Turbulent Wind Flow over a High Speed Train

R K Cooper
School of Aeronautical Engineering
Queen's University Belfast
r.cooper@qub.ac.uk

Keywords: train aerodynamics, cross-wind effects

Abstract:

The flow of a turbulent cross-wind over a stationary train, including the effect of an embankment, has been simulated by CFD. The coefficient of rolling moment about the lee rail have been compared with experimental data. Agreement is satisfactory for flat ground and a low (4m) embankment. The level of turbulence intensity was an important parameter for obtaining a correct simulation.

Acknowledgement:

Permission from Network Rail WCML, to use aerodynamic data obtained by BMT Fluid Mechanics Ltd., is gratefully acknowledged.

Introduction

Strong cross-winds may overturn trains, so an understanding of the fluid mechanics is important. To facilitate the proper estimation of the probability of a train overturning, accurate data for the aerodynamic rolling moment about the lee rail is essential. (Of course, many other parameters are required.) The flow of a turbulent cross-wind over a train moving across an embankment is complex, and difficult to model experimentally. Many experiments have been done with stationary model trains; some including turbulent flows. The aim of this work is to use such data to verify a CFD simulation with a stationary model train on an embankment. Clearly, even the 'best' such experiment is an approximation. However, CFD provides the ability to model the motion of the train with respect to the ground, with a turbulent cross wind, and this is the ultimate aim.

Experimental Data

It has been surprisingly difficult to obtain accurate aerodynamic data for trains in cross winds. The close proximity of train to ground implies that under-body flow must be carefully modelled, including the effect of rails. The effect of free stream turbulence has been found to be significant, and apparently contradictory results have been observed: e.g. for an APT leading vehicle, Fig. 1 [1]. To model turbulence with a sufficiently large integral length scale has proved to be difficult. Simulation of the motion of the train may be less significant than providing the correct turbulence scale [2]. This hypothesis may be tested using CFD simulation, provided the CFD method can be verified for a stationary train.

Electric locomotive hauled Mark 3 passenger coaches (Fig. 2), and the diesel powered High Speed Train (HST, or Intercity 125, Fig. 3), have been in use on Britain's railways for more than 30 years, without an overturning event, so provide a reference case. Recent experiments at BMT Fluid Mechanics in an atmospheric boundary layer (ABL) simulation [4] have provided aerodynamic data for the Mark 3 passenger coach. Models of a train (Class 87 locomotive and two coaches) of 1/7 scale and 1/30 scale were tested. Only the latter, shown in Fig. 4, is relevant to the present study. The ABL wind tunnel provided a good simulation at 1/30 scale, of the mean velocity profile, turbulence intensity profile, and turbulence length scale, compared with the ESDU model. The 'wind' was used to simulate the resultant flow with respect to a moving train. (Clearly, this was an approximation, but the effect of the degree of approximation is not considered here.) The side force, lift and rolling moment about the lee rail were obtained from a high frequency balance. Mean force and moment coefficients were obtained as a function of resultant yaw angle. Also, extreme value coefficients normalised with respect to an extreme resultant speed were obtained. Only the mean coefficients are considered in this report. The effect of Reynolds number was examined by comparing data for two model scales, over a range of tunnel speeds. For Reynolds number (based on body height and relative speed) exceeding $2*10^5$, no significant changes in surface pressure distribution or mean forces were observed. This proprietary data is considered to be amongst the most reliable, as a simulation of the full-scale case. The experiment was an approximation of reality, since the model train was stationary. But the flow turbulence was close to reality, so the effect of turbulence at least, should be representative.

A 1/50th scale wind tunnel model representing the Class 87 and Mark 3 coach has been tested at Queen's University Belfast. The side force and rolling moment about the lee rail were obtained for steady and unsteady flow cases.

Computational Domain

The CFD software used was Fluent 6. The Gambit meshing package was used to create the computational grid. A basic HST geometry was defined using a solid modeller, at full scale. The simplified train shape had no bogies or inter-vehicle gaps. Nose shape approximated the HST diesel locomotive, Fig. 3, with a solid under-body approximating the bogies. The cross-section was a close approximation of the Mark 3 coach, as a cylindrical body. Details, such as the roof ribs, were omitted. Note that this is not the same as the wind tunnel model, but the most significant difference is the nose shape.

The aim was to create as much as possible of the computational domain using structured grid. This involved considerable time and effort by two students [5, 6]. The regions around the nose and tail were unstructured. A box with a semicircular top was created around the train. The nose and tail were partitioned from the cylindrical centre section and the cylindrical volumes were further partitioned into parallelepiped boxes, as shown in Fig. 5. The train on an embankment was placed in an enclosing box, with a round top. This was extended by further regular volumes, as required. A typical mesh section is shown in Fig. 6. The mesh density in the structured region was easy to control and modify. This apparently simple grid evolved gradually, with much trial and error. The final grid had about 430,000 nodes.

The aim was to model wind tunnel cases, so the parameters were chosen to model incompressible flow at the Reynolds number of the experiment. The realisable k-e turbulence model was used. Wall functions were used to determine the boundary turbulence quantities. The cell sizes near the train surface and ground plane were chosen to give a satisfactory resolution of the wall boundary condition. The value of y^+ was maintained in the desirable range, viz. 30-60, over most of the embankment and train surface, with the exception of the lower train surface, which gave values 150-250. Probably, the grid in the gap region should be refined. The flow velocities in this region were small, so small changes would not necessarily have much effect of the forces.

The inflow velocity profile was defined to match the experimental profile. For the ABL simulation this closely matched the logarithmic profile with a surface roughness length of z_0=0.03m (full scale), corresponding to typical rural terrain, using the ESDU model. The inflow turbulence intensity and length scale were set, initially, to 3% and 3m, respectively.

Results

Train on flat ground

Flow streamlines around the train are shown in Fig. 7-9. For yaw angles less than about 70^0 a strong vortex is formed on the lee side. The vortex structure becomes unsteady at about 50^0. The computed coefficient of side force is compared with the QUB experimental data for a uniform inflow profile [1], in Fig. 10. The Reynolds number was $1.6*10^5$ for the experiment and 10% less for the CFD. There is a significant difference in the range 60^0 to 80^0. The CFD was able to replicate observed flow features on the windward side of the train. The attachment line moved down with increasing Reynolds number. This was associated with movement of a separation line on the ground plane upstream of the train, Fig. 9. This observation is significant, since the separation and attachment lines would be sensitive to flow turbulence as well as Reynolds number.

The computed side force coefficient is compared with the BMT experimental data for a logarithmic inflow profile, with Reynolds number of about $2.5*10^5$, in Fig. 11. Results for the coefficient of rolling moment about the lee rail are shown in Fig. 12. The experimental values of turbulence intensity at 3m height, were about 20% and 24m (referred to full scale), respectively. The CFD inflow turbulence intensity was 3%, with a length scale of 3m. The CFD did not simulate the flow correctly, as shown by the large difference in the results. The turbulence intensity was increased to 10%, and a much closer agreement with experiment was obtained. Visualisation of the flow streamlines showed that the separation on the ground upstream of the train was probably eliminated. Clearly, the turbulence parameters significantly affect the CFD modelling of this flow. (The investigation is still in progress, so the results are incomplete. In particular, the effects of turbulence length scale or ground surface roughness have not been investigated.) The results suggest that some of the observed variations between different wind tunnel experiments may be due to this effect. The highly turbulent inflow of the ABL experiment seems to eliminate the upstream separation. It also makes the flow over the train less susceptible to Reynolds number effects.

Train on an embankment

For a train on a 4m high embankment, experimental and CDF results are shown in Figs. 13 and 14. The inflow turbulence intensity was 3%. The CFD and experimental results are similar for the rolling moment, but not side force. This appears to contradict the result for the flat ground case above. The flow streamlines around the embankment and train are shown in Fig. 15. The flow is attached to the embankment slope and separates cleanly at the edge, reattaching upstream of the rail. It is surmised that the well-defined separation causes the flow to be less sensitive to inflow turbulence.

Train motion over the ground

It was easy to simulate the effect of the train moving over the ground with the CFD. Preliminary runs indicated only a small change from the corresponding steady flow case, but the inflow profile was not correctly skewed with height. The prospects for examining the effect of train motion and unsteady cross-wind gusts is encouraging.

Conclusions

CFD has been applied to the case of a train in a turbulent flow. The boundary layer behaviour, particularly on the ground just upstream of the train, was affected by the inflow turbulence intensity and scale, which thus had a strong influence on the forces and rolling moment. With appropriate turbulence intensity, the side force coefficient was predicted to good accuracy.

Bibliography

1. Ahmed, K., Development of wind tunnel techniques for unsteady train aerodynamics, MPhil Thesis, QUB Aeronautical Engineering, 2003.
2. Baker, C J, Ground vehicles in high cross winds. Part 1: Steady aerodynamic forces. J. Fluids and Structures, 1991, **5**, 69-90.
3. Baker, C J, Ground vehicles in high cross winds. Part 2: Unsteady aerodynamic forces. J. Fluids and Structures, 1991, **5**, 91-111.
4. WCRM Wind Loading Studies, Atmospheric Boundary Layer Studies. BMT Fluid Mechanics Ltd. Report 43309rep4v3, Final, 16 January 2003.
5. Fanning, C., CFD investigation of aerodynamics of a high speed train, QUB Aeronautical Engineering, MEng project report, May 2003.
6. Chraibi, H., Turbulent flow over a high speed train on an embankment, QUB Aeronautical Engineering, summer project report, Aug. 2003.

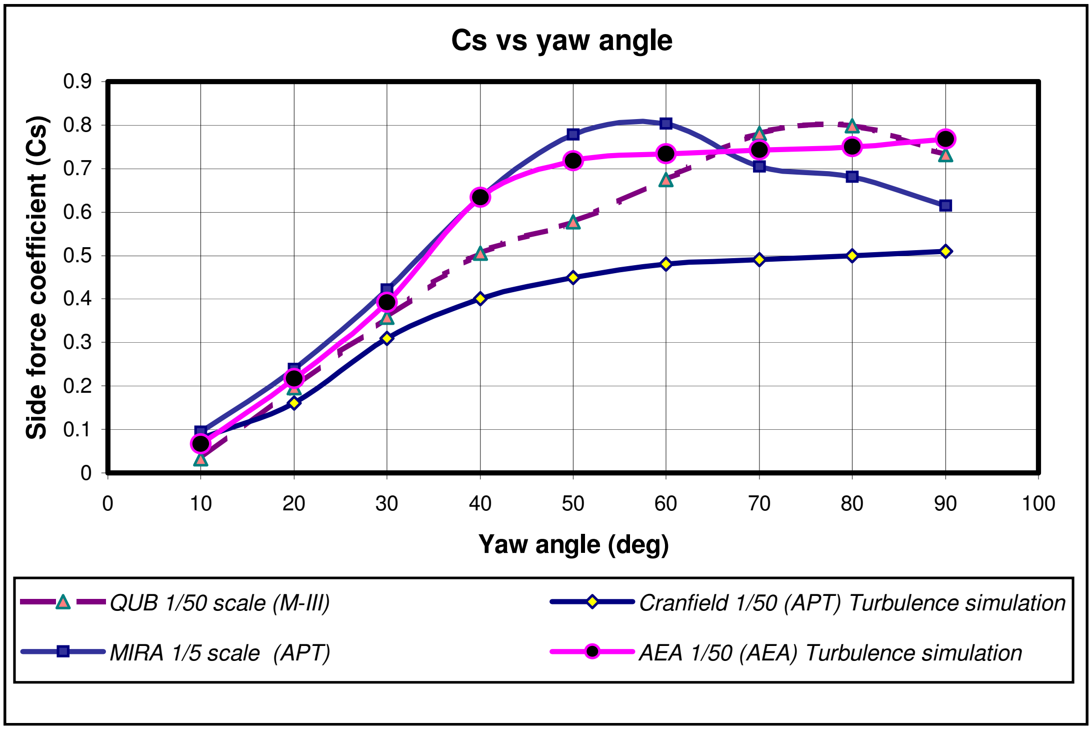

Fig. 1. Coefficient of side force vs. yaw angle: APT (various) and Mark 3 coach (QUB)

Fig 2. Class 87 locomotive and Mark 3 coaches: prototype for wind tunnel model

Fig 3. High Speed Train with Mark 3 coaches: prototype for CFD model

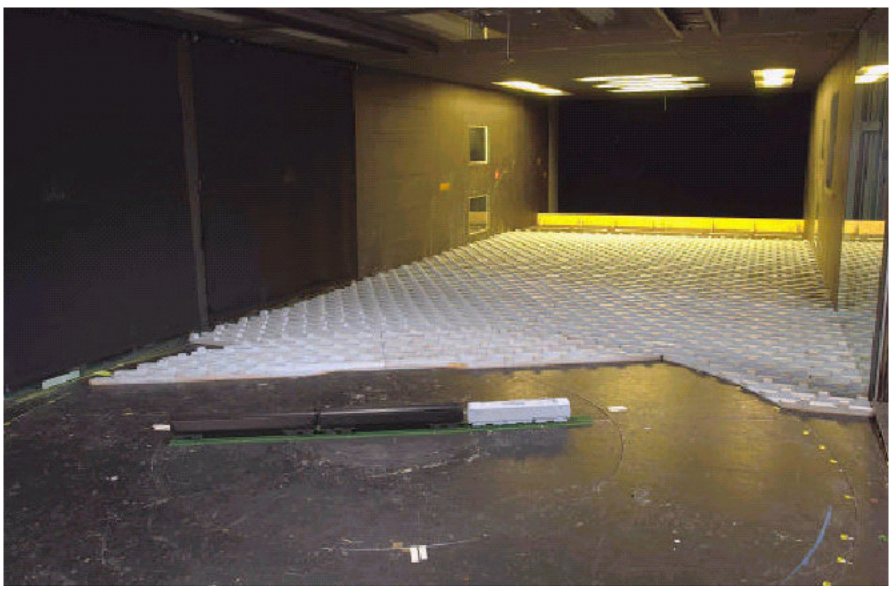
Fig.4. Model train (Class 87 locomotive + 2 Mark 3 coaches) in ABL wind tunnel (©BMT Fluid Mechanics Ltd.)

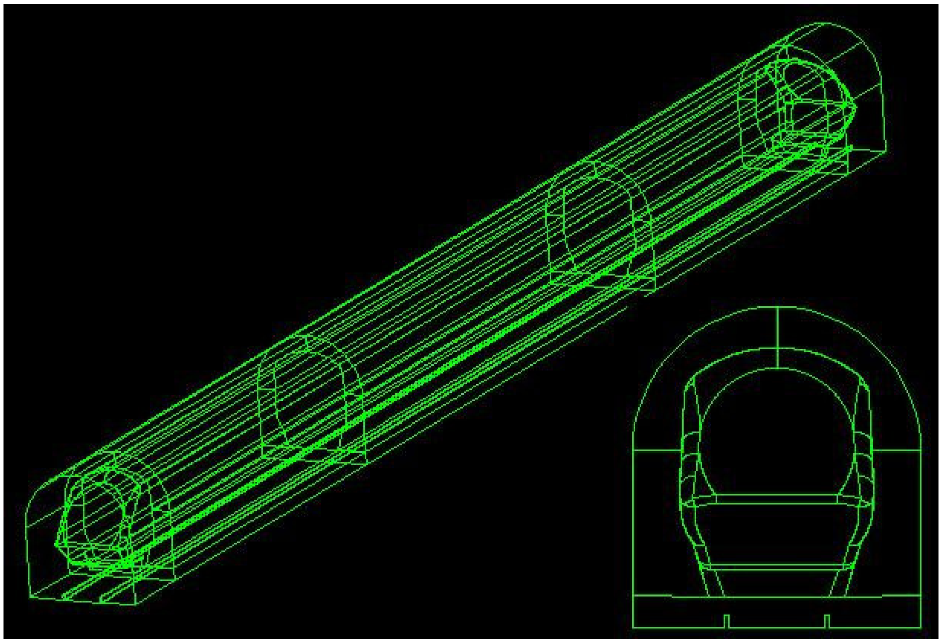

Fig. 5. Grid block structure around train.

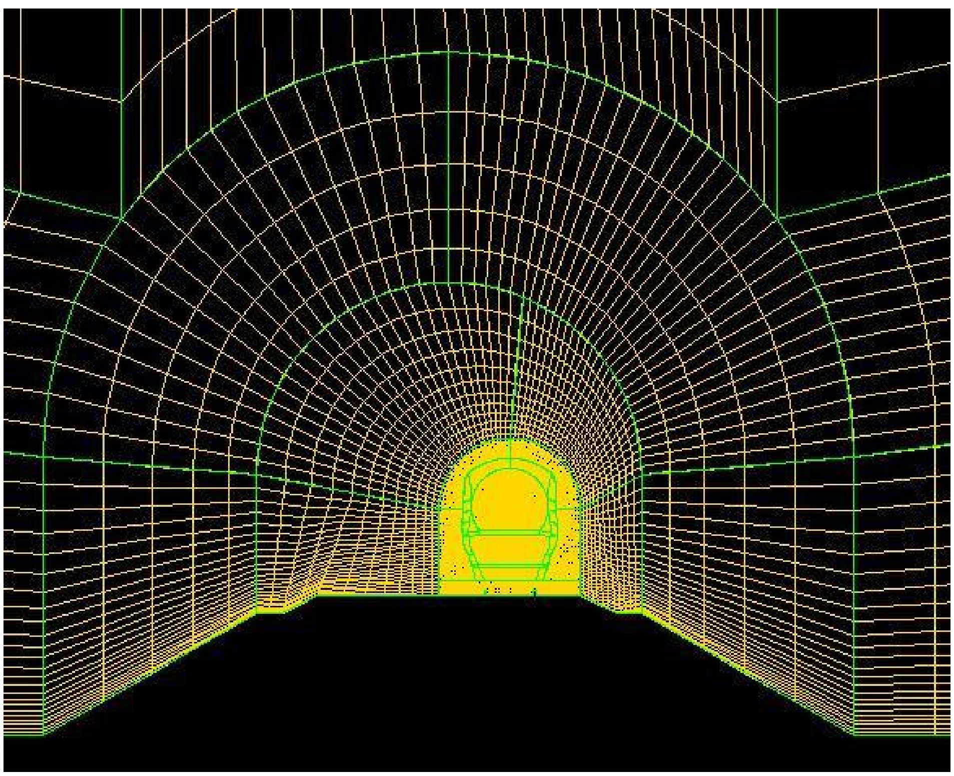

Fig. 6. Mesh section for train on embankment of height 4m.

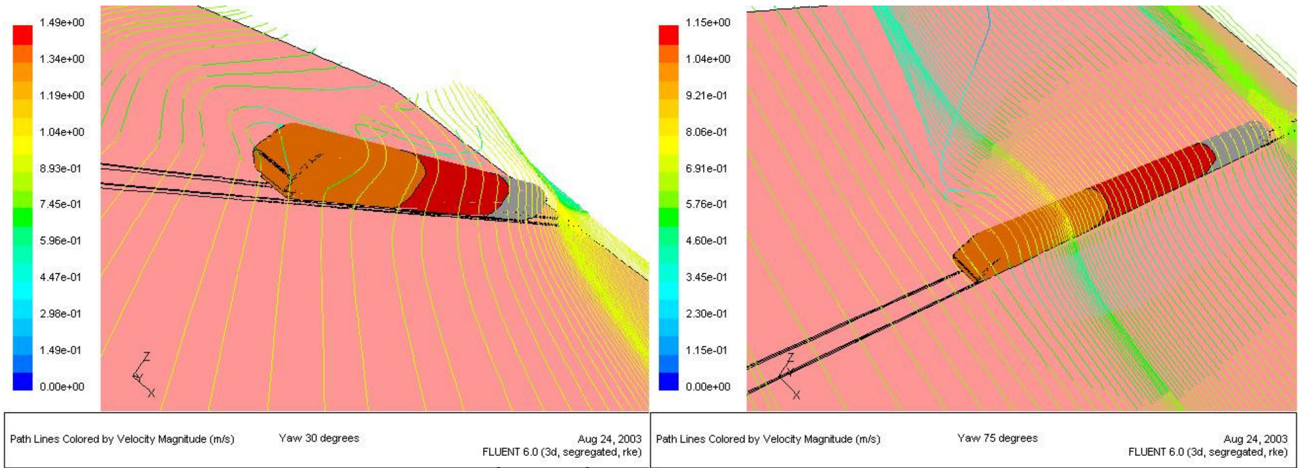

Fig. 7. Flow on flat ground at yaw angles of 30^0 and 75^0

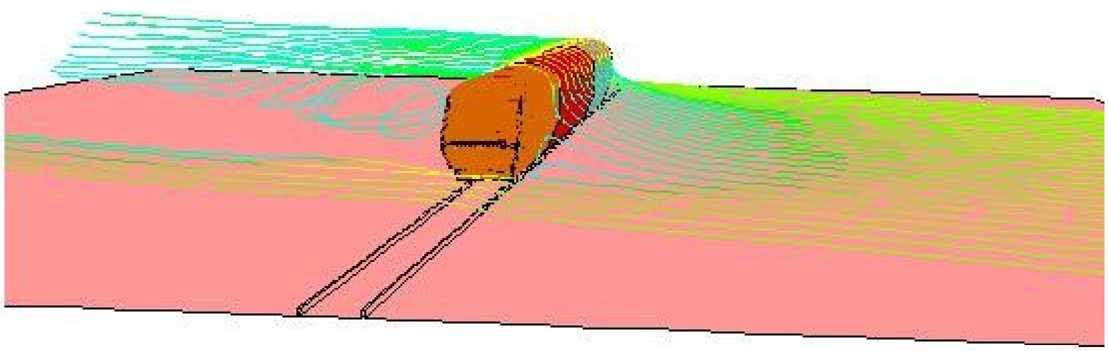

Fig. 8. Flow on flat ground at yaw angle of 60^0

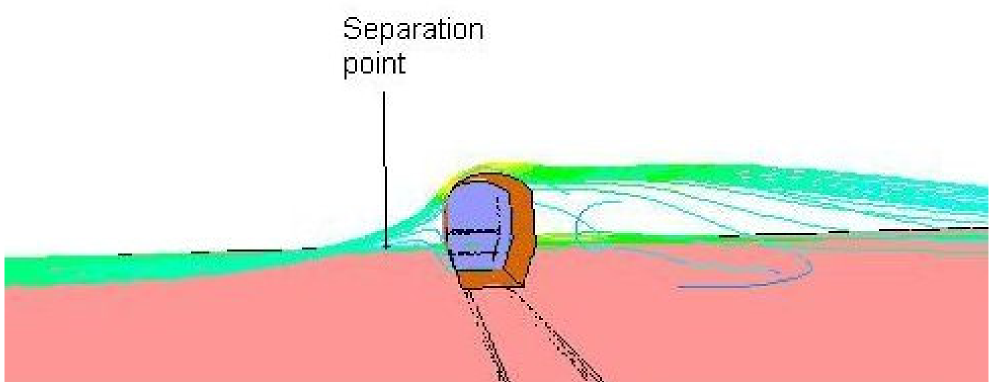

Fig. 9. Flow on flat ground at yaw angle of 60^0

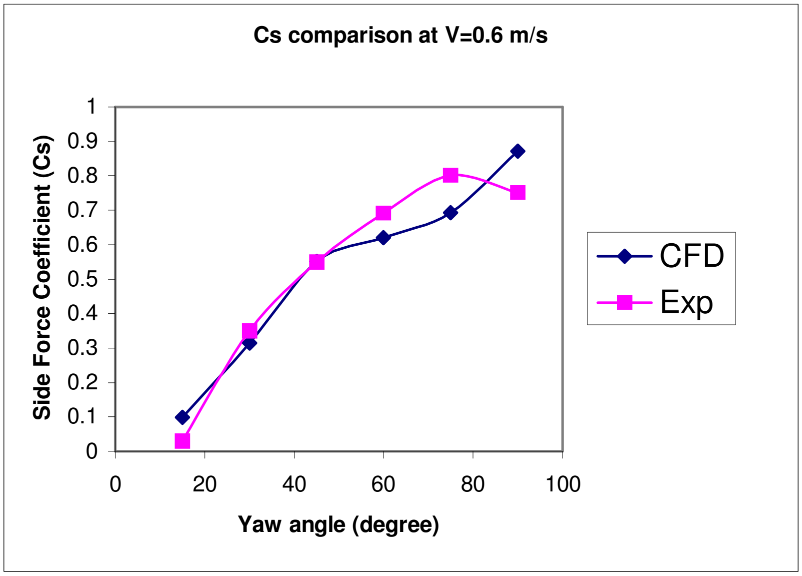

Fig. 10. Side force coefficient vs. yaw angle: QUB experiment, Re=1.6*10^5, flat ground.

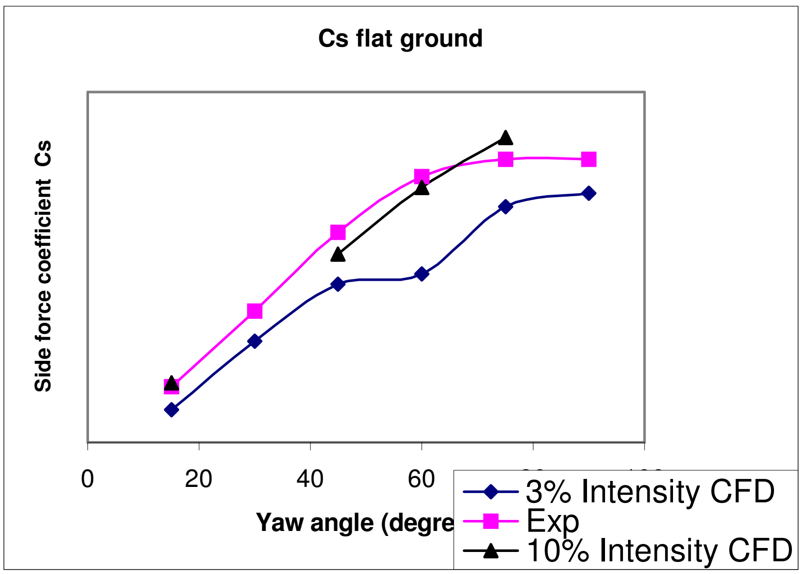

Fig. 11. Side force coefficient vs. yaw angle: BMT experiment, Re=2.5*10^5, flat ground.

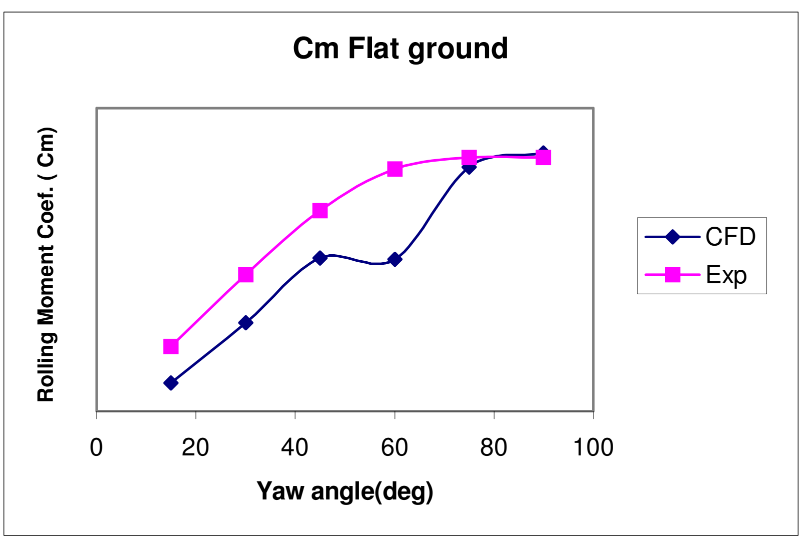

Fig. 12. Coefficient of rolling moment about lee rail vs. yaw angle:
BMT experiment, Re=2.5*10^5, flat ground. CFD turbulence intensity 3%.

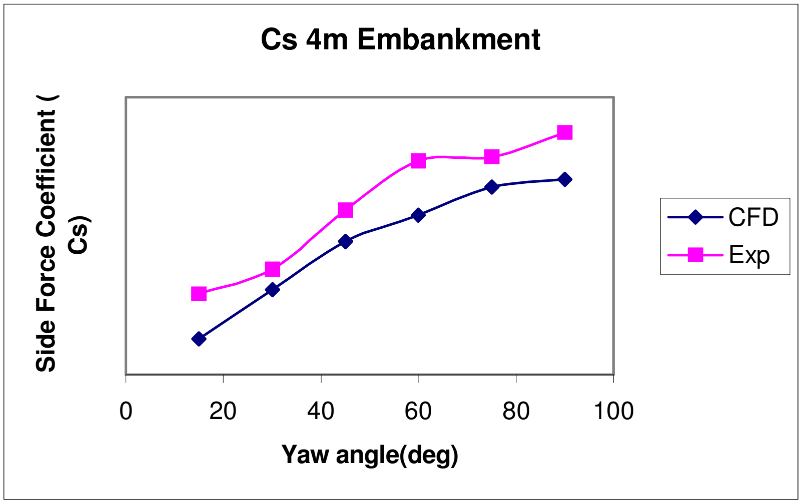

Fig. 13. Side force coefficient vs. yaw angle: BMT experiment, Re=2.5*10^5, 4m embankment.

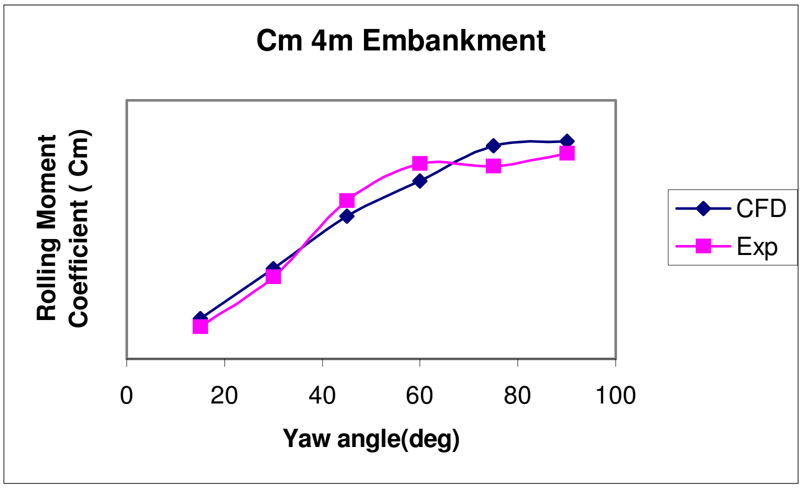

Fig. 14. Coefficient of rolling moment about lee rail vs. yaw angle:
BMT experiment, Re=2.5*10^5, 4m embankment. CFD turbulence intensity 3%.

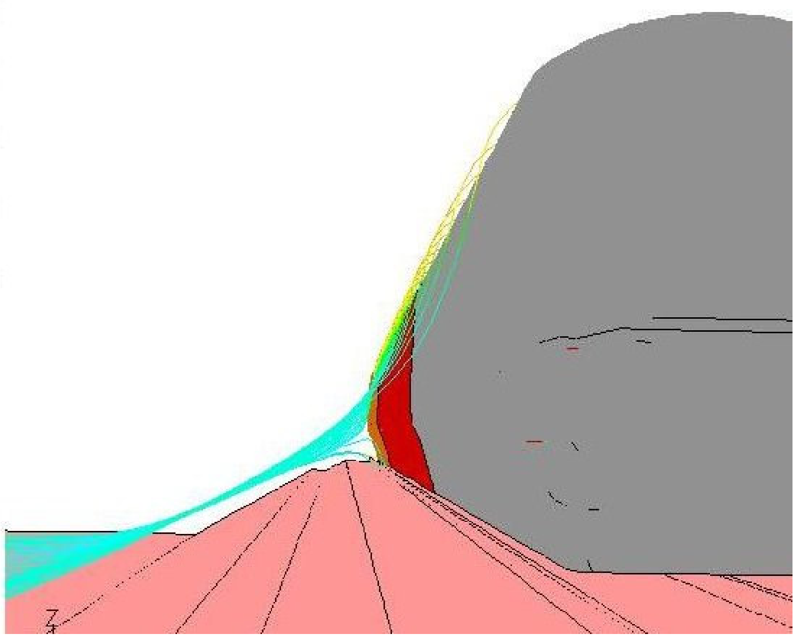

Fig. 15. Flow over train on 4m embankment.