The Accuracy of Different Turbulence Models (URANS, SAS and DES) for Predicting High-Speed Train Slipstream

Shibo Wang[a,*], James R. Bell[a], David Burton[a], Astrid Herbst[b], John Sheridan[a], Mark C. Thompson[a]

[a] *Fluids Laboratory for Aeronautical and Industrial Research (FLAIR), Dept. of Mechanical Engineering, Monash University, Australia*

[b] *Centre of Competence for Aero- and Thermodynamics, Bombardier Transportation, Västeras, Sweden*

Abstract

Slipstream, i.e., the air movement induced by a high-speed train (HST) as it passes, is a safety hazard to commuters and trackside workers, and can even cause damage to infrastructure along track lines. Because of its importance, many numerical studies have been undertaken into this phenomenon. However, to the authors' knowledge, a systematic comparison of predictions from different turbulence models used to simulate slipstream has not yet been conducted. This study aims to investigate and evaluate the capability of three widely used turbulence models: URANS, SAS and DES; to predict slipstream from a full featured train model, comparing results with experimental data to determine the fidelity of the models.

Keywords: High-speed trains, Train aerodynamics, Slipstream, Computational Fluid Dynamics (CFD), Unsteady Reynolds-Averaged Navier-Stokes equations (URANS), Scale-Adaptive Simulation (SAS), Detached Eddy Simulation (DES)

1. Introduction

The slipstream of a high-speed train is highly turbulent, three-dimensional and time-dependent, which poses a significant challenge to predict numerically. Much effort has been channelled into improving the accuracy and efficiency of the numerical simulations of complex turbulent flows, for example, through the development of more complex turbulence models. Generally, a model that captures more of the full range of flow structures is more computationally demanding. Therefore, a trade-off generally exists between accuracy and computing cost. To the authors' knowledge, a systematic comparison of different turbulence models to predict slipstream is yet to be conducted. In this study, three current state-of-the-art methods (i.e., URANS, SAS, DES) are studied, and compared based on their capability to predict both time-averaged and transient flow features.

2. Numerical method

2.1. Geometry

This study is based on a *Deutsche Bahn Inter-City-Express 3* (ICE3) high-speed train, a widely operated train operated in European and Asian countries. The numerical analysis was conducted based on a slightly geometrically simplified ICE3 model. It used a length-width-height ratio of approximately 50:3:4. Although the train model was simplified, omitting details such as the gaps between carriages and the air-conditioning units, it still included important geometry features that have a strong influence on the wake, in particular, the bogies and snowplows. The train was positioned on a standard single-track ballast rail (coloured in green), the dimensions of which are based on the European Regulations [1], as shown in Figure 1.

2.2. Computational domain and grid description

The train was located in a hexahedral computational domain, as illustrated in Figure 2. Its dimensions were normalised by the width (W) in the cross-stream directions, and by the length (L) of the train in the streamwise direction.

*Corresponding author
Email address: shibo.wang@monash.edu (Shibo Wang)

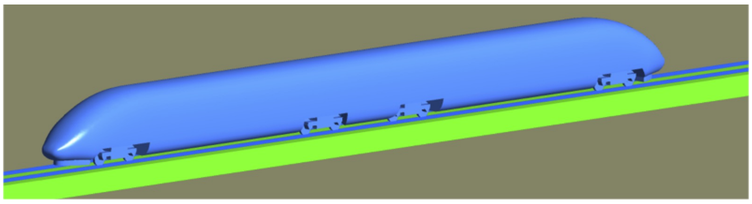

Figure 1: The simplified version of the train model used for numerical simulations.

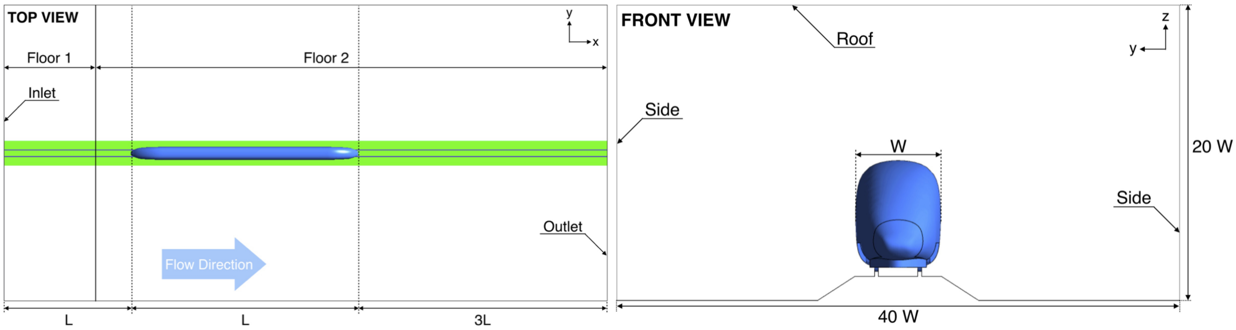

Figure 2: The schematic of computational domain (not to scale), showing the placement of the train and domain dimensions.

The uniform velocity boundary condition was applied at the inlet. The free-stream Reynolds number based on the train width was set to 7.2×10^5. A zero static-pressure boundary condition was applied at the outlet boundary. Symmetry boundary conditions were used at the roof and side boundaries. The floor boundary consists of the ground, ballast and rails. In order to replicate the splitter plate introduced to remove the floor boundary layer in the wind tunnel experiments, the floor was split into two parts, namely *floor 1* and *floor 2*. Floor 1 was $0.7L$ long, and employed a zero-shear wall condition. Floor 2 was $4.3L$ long with a no-slip wall condition. Additionally, a no-slip wall condition was applied to all train surfaces.

A Cartesian cut-cell grid with substantially increased mesh concentration around the train and in the wake was developed to achieve a higher resolution in the slipstream measurement regions and to accurately capture the boundary layers and induced flow separation from small-scale geometrical features. The grid had approximately 26.6 million cells. The train surface had 10 inflation layers to capture the boundary layer, and the wall y^+ at the first cell was maintained approximately between 1 to 30. As an aim of this study was to compare and contrast the capabilities of different numerical models, the same grid was used for each simulation. The influence of grid resolution on the numerical predictions is not reported in this study; however, it should be noted that considerable care was taken to generate a subjectively optimal mesh, through the generation of a sequence on successively improved meshes combined with self-consistency testing and experimental validation. The experiment was conducted by Bell et. al. [2] in the Monash University 1.4 MW closed circuit wind tunnel.

2.3. Governing equations and solver details

Due to a high degree of variation in slipstream flow observed between experimental runs, it seems likely that the highly unsteady flow can only be simulated accurately by transient simulation. Currently, the most widely used transient solvers are URANS, SAS, DES and Large Eddy Simulation (LES). Due to the high computational cost of (pure) LES at high Reynolds numbers, it is still limited to studying fundamental flows over simple geometries [3]. Therefore, this study focused on three less expensive numerical approaches that appear more applicable to high-speed train aerodynamics research: URANS, SAS and DES.

Even though URANS can provide a time-dependent solution, it does not provide spectral content of the flow. At best, it only predicts the large-scale dynamics of the main flow structures. For example, Schulte-Werning et al. [4] utilised URANS to study the unsteady wake structure and further investigate the last-car-oscillation effect. SAS modifies the classic RANS approach by incorporating the von Karman length scale. Interestingly, the modified model can capture the larger-scale temporal and spatial scales, and captures more of the turbulence spectrum as the spatial and temporal resolution are increased [5]. To the authors' knowledge, SAS has not yet to be applied for studying train aerodynamics. DES is a blend of RANS and LES models, utilising RANS to approximate the boundary layer and applying LES to capture the time-dependent flow away from boundaries. Therefore, the turbulence spectrum can be partially resolved, and spectral analysis can be used to analyse the chaotic wake structures [6]. This study used a modified DES model, the *Improved-Delayed-DES* (IDDES) model, which had an improved on wall-modelling capability. All results are obtained using the commercial CFD software package *FLUENT* as part of the ANSYS 16.2 suite.

The RANS turbulence model used as part of all higher-level turbulence models was the k-ω Shear Stress Transport (SST) model. The time-step was normalised by T_{ref}, which was calculated as $T_{ref}=\frac{\text{freestream velocity}}{\text{train height}}$, i.e., the time taken for the fluid to advect 1 train height. The time-steps chosen for URANS, SAS and DES were $0.4T_{ref}$, $0.04T_{ref}$ and $0.004T_{ref}$, respectively. The unsteady statistics averaged the flow over $312T_{ref}$ after the flow was checked to be dynamically steady through comparisons with predictions from smaller averaging periods.

3. Result and analysis

3.1. Time-averaged flow structure

The dominant flow structure around a high-speed train is a counter-rotating vortex pair in the wake. This structure originates from boundary-layer vorticity fed into the wake as the flow separates at the tail of the train. This vorticity realigns into a streamwise counter-rotating vortex pair as the fluid passes beyond the complex near wake. Further downstream the vortices move downwards and outwards, through the combined effects of self induction and image vortices situated beneath the ground plane. One assessment of the capability of each model to accurately predict the time-averaged flow field was based on the x-vorticity map at a plane $1H$ downstream of the tail, as shown in figure 3(a). In this figure, the y-position was normalised by W, and the z-position by H. The formation of the vortex was also visualised through in-plane velocity vectors (white arrows); with the vortex boundary identified via $\Gamma_2 = 2/\pi$ (black solid line). Based on this figure, all three methods provide a reasonable prediction of the near-wake time-averaged wake structure, accurately predicting the location and extent of the counter-rotating vortices.

3.2. Transient flow features

One measure of characterising the unsteady wake behaviour is the Strouhal number of the oscillating twin vortices. For the present study this was determined at a monitor point $1H$ behind the tail. The URANS, SAS and DES predictions of the Strouhal number were 0.113, 0.243 and 0.206, respectively, compared with a result from wind tunnel testing of $0.20 \sim 0.21$ [2]. Hence, for this measure DES provides a closer prediction, while URANS significantly under predicts the wake frequency and SAS slightly over predicts it. Of course, it needs to be borne in mind that the cost of SAS is approximately 1/10th of DES, and URANS is approximately 100 times less expensive than DES. Views of the instantaneous wake structure as predicted by the different approaches are also given in figure 3(b). This wake is depicted using isosurfaces of Q-criterion at an arbitrary time instant. Clearly URANS does not capture the chaotic finer-scale flow structures explicitly, although the meandering large-scale counter-rotating vortex pair is visible, even though it oscillates at the wrong frequency. Both SAS and DES predict smaller-scale features of the wake, and there is some evidence that DES predicts features down to a smaller length-scale, as might be expected.

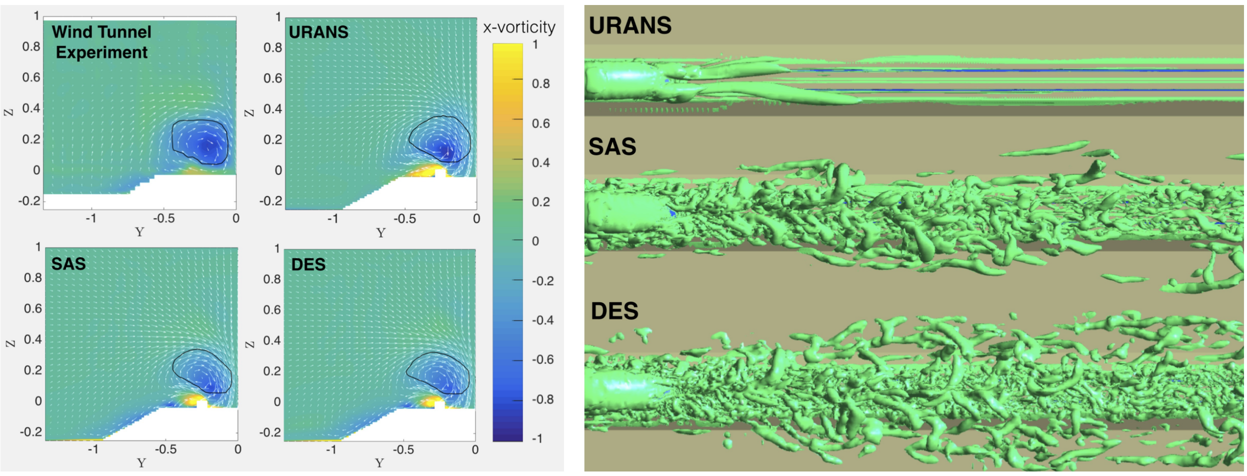

Figure 3: Left: Comparison of the time-averaged flow structure, visualised through vorticity contours in a cross-stream plane at $1H$ behind the tail; Right: Comparison of the transient wake structure, visualised by isosurfaces of constant Q criterion.

3.3. Slipstream velocity predictions

The slipstream velocity was measured at: (1) the trackside height along the length of the train, (2) $1W$ offset from the centre plane, and (3) $0.05H$ above the top of rail, as specified by European regulations [7]. The slipstream velocity was calculated through the following equations, with all velocity components normalised by the free-stream velocity:

$$U_{GF} = 1 - \frac{U_{TF}}{U_L}\ ,\ U_{slipstream} = \sqrt{U_{GF}^2 + V^2}.$$

Here, U_{GF} is the ground-fixed streamwise velocity; U_{TF} is the train-fixed streamwise velocity; U_L the freestream velocity; V the lateral velocity; and $U_{slipstream}$ the slipstream velocity.

Qualitatively, the slipstream profiles for the three methods have the same trend: a local peak near the head, with the slipstream velocity gradually increasing towards the tail, as presented in Figure 4. After another local peak at the tail, the slipstream velocity reaches its maximum in the near wake and then decays. Quantitatively, URANS obtained a maximum slipstream velocity of 0.19, while SAS and DES predicted a magnitude between 0.1 and 0.11. These predictions can be compared with experimental results from tests conducted at Monash University and DLR in Germany: wind-tunnel testing gave 0.14, a moving model rig experiment gave 0.1 and full-scale testing indicated 0.09. Thus, SAS and DES methods show better consistency with experiments. The discrepancy beyond $5H$ downstream between the numerical and experiment results are currently under investigation.

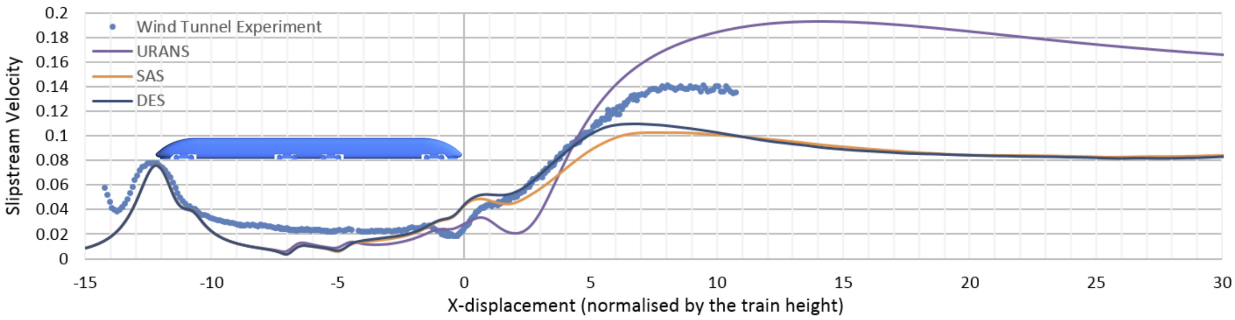

Figure 4: The comparison of slipstream velocity profiles measured at $z = 0.05H$.

4. Conclusion

Three widely used turbulence models, URANS, SAS and DES, have been evaluated based on their capabilities for the prediction of high-speed train wake structure and corresponding slipstream. URANS predicts the dominant wake flow structure qualitatively. However, due to its inability to predict even medium-scale turbulent features, the time-mean wake is not accurately predicted and thus its capability to estimate the slipstream velocity profile is limited. Both the time-averaged and low frequency unsteadiness obtained from SAS and DES are in good agreement, and are reasonably consistent with full-scale and wind-tunnel experimental measurements. Although DES predicts turbulence down to finer scales, its computational cost is approximately one order of magnitude higher than SAS simulation, in large part because of the order of magnitude smaller timestep used for DES.

5. References

[1] European Committee for Standardisation. Cen railway applications - aerodynamics - part 4: Requirements and test procedures for aerodynamics on open track, en 14067-4:2005+a1. 2009.

[2] J.R. Bell, D. Burton, M.C. Thompson, A.H. Herbst, and J. Sheridan. Flow topology and unsteady features of the wake of a generic high-speed train. *Journal of Fluids and Structures*, 61:168 – 183, 2016.

[3] Hemida H. and Krajnović S. Les study of the influence of the nose shape and yaw angles on flow structures around trains. *Journal of Wind Engineering and Industrial Aerodynamics*, 98(1):34 – 46, 2010.

[4] Schulte-Werning B., Heine C, and Matchke G. Unsteady wake flow characteristics of high-speed trains. *Proc. Appl. Math. Mech.*, 2:332–333, 2003.

[5] Egorov Y., Menter F.R., Lechner R., and Cokljat D. The scale-adaptive simulation method for unsteady turbulent flow predictions. part 2: Application to complex flows. *Flow, Turbulence and Combustion*, 85(1):139–165, 2010.

[6] Muld T.W., Efraimsson G., and Henningson D.S. Flow structures around a high-speed train extracted using Proper Orthogonal Decomposition and Dynamic Mode Decomposition. *Computers and Fluids*, 57:87–97, 2012.

[7] Commission regulation (eu) no 1302/2014 of 18 november 2014 concerning a technical specification for interoperability relating to the 'Rolling stock — locomotives and passenger rolling stock' subsystem of the rail system in the European union. *Official Journal of the European Union*, November 2014.