). The investigation also examined the effect of train slipstreams on the movement of light, mobile objects such as pushchairs. A variety of loaded and unloaded, single and double, pushchairs were placed on a platform 1.5 m from the edge and their movement was measured while a variety of passenger and freight trains passed. It was found that freight trains were responsible for approximately 90% of the pushchair movement, even though freight trains travel much slower than passenger trains. The consequence of a train's slipstream moving pushchairs outside of experimental conditions could be injury or fatality which would greatly damage customer confidence in the railways and could have a further effect on railway revenue (Pope, 2006).

A European-wide move to standardise the criteria for certification of railway vehicles has lead to the development of regulations for rail operators regarding slipstream velocities and pressures generated by trains (TSI, 2008). At present there are no requirements for the maximum slipstream velocities or pressures generated by vehicles that travel below 190 km/h. Slipstream velocity

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* Corresponding author. Tel.: +44 121 4147971.
E-mail address: dcf147@bham.ac.uk (D. Flynn).

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data collected by Figura-Hardy (2002) and presented in Sterling et al. (2008) shows that the slipstream velocities produced by freight trains, which operate below 190 km/h, are far from negligible. The slipstream velocities measured on a station platform were approximately 0.4 of train speed, corresponding to a gust of 13.2 m/s. The velocities are within the range that Jordan et al. (2008) deemed sufficient to cause a person to become unsteadied, although factors such as gust duration, build-up time and gustiness will all have an effect. At present the slipstream velocity required to unsteady a person is not entirely understood therefore further investigation is required to quantify this value.

Full-scale aerodynamic data is inherently credible but the process of acquisition is often arduous. The amount of data collected during full-scale measurement campaigns is often restricted by site access, measurement capability and safety restrictions. Furthermore, the data acquired from a single velocity or pressure probe in the slipstream of a train is not sufficient to elucidate the nature of the flow. To gain a clear understanding of the flow around a full-scale train would either require a large number of probes or an extended measurement campaign. For this reason, physical model-scale (Baker et al., 2001) and numerical (Hemida et al., 2014) experiments have gained favour with researchers because of the comparative simplicity with which slipstream measurements can be made. Furthermore, model-scale testing is often performed indoors and thus is not reliant on specific atmospheric conditions such as low wind speeds. Model-scale aerodynamic testing has also become an accepted method of certification for the design of a train (CEN, 2011) and the issue of scale is compromised on by assuming Reynolds number (*Re*) independence above 250,000.

Model-scale experiments were conducted (Soper, 2014) in order to investigate the effect of loading efficiency on the slipstream of a Class 66 hauled container freight train. Soper (2014) showed previously unseen slipstream velocity peaks at the front of the train, in the order of 1.3 of train speed. Slipstream growth and turbulence intensity were shown to be higher in train consists with lower container loading efficiency.

In the last decade, numerical simulations have become a common method of the aerodynamic assessment of railway vehicles. The majority of investigations were conducted to understand the crosswind characteristics of high speed trains (Hemida and Krajnović, 2010; Diedrichs, 2003; Hemida and Krajnovic, 2005). Due to the wakes of bluff bodies being dominated by large turbulent scales large-eddy simulation (LES) is often used to resolve the flow around simplified trains (Hemida and Krajnović, 2010; Hemida and Krajnovic, 2005). The implications of using LES are discussed in Section 5, but in general LES provides a more accurate solution than Reynolds-averaged Navier–Stokes (RANS) methods with much higher computational costs.

RANS methods were used to predict force coefficients on a 1/40th scale freight train which was subjected to a crosswind at a range of yaw angles (Golovanevskiy et al., 2012). The Spalart–Allmaras one equation model (Spalart and Allmaras, 1992) was used for turbulence closure. The flow around a bluff-body such as a freight train will induce large local strain rates which in turn will greatly increase the eddy-viscosity, and thus effective viscosity. High levels of effective viscosity can reduce the realism of the flow thereby producing spurious results. There is poor comparison between the numerical and experimental data (Golovanevskiy et al., 2012) which could be due to the poor turbulence model choice.

Hemida and Baker (2010) investigated the flow around a freight wagon subjected to a 90° yaw crosswind. The wagon was assumed to be in the middle of a long train, away from asymmetrical flow from a locomotive or rear wagon and periodic boundary conditions were used to represent the effect of adjacent wagons on the flow behaviour. The flow was resolved using LES although validation was not performed against physical experiments, thus the results cannot be fully verified.

Östh and Krajnović (2014) used LES in order to investigate the effect of simulating the flow around an isolated wagon and the flow around a wagon with adjacent half-wagons using periodic boundary conditions. The work provides a good insight to the mean and instantaneous flow structures, although analysis of the slipstream flow properties is neglected. Furthermore, only a mesh sensitivity study is conducted and no direct validation with experimental results takes place and thus the realism of the results cannot be substantiated.

Detached-eddy simulation (DES) (Spalart et al., 1997) has been used for crosswind assessment of a number of ground vehicles (Favre et al., 2010, Hemida and Krajnović, 2009) and is often employed because of the reduction in computational expense in comparison to LES, at the wall. Delayed-detached eddy simulation (DDES) (Spalart et al., 2006) has been used successfully to investigate the wake of a model-scale high speed train (Muld et al., 2012). The results compared well to experimental work although the implications of the results are questionable because the *Re* of the case is 60,000, 24% of the minimum *Re* required by CEN (2011).

The present work uses the open-source software, OpenFOAM (Open Foundation, 2012) to conduct a DDES in order to investigate the flow properties and behaviour of the slipstream of a 1/25th scale model Class 66 freight train. The simulations are validated against physical experiments (Soper, 2014) and this paper contains the first use of numerical simulations to investigate the slipstream of an operational freight train.

Section 2 contains a description of the model, Section 3 briefly describes the moving-model experiments and Section 4 shows the computational domain and boundary conditions. Section 5 describes the numerical method, Section 6 discusses the numerical schemes and Section 7 shows the computational mesh. Section 8 contains the results and in Section 9 conclusions are drawn.

2. Model description

The freight train model used in the present work is a 1/25th scale Class 66 locomotive with 4 fully-loaded FEA type B container wagons in tow. Rails were also included in the simulations. The scale of the computer-aided design (CAD) model was chosen to be the same as the physical model.

Fig. 1 shows the CAD model used in the numerical work and the physical model used in the experimental work (Soper, 2014). The models have a good degree of similarity although some simplifications are made to the CAD model to allow for a higher-quality mesh and thus a more accurate solution.

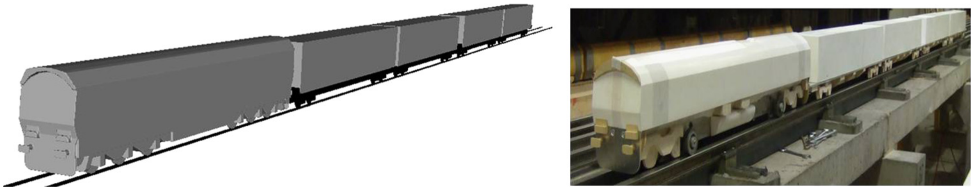

Fig. 1. Train models used in the numerical (left) and physical experiments (right) (Soper, 2014).