VALIDATION OF CFD FOR THE FLOW UNDER A TRAIN WITH 1:7 SCALE WIND TUNNEL MEASUREMENTS

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Abstract. With the occurrences of ballast stones projecting from the track during high speed operation without snow or ice the aerodynamic load on the track induced by the train has come into focus. Within the research cooperation “Aerodynamics in Open Air” (AOA) aimed at understanding the ballast projection phenomena one part looked at CFD simulation of the flow under the train. A generic train-underfloor wind tunnel experiment was used to validate commercially available computational approaches and particularly turbulence modeling with given limitations on mesh size such that at least one car of the train can be simulated with at the time available computer resources among the partners in the AOA project. The results presented were attained with CD-Adapco’s codes Star-CD and Star CCM+.

The flow is challenging with impingement, separation and reattachment about the rounded and edgy details of the bogies followed by flow about a funnel shaped bogie cavity end with vortices about the angled edges and highly turbulent flow separation after the funnel apex interacting with the inter car gap. The Reynolds no. (Re) was not enough for high-Re models wherefore only low-Re models were assessed. k-ε based RANS models performed well about the bogie but as all RANS models struggled after the funnel apex. Contrary DES performed well after the funnel but the performance about the bogie was dependent on model, method and convective discretisation. The original formulation of DES based on the S-A model suffered from depleted stresses which is alleviated with the DDES formulation. The DES k-ε model with blending of Mars 1.0 and central differences for the convective discretisation showed good overall accuracy. The same seems to be the case for the DDES, however, local peaks in the fluctuating velocity at mesh transitions causes some uncertainty in the results. The reason is not known but only occured when using a convective blending scheme.
1 INTRODUCTION

It has been known for many years that ballast stones can cause severe damage to trains if the movement is initiated sufficiently for a stone or stones to reach the train. Particularly the phenomena got attention in Germany and Japan [1, 2], and later in Sweden [3]. The induced momentum can cause an avalanche effect of stones being projected from the ballast bed to the train. When leaving the underside of the train stones reportedly projected up to 40 m to the side and 6 m up in the air behind the train [1] potentially damaging other trains or track side infrastructure. These problems were associated with snow and ice falling from the train. For this reason the ballast level was lowered below the sleeper level by about 4 cm in countries with cold climate as Germany and Sweden such that ice falling from a moving train would always hit a sleeper and be destroyed. In Japan various measures were applied to trains and track. The lowering of the ballast level solved the problem and also at high speeds there was no significant problem summer or winter. During homologation runs in Belgium with ICE 3 the problem re-occurred and significantly damaged the underside of the train [4]. Later incidents have also occurred on new high speed lines in Spain, Italy [4], UK [5] and South Korea [6]. This has lead to speed restrictions which impair the high speed train operation.

Since TGV has been running in Belgium without problems and likewise ICE 3 in Germany the phenomenon is partly associated with the train induced aerodynamic loads and partly with the specific track conditions. As the train speed increases the problem will increase in importance. Therefore characterisation and in the long run limitation of aerodynamic loads on track is necessary in order to have continued development of high speed train operation.

The identification of the new phenomena of ballast projection without influence of snow or ice falling from the train led to the project Aerodynamics in Open Air (AOA) where WP 1 was devoted to underfloor aerodynamics and essentially extending the knowledge about ballast projection. AOA was a DeuFraKO (German-French cooperation) project extended to include other interested railway parties in Europe. The work included full scale measurements of the flow under a train, wind tunnel measurements of ballast dislodgement, measurement and simulation of stone projection behaviour, numerical simulation of the flow under trains and modelling of the overall process [4].

Investigations of particle dislodgement, particularly sand grains [7-9], show that the main parameter determining the dislodgement is the shear stress. Measurement of the shear stress on the track under a train is very difficult [10]. The alternative is to measure the flow properties above the track. Also this has difficulties and limitations with respect to spatial and temporal resolution. Due to the shifting train surface passing above the track alternating between rough and smooth surface the flow field and turbulence are varying making it difficult to establish the relationship between the load on the track and the measurement of flow properties above the track. Model scale measurements are also challenging since the relative movement between train and track is required meaning either moving belt or moving train. Both poses challenges to get even limited data as well as being costly. It is therefore of great interest to use computational fluid dynamics (CFD) where the whole flow field is available and the relation between train geometry and the load on the track can better be deduced. CFD can also assist full scale measurements by at the same time have the shear stress on the track and the flow properties above it.

On the other hand the highly turbulent flow under a train poses challenges also for simulations including large separation regions, reattachment, separation at both sharp edges and cylindrical surfaces, longitudinal vortices, geometrical expansions and contractions. The Couette type flow is regularly interrupted by the passing bogies with many geometrical details and the cross-sectional changes at the inter-car connections.
For this reason within the AOA project a 1:7 scale wind tunnel set-up of a generic underfloor arrangement reported in an accompanying paper [11] was designed to validate commercially available computational approaches and particularly turbulence modelling. Since the flow contains features that are known to be troublesome for standard RANS (Reynolds averaged Navier-Stokes) approaches also more recent developments as DES (detached eddy simulations) [12, 13] combining RANS and LES (large eddy simulations) have been evaluated. For high Reynolds number (Re) flows where LES is too computationally expensive DES is a less costly alternative combining the good prediction performance and efficiency of RANS in near wall regions and the accuracy of LES where the turbulent length scale can be resolved down to the transfer range of the energy spectra. DES has particular benefits over RANS and URANS when the flow has significant separation regions with transient behaviour. On the other hand DES is inherently transient wherefore the computational cost is significantly higher than for steady RANS methods. The shortcoming of the originally proposed DES approach, grid induced separation due to a near wall transition from RANS to LES has been addressed within DDES (delayed detached eddy simulations) [14, 15]. One DDES method has been evaluated on the generic underfloor arrangement denoted BIAC (bogies in a channel).

The end goal is to predict the loads on the track and be able to relate it to features on the train. In this industrial context very accurate predictions are not necessarily required although it would be desirable. Local deficiencies in the flow predictions can be acceptable as long as the overall flow field is reasonably correct particularly towards the track and the origin of locally higher loads on the track can be discerned. Further to using commercially available models and software the study is limited to mesh sizes such that at least one car of the train can be simulated with at the time available computer resources among the partners in the AOA project.

2 GEOMETRY AND MESH

The wind tunnel test was on a generic underfloor geometry in scale 1:7 representing motor bogie, inter car gap and trailer bogie. Since the main flow features are expected – and was also seen in the measurements – to occur before the trailer bogie, the computational effort was reduce by leaving out the trailer bogie and cavity, Fig. (1). The channel height $h = 68 \, mm$ and the domain extent was:

- $x$: -1085 to 833 $mm$; $y$: -250 to 250 $mm$; $z$: -109.5 to 68 $mm$

The simulations were mainly on a mesh with polyhedral cells, Fig (2), but to not have restrictions to one code also a tetrahedral mesh was used. The tetrahedral mesh had a similar general cell size but naturally have more cells. The mesh was designed to cater for DES, and no coarsening for RANS was investigated. The inlet and outlet sections were extruded from the volume mesh. The general cell size $\Delta$ was 4.3 $mm$, corresponding to 30 mm on a full scale train. Some refinements were used on the bogie surface mesh to resolve small cylindrical parts, Fig. (2). Due to overall mesh size restriction the complex bogie geometry still has a relatively coarse mesh. In this sense the study has an industrial engineering focus rather than scientific and will give the accuracy and deficiencies of various approaches with the given restrictions on the mesh. Mesh refinement was done in two steps, first the volume mesh around the shear layers, Fig. (3), secondly the prism layers normal to the walls such that the wall normal cell height was halved and the no. cells doubled within the same total prism layer height. The volume mesh was refined to $2\Delta/3$ in the region shown in Fig. (3). Additionally the shear layer ahead of the bogie and in the inter car gap as well as around the rear edges of the bogie cavity was refined to $\Delta/3$. 


The low-Re reference or basic mesh have 6 prism layers adjacent to the walls, first layer being 0.043 \textit{mm} giving $y^+$ about 2 and lower. Due to overall mesh restrictions the number of prism layers were limited and the growth rate was as high as 1.7. A high-Re mesh variant had one prism layer of 1.4 \textit{mm} height. On the polyhedral mesh the cells adjacent to the outer prism layer are approximately half the size in the normal direction. The number of cells of the different meshes is given in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>BIAC mesh</th>
<th>Low / high-Re</th>
<th>Cell type</th>
<th>No. fluid cells</th>
<th>No. surface cells bogie</th>
<th>No. surface cells total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reference</td>
<td>low-Re, low-Re</td>
<td>Poly, Tet</td>
<td>2 446 285</td>
<td>62 139</td>
<td>202 606</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7 768 470</td>
<td>104 004</td>
<td>321 592</td>
</tr>
<tr>
<td>2</td>
<td>Volume ref.</td>
<td>low-Re</td>
<td>Poly</td>
<td>4 846 779</td>
<td>159 932</td>
<td>363 840</td>
</tr>
<tr>
<td>3</td>
<td>Volume ref. + prism ref.</td>
<td>low-Re</td>
<td>Poly</td>
<td>6 894 994</td>
<td>159 932</td>
<td>363 840</td>
</tr>
</tbody>
</table>

Table 1: Meshes and number of cells.

Figure 1: Computational domain.

Figure 2: Computational polyhedral mesh. Left: volume mesh. Right: bogie surface mesh.

Figure 3: Surface mesh showing shear layer refinements.
3 SIMULATIONS AND RESULTS

The simulations used constant inlet conditions with Re 1.1\times 10^5 based on the channel height \( h \), 3\% turbulent intensity and \( h/2 \) turbulent length scale. Tables 2 and 3 show the simulations performed. Within the AOA project additionally Politecnico di Milano performed a RANS simulation using Fluent with the realizable \( k-\varepsilon \) turbulence model and DB AG a LES simulation using CFX, both on the tetrahedral mesh. The reason for the LES on a non-purpose mesh was that the DES failed on the unstructured grid. The results are compared to LDA measured data reported in an accompanying paper [11].

All simulations were performed with Star-CD v4 or v4.04 except for the Realizable \( k-\varepsilon \) and the DDES which was made with Star CCM+. The SIMPLE pressure-correction type solution algorithm was used for the algebraic finite-volume equations. For the transient simulations a second-order \emph{Three level implicit} time discretisation was employed. Each DES simulation was started from the converged corresponding RANS simulation. Averaging started after about 535 \( h/U_{\text{ref}} \) and was performed for about 160 \( h/U_{\text{ref}} \) corresponding to about 11-12 passages of the motor bogie and inter car gap regions. The DDES was averaged over a time corresponding to 6 passages of the motor bogie and inter car gap regions and the DES SA with blending over 3 passages. The later due to lack of time will have uncertainty in the result, however, sufficiently accurate for the purpose here.

In general the convective discretisation employed the Star specific monotone advection and reconstruction scheme (MARS), a second-order accurate TVD like bounded scheme. A compression factor controls the amount of second-order upwinding, low values representing more upwinding (numerical diffusion) and high values less upwinding. The recommended value for RANS of 0.5 was generally used which gives a compromise between computational efficiency and sharpness in the resolution of gradients. A variation of 0.9 was also simulated. For the DES the minimum numerical diffusion is attained with a blending scheme between MARS 1.0 and central differencing (CD), where the aim is to use CD in the LES region. In Star CCM+ MARS is not available hence a similar blending scheme is employed with 2\textsuperscript{nd} order upwind replacing MARS 1.0.

The simulations were mainly on a low-Re mesh with \( y^+ \) about 2. A high-Re mesh was also tested, however, the RANS solution was transient and with DES the transition to the LES region was already after the first cell and the results were not good. The conclusion was that the Reynolds number was too low to test a high-Re approach.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Low / high-Re</th>
<th>Mesh no.</th>
<th>Turbulens model</th>
<th>Convective discretisation</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BT-Qke</td>
<td>low-Re</td>
<td>1</td>
<td>Quadratic ( k-\varepsilon )</td>
<td>Mars 0.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>BT-Qke tet</td>
<td>low-Re</td>
<td>1,tet.</td>
<td>Quadratic ( k-\varepsilon )</td>
<td>Mars 0.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>BT-Ske</td>
<td>low-Re</td>
<td>1</td>
<td>Standard ( k-\varepsilon )</td>
<td>Mars 0.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>BT-kOmegaSST</td>
<td>low-Re</td>
<td>1</td>
<td>( k-\omega )SST</td>
<td>Mars 0.5</td>
<td>URANS</td>
</tr>
<tr>
<td>5</td>
<td>BT-Qke Vref</td>
<td>low-Re</td>
<td>2</td>
<td>Quadratic ( k-\varepsilon )</td>
<td>Mars 0.5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>BT-Qke Vref Pref</td>
<td>low-Re</td>
<td>3</td>
<td>Quadratic ( k-\varepsilon )</td>
<td>Mars 0.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>BT-Qke M09</td>
<td>low-Re</td>
<td>1</td>
<td>Quadratic ( k-\varepsilon )</td>
<td>Mars 0.9</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>BT-Qke Lsmall</td>
<td>low-Re</td>
<td>1</td>
<td>Quadratic ( k-\varepsilon )</td>
<td>Mars 0.5</td>
<td>1/10\textsuperscript{th} turb. length scale</td>
</tr>
<tr>
<td>9</td>
<td>BT-Rke</td>
<td>low-Re</td>
<td>1</td>
<td>Realizable ( k-\varepsilon )</td>
<td>2\textsuperscript{nd} order Upw.</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>high-Re</td>
<td>4</td>
<td>Quadratic ( k-\varepsilon )</td>
<td>Mars 0.5</td>
<td>Unsteady, no solution</td>
</tr>
</tbody>
</table>

Table 2: RANS and URANS simulations.
The mesh refinements showed only small and local changes to the flow field in relation to the discrepancies with measurements. In combination with the good correspondence to measurements achievable with DES, it was concluded that the reference mesh is sufficient to assess the influence of simulation approach.

No. | Name | Low / high-Re | Mesh no. | Turbulence model | Convective discretisation | Courant no. | Comment |
--- | --- | --- | --- | --- | --- | --- | --- |
10 | BT-DES | low-Re | 1 | k-ε | Blend Mars 1.0 & CD | Max 57 Mean 0.11 | Time step 0.00567 h/U_{ref} |
11 | BT-DES dt5 | low-Re | 1 | k-ε | Blend Mars 1.0 & CD | Max 199 Mean 0.36 | Time step 0.0189 h/U_{ref} |
12 | BT-DES HiRe | high-Re | 1 | k-ε | Blend Mars 1.0 & CD | Max 117 Mean 0.09 | Time step 0.00567 h/U_{ref} |
13 | BT-DES M09 | low-Re | 1 | k-ε | Mars 0.9 | Max 177 Mean 0.36 | Time step 0.0189 h/U_{ref} |
14 | BT-DES SA M05 | low-Re | 1 | S-A | Mars 0.5 | Max 7.4 Mean 0.27 | Time step 0.0189 h/U_{ref} |
15 | BT-DES bl | low-Re | 1 | S-A | Blend Mars 1.0 & CD | Max 3.1 Mean 0.09 | Time step 0.00567 h/U_{ref} |
16 | BT-DDES | low-Re | 1 | S-A | Blend 2nd order Upwind & CD | Max 910 Mean 0.25 | Time step 0.0189 h/U_{ref} |

Table 3: DES simulations. No. 15 has shorter averaging time.

3.1 General flow field

Figs. (4-7) gives an impression of the flow field. The flow in the BIAC at the forward edge of the bogie cavity separates much like a backward facing step. A shear layer forms and hits the trackside parts of the bogie. Around these there is separation about rounded shapes and sharp edges, reattachment and split of the flow where some goes into the cavity. At the funnel shaped downstream bogie cavity end the flow is collected and directed towards the track at the apex, causing massive separation.

![Non-dimensional axial velocity](image)

Around the angled funnel edges two counter rotating vortices form. Also the wheels cause longitudinal vorticity. The inter car gap is a cavity with recirculation flow having a lateral component. The bogie parts retard the flow particularly between the wheels. At the end of the
bogie cavity the flow is accelerated. Typical for a confined flow the reduction of flow in the central part causes increased flow towards the outer parts of the channel. At the funnel apex there is a strong flow out of the cavity causing a separation bubble. Above this separation bubble the flow is also accelerated due to the confining walls.

Fig. (5) gives an impression about the differences in flow by the “best” RANS simulation (no. 1) and the more accurate “best” DES simulation (no. 10). The general flow features are
similar and as mentioned flow differences may be emphasised by the confining channel walls. After the funnel apex the separation is larger for the RANS while the vertical spread of the retardation is larger for the DES. It was found that the turbulence induced Reynolds stresses where larger in the DES than in the RANS.

![Visualization of instantaneous vortical structures with iso-surface of $\lambda_2 = -4e-5$ for BT-DES.](image)

Figure 7: Visualization of instantaneous vortical structures with iso-surface of $\lambda_2 = -4e-5$ for BT-DES.

### 3.2 RANS

Fig. (8) shows the lateral variation of the mean axial velocity at different heights just upstream of the inter car gap. The BT-DES results are included for extra reference since these where found to be fairly accurate. The mesh refinements showed only small and local changes to the flow field in relation to the discrepancies with measurements. On the tetrahedral mesh the flow was largely the same as on the polyhedral mesh. However, the discrepancies were slightly larger than found with the mesh refinements suggesting some influence of the cell type. The benefits of polyhedral cells and the differences to tetrahedral cells are discussed in [16, 17]. The main part of comparisons is on the reference mesh limiting the influence of the mesh.

The results with the standard $k-\varepsilon$ model are fairly similar to BT-Qke but with a smaller separation after the funnel apex. It is well known that the standard $k-\varepsilon$ model overly produce turbulence at flow impingement [18] and under predict separation, however, in this case it reduces the too large separation predicted by the RANS models, see Fig. (4) and (8). With the $k-\omega$ SST RANS turbulence model it was not possible to have a steady solution. It was instead necessary to solve this with unsteady RANS. For this particular case the solution was less accurate than with both the quadratic and standard $k-\varepsilon$ models. The realizable $k-\varepsilon$ model, which is largely the standard $k-\varepsilon$ model with $C_\mu$ being computed from the flow variables to ensure physical realizability of the modelled Reynolds-stresses and the turbulent time scale rather than being a constant, shows differences to both the quadratic and standard $k-\varepsilon$ models but is not an improvement.

The simulation with less diffusive convective discretisation MARS 0.9 gave in general very small differences in flow field with in some areas slightly higher turbulence. For later reference to the DES simulations a simulation was performed with 10 times smaller turbulent length scale on the inlet boundary, i.e. 10 times larger dissipation rate. This had no influence on the solution.
3.3 RANS vs. DES and DDES

The results look at two regions of different character: close above the bogie showing how well the flow impinging and separating about the bogie details are predicted with the relatively coarse mesh resolution of the bogie details Fig. (10), and at the funnel shaped end of the bogie cavity into the subsequent channel section showing the capability to resolve the large scale turbulence, separation and counter rotating vortices Figs. (10-11).

The idea with detached eddy simulations is to solve thin boundary layers near walls with RANS and switch to LES away from walls in highly separated regions, the RANS turbulence model then acting as sub grid model. The simulation is transient by nature and resolves the larger scales of the turbulence as set by the grid size. Here two DES formulations have been applied, the original formulation proposed by Spalart et al. [12] with the Spalart-Allmaras (S-A) one equation turbulence model and a second based on the two equation $k-\varepsilon$ turbulence model [13]. There are two distinct differences between the models, the length scale and the structural equilibrium. Whereas the S-A model assumes local equilibrium the $k-\varepsilon$ model is able to account for local dissipation and thereby better capture effects like the interaction between separated shear layers with a wake.

In the S-A model the length scale is the distance to the nearest wall $d$, which in the DES formulation is replaced with

$$\tilde{d} = \min(d, C_{DES} \Delta_{DES}).$$

$C_{DES}$ is a constant and $\Delta_{DES}$ is the grid length scale. When the distance to the nearest wall is larger than the grid scale ($C_{DES} \Delta_{DES}$) the model is in LES mode. Here this occurs in the first or second cell outside the prismatic layers. In the DES $k-\varepsilon$ model the dissipation of turbulent kinetic energy ($\rho \varepsilon$) is reformulated using the turbulent length scale as...
\[ D_k = \rho \frac{k^{3/2}}{\bar{l}}, \quad (2) \]

where
\[ \bar{l} = \min(\frac{k^{3/2}}{\varepsilon}, C_{DES} \Delta_{DES}). \quad (3) \]

The model is in LES mode when the turbulent length scale is larger than the grid scale. Fig. (9) shows the RANS and LES regions in the case of the DES \( k-\varepsilon \) simulation according to Eq. (3). At the inlet the turbulent length scale is larger than the grid scale. Since there are no fluctuations generated, cf. Figs. (4-5), the dissipation of turbulent kinetic energy is larger than in the RANS simulation. Close to the walls the DES enters RANS mode quickly. Before the bogie cavity and generation of fluctuations the flow is in RANS mode. To correctly predict turbulence with a length scale larger than the grid scale at the inlet and downstream with DES the boundary condition needs to include velocity fluctuations. This is the normal case with LES but goes against the idea with DES, when it would be used as a wall model for LES (WMLES). The sensitivity of the simulation to the inlet turbulent length scale was tested with RANS but showed no noticeable influence. The turbulence level in the channel centre declines quickly and the turbulence in the flow approaching the bogie is dominated by the effect of upstream walls and shear layer. After the bogie cavity the flow is largely in LES mode outside the prism layers.

![Figure 9: RANS/LES regions in BT-DES, light – RANS, dark – LES. a) \( y = 100 \, \text{mm} \). b) at the end of the inlet channel. c) channel section between motor bogie cavity and inter car gap. For b) and c) right half is with mesh.](image)

In DES the grid length scale \( \Delta_{DES} \) is normally defined for structured grids as the longest edge length. In this case with polyhedral cells the definition is two times the longest distance between the cell centre and a cell face centre. A deficiency found with the DES S-A formulation discussed in [14] was that if the grid size parallel to the wall is less than the boundary layer height the transition to LES occurs in the boundary layer. At this position the mesh may be insufficient to resolve the turbulence whereby “depleted stresses” occur, lowering the skin friction and possibly inducing separation. Grid induced separation was noted by Menter and Kunz [15] who modified a DES version based on the \( k-\omega \) SST model using the already existing function identifying the boundary layer height based on flow properties, \( F_2 \), to avoid transition to LES mode inside the boundary layer. Spalart et al. [14] used an adaptation of this for the DES S-A model denoted DDES (applicable to any eddy viscosity based turbulence model).
Here the first DES model tested was the S-A version with $C_{DES} = 0.65$. The convective discretisation was MARS 0.5 which is not the most appropriate since it does not minimize the numerical diffusion for the LES region. The results showed clear indications of depleted stresses with very low wall friction, only 25% of the RANS BT-Qke on the tracks side wall, and premature separation and too large separation about the bogie. After the significant separation and turbulent region following the funnel apex the results where improved and better than with RANS. An additional simulation using blending of Mars 1.0 and CD for the convective discretisation confirmed that the very low shear stress is due to the model formulation. The lower numerical diffusion did however improve the solution, Fig. (10).

Due to the deficiencies noted above the DES $k$-$\varepsilon$ model was tested ($C_{DES} = 0.73$). First with MARS 0.9 having only a small portion of upwinding. The prediction was significantly improved compared to BT-DES SA M05 while still showing too large retardation region by the bogie towards the track side at some positions, which also gave some residual effects downstream. The next step was to use the recommendation from CD-Adapco to minimise the numerical diffusion by employing the blending of MARS 1.0 and CD for the convective discretisation, as well as having a mean Courant number of 0.1. This meant having a time step 0.3 times that of the previous DES simulations. The simulation results over the bogie significantly improved compared with the BT-DES M09 results and the already good results after the bogie cavity was further improved. The DES $k$-$\varepsilon$ model with blending gave very good results compared to the measurements and emphasised the benefits in accuracy achievable when resolving the large scale dynamics as with DES over RANS in the complex, highly turbulent and separated region after the bogie cavity. It was confirmed that the improvement was due to the change in convective discretisation rather than the decreased time step by an additional simulation using the larger time step, BT-DES dt5. Due to more iterations per time step the computational effort was very similar as with the smaller time step.

Figure 10: Non-dimensional mean axial velocity. Left: just above the bogie at various lateral positions offset by 1.0. Right: In the channel just upstream of the inter car gap at various heights offset by 1.0. Coordinates non-dimensional with the channel height, $h$. Bi01 and Biac II denotes measurement data from the first and second campaigns respectively [11].
The implementation of DDES into CCM+ gave the opportunity to test this. For some reason internal mesh planes on either side of the inter car gap with half polyhedral cells on one or both sides of the plane seemed to have some influence on the resolved turbulence as can be seen in Fig. (13b) at $x = \pm 2h$. The results therefore need to be taken as preliminary. The averaging time was also shorter, about 6 passages of the motor bogie and inter car gap regions. However, the impact seems local and at least the results for $x < -2h$ should be valid, which are very good compared with the measurements and similar to that of the DES $k$-$\varepsilon$ model with blending indicating the benefit of the DDES formulation over the bogie. Particularly the wall shear stress was significantly improved and similar to that of the DES $k$-$\varepsilon$ model. In Fig. (13b) at $x = -13h$ where there is another mesh change from extruded cells to polyhedral cells the DES $k$-$\varepsilon$ model with blending has a unphysical peak in $u_{\text{rms}}$. The effect is judged local and insignificant to the overall results, however, it is not seen with Mars 0.9 convective discretisation. Further investigations are required to determine if the blending scheme is contributing to the local peaks seen at changes in mesh size. On the other hand the peaks are not seen with DES S-A employing blending.

3.4 Wall shear stress

Fig. (12) shows the local friction coefficient on the trackside wall for BT-Qke and BT-DES. The results are typical for the RANS and DES simulations and the mesh refinement does not
change the qualitative picture. For the DES the mean wall shear stress is computed from the average velocity components as

\[ \tau_w = \mu \frac{U_{\|}}{y_{\perp}}, \quad (4) \]

where \( \mu \) is the dynamic viscosity, \( U_{\|} \) is the mean velocity parallel to the wall and \( y_{\perp} \) is the wall normal distance (0.0214 mm) to the cell centroid.

There are two main differences:

1. The general level is lower in the DES than the BT-Qke RANS, starting from the beginning to middle of the bogie cavity. The average shear stress on the trackside wall neglecting the inlet channel section is 15 % lower in the DES.

2. The peak fiction in the centre of the channel is in the DES right after the funnel apex whereas it is further downstream in the BT-Qke RANS. The peak value is in addition about 37 % higher than for the DES (conversely the DES peak value is 27 % lower than the BT-Qke RANS).

![Figure 12: Mean local friction coefficient on track side wall. For the DES it is computed from the near wall mean velocity (U & V components).](image)

Fig. (13a) shows the local friction coefficient along the centreline on the track side wall where it is included the instantaneous value for BT-DES. At least downstream of \( x = -4h = -272 \text{ mm} \), possibly earlier, the core flow turbulence impacts the near wall flow on the track side meaning that the RANS part of the DES is effectively a wall model for the outer LES. The intention with DES was not to be a wall model for LES whereas some attempts have been made [14]. The improvement DDES is neither aimed at improving WMLES application and an under estimation of the friction coefficient by 15 % due to a shortcoming denoted “log-layer mismatch” is mentioned [14]. Travin et. al [19] addresses the issue of using DES or DDES as WMLES and suggests some adjustments to this purpose. Having Figs. (4-5) in mind it seems like the initial decrease in friction coefficient from the beginning of the bogie cavity is connected to a growing boundary layer with increasing turbulence content without fluctuations yet being generated.

The second difference above can partly be connected to the differences in flow field after the funnel apex, Figs. (4, 6, 11, 13b). For BT-Qke the separation bubble is larger and the retardation at the train side remains longer. In combination with the constricting channel walls and lower turbulent viscosity the speed up near the trackside wall is larger and remains longer. The turbulence generated at the separation shear layer spreads slower towards the track side wall where the peak occurs later, at the end of the inter car gap. The conditions in the central
part of the channel after the funnel apex with significant streamline curvature and longitudinal pressure gradients are known to be difficult for the RANS turbulence models. Under a train the trackside wall would be moving and rough and without confining walls the flow would be able to move laterally. In this sense it is expected that the wind tunnel configuration is more difficult for the RANS models than under a train.

When looking closer at the track side wall friction coefficient it was noticed that different turbulence models gave quite large differences already at the end of the inlet section. A small two-dimensional test case was designed corresponding to the BIAC inlet section to assess the influence of the wall normal spacing and stretching. In the stream wise direction there was 100 cells of uniform length 4.3 mm. Relative local friction coefficient towards the end is given in Table 4. To check whether the block profile at the inlet was a cause of the differences periodic boundary conditions were applied with the same and constant mass flow rate. The results are very similar confirming a clear variation between the models that can be reduced – but not removed – by reducing the wall normal spacing and growth rate to what is normally recommended. The wall friction can also be tweaked by adjusting the model parameters. The values with Ske becomes almost the same as the Qke if $C_\mu = 0.07$.

![Figure 13](image)

**Figure 13:** a) local friction coefficient ($c_f$) on track side wall, mean and for BT-DES also the instantaneous. b) mean axial velocity and $u_{rms}$ at $z/h = 0.88$. Biac II denotes measurement data from the second campaign [11].

<table>
<thead>
<tr>
<th>Turbulence model</th>
<th>Convective discretisation</th>
<th>$Y^+ = 2$ Growth rate 1.7 nominal $c_f$</th>
<th>$Y^+ = 2$ Growth rate 1.3 nominal $c_f$</th>
<th>$Y^+ = 1$ Growth rate 1.3 nominal $c_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prism layers</td>
<td>Inlet channel section</td>
<td>Fully developed channel section</td>
<td></td>
</tr>
<tr>
<td>Qke</td>
<td>Quadratic $k-\varepsilon$</td>
<td>Mars 0.5</td>
<td>Mars 0.5</td>
<td>Mars 0.5</td>
</tr>
<tr>
<td>Ske ($C_\mu = 0.09$)</td>
<td>Standard $k-\varepsilon$</td>
<td>Mars 0.5</td>
<td>Mars 0.5</td>
<td>Mars 0.5</td>
</tr>
<tr>
<td>KoSST</td>
<td>$k-\omega$SST</td>
<td>Mars 0.5</td>
<td>Mars 0.5</td>
<td>Mars 0.5</td>
</tr>
</tbody>
</table>

Table 4: Simple 2-D channel corresponding to the BIAC inlet channel. Relative friction coefficient. Two cases: inlet channel section with constant velocity inlet (value towards the end) and fully developed channel with the same mass flow rate by use of periodic boundary conditions.
4 CONCLUSIONS

The study shows the drawbacks and benefits of numerical approaches available in commercial software for an engineering application by comparison with measurements on a generic train underfloor arrangement. The wind tunnel setup is expected to contain many of the flow features under a train, albeit the deviations of constraining walls and a track not moving relative to the train introduces some differences and may also make the flow field more challenging for RANS models. At least when it is not feasible to have a very good mesh resolution of all geometry and to follow best practice in prism layer growth rate there are clear differences between RANS models, although even the best performing models failed to correctly predict the highly turbulent separation at the funnel apex. In this part of the flow all the DES models where considerably more accurate showing the necessity to resolve the large scale dynamics for accurate predictions. The original DES S-A model showed clearly to suffer the deficiency “depleted stresses” significantly reducing the wall shear stress causing separation to occur prematurely, noticeable over the bogie. The still relatively good results suggests the flow to be dominated by sharp edge separation. The DES based on the $k$-$\varepsilon$ model showed better performance, particularly as the numerical diffusivity in the convective differencing scheme reduced. It seems connected to susceptibility to the initiation of fluctuations, i.e. resolved turbulence, that starts in the shear layer at the beginning of the bogie cavity. As in all DES the fluctuations needs to be triggered which is more easily done with less diffusivity. A preliminary DDES showed an improved performance over the DES S-A without “depleted stresses” and is comparable to that of the DES $k$-$\varepsilon$ model with blending, both predicting the flow fairly accurately. Since there is an order of magnitude difference in computational time between a RANS and DES, the reasonable performance of the best RANS with known deficiencies is still a practical alternative and first choice. However, the clear benefits of DES or DDES are the aim for the future as computer capacity improves and knowledge about the models increase. The local peaks in DES fluctuating velocity seen with the blending scheme at changes in mesh size, particularly with CCM+, can be of interest if others have noticed as well.

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